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ESCUELA DE INGENIERIAS INDUSTRIALES

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Design of Drying Chamber

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TFG REALIZADO EN PROGRAMA DE INTERCAMBIO

TÍTULO:	Design of Drying Chamber
ALUMNO:	Alejandro López Perales
FECHA:	3/6/2025
CENTRO:	Faculty of Mechanics
UNIVERSIDAD:	Vilnius Tech
TUTOR:	Vytautas Bučinskas

Resumen en español (máx. 150 palabras)

La cámara de secado diseñada en este proyecto está destinada a ser utilizada para el secado de un material piezoeléctrico procedente del laboratorio de la Universidad. El agua contenida en su estructura afecta a las características del material, por lo que es necesario un secado controlado para optimizar los resultados. La tesis describe el diseño de una cámara. Basado en una antigua impresora 3D, el proyecto se ha centrado en calcular y diseñar las nuevas piezas necesarias para el nuevo propósito de la impresora. Después de que estos dispositivos se instalen y adapten con precisión, la cámara permitirá al usuario decidir los parámetros del proceso de secado y el sistema utilizará la información de los sensores y actuadores para alcanzar y mantener esos estándares a los niveles deseados. La tesis aporta no solo el diseño físico, sino también el algoritmo necesario que gobierna el funcionamiento del dispositivo. El trabajo también incluye las piezas requeridas.

Palabras clave: cámara, secado, ventilador, humedad, temperatura, sensor, calor

Abstract (max. 150 words)

The drying chamber designed on this project is intended to be used for drying a piezoelectric material from the laboratory. The water contained in its structure affects the output characteristics of the material, so controlled drying is needed to optimize the results. The thesis describes the design of a chamber. Based on an old 3D printer, the project has been focused on calculating and designing the new parts needed for the new purpose of the printer. After these devices are precisely installed and adapted, the chamber will allow the user to decide the parameters of the drying process and system will use the information of the sensors and actuators to reach and maintain those standards to the desired levels. The thesis provides not only physical design but also the necessary algorithm that governs the functioning of the device. The work also includes the required parts.

Keywords: chamber, drying, fan, humidity, temperature, sensor, heat

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF MECHANICS
DEPARTMENT OF MECHATRONICS, ROBOTICS AND DIGITAL MANUFACTURING

Alejandro López Perales

DESIGN OF DRYING CHAMBER

Final Bachelor's Project

Study programme MECHATRONICS AND ROBOTICS,
Code 6121EX048

Vilnius, 2025

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
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Alejandro López Perales

DESIGN OF DRYING CHAMBER

Final Bachelor's Project

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Supervisor: __Vytautas Bučinskas___ ________ 2025 25 28
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2025 05 28

TASK FOR BACHELOR THESIS

13 February 2025 No. 1
Vilnius

For student Alejandro Lopez Perales

Bachelor Thesis title: Design of Drying Chamber

Approved on ________________________________.

The Final work has to be completed by _____________.

TASK FOR FINAL THESIS:

Initial data:

The robot calibration tool should be suitable for use in a industrial robot. Such a device shall be capable for sensing all types of obstacles and holes. It should have 6 degrees of freedom. System should be mounted directly on robot arm. The system has been developed to be able to operate with real robotic movement errors.

Explanatory part:
1. Introduction. Analysis of analogical devices. Substantation of the taken technical decision.
2. Calculations needed for the design process.
3. Description of the design and working principle. Electric-block scheme. Algorithm of management of device.
4. Work safety. General provisions and requirements for safe working and environmental protection. Work safety of specific devices.
5. Evaluation of economic indicators of the designed or upgraded device.
6. Final conclusions and recommendations.
7. Literature reference list.

Drawings:
1. General drawing of the device (1 sheet A1); 2. Assembly drawing of the device (node) (1 sheet A1); 3. Algorithm of management of device (0,5 sheet A1); 4. The work drawings of the chosen part (2 sheets A3); 5. Structural composition of device (0,5 sheet A1) 6. Economic indicators (0.5 sheet A1).

Supervisor .... prof. dr. Vytautas Bučinskas
(Signature) (Academic Title, Name, Surname)

Task accepted

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(Student's signature)
Alejandro Lopez Perales
(Student's Name, Surname)
2025-05-02
(Date)

Vilnius Gediminas Technical University
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Mechatronics and robotics study programme bachelor (master) thesis.

Title: **Design of drying chamber..**

Author **Alejandro Lopez Perales.........** Academic supervisor **Vytautas Bucinskas**

Thesis language

- [ ] Lithuanian
- [X] Foreign (English)

Annotation

The drying chamber designed on this project is intended to be used for drying a piezoelectric material from the laboratory. The water contained in its structure affects the output characteristics of the material, so controlled drying is needed to optimize the results.

The thesis describes the design of a chamber. Based on an old 3D printer, the project has been focused on calculating and designing the new parts needed for the new purpose of the printer. After these devices are precisely installed and adapted, the chamber will allow the user to decide the parameters of the drying process and system will use the information of the sensors and actuators to reach and maintain those standards to the desired levels.

The thesis provides not only physical design but also the necessary algorithm that governs the functioning of the device. The work also includes the required parts.

Structure: Introduction, overview of analogic constructions, overview of specific nodes, calculation of the project, description of the construction and operational principle, work safety, economic calculation, conclusions and list of literature.

Thesis consist of: 51 p. text without appendixes, 27 pictures, 5 tables and 18 bibliographical entries.

Appendixes included: Bill of material and drawings of the device.

Drawings: General view, Assembly, Detailed part 1, Detailed Part 2, Detailed Part 3, Algorithm of control, Control structure and Economic charts.

Keywords: chamber, drying, fan, humidity, temperature, sensor, heat

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Komentaras

Pagal šį projektą suprojektuota džiovinimo kamera skirta naudoti pjezoelektrinei medžiagai džiovinti iš laboratorijos. Jo struktūroje esantis vanduo turi įtakos medžiagos išėjimo charakteristikoms, todėl norint optimizuoti rezultatus, reikalingas kontroliuojamas džiovinimas.

Darbe aprašomas kameros dizainas. Remiantis senu 3D spausdintuvu, projektas buvo sutelktas į naujų dalių, reikalingų naujai spausdintuvo paskirčiai, apskaičiavimą ir projektavimą. Po to, kai šie prietaisai bus tiksliai sumontuoti ir pritaikyti, kamera leis vartotojui nuspręsti džiovinimo proceso parametrus, o sistema naudos jutiklių ir pavarų informaciją, kad pasiektų ir išlaikytų tuos standartus iki norimo lygio.

Darbe pateikiamas ne tik fizinis dizainas, bet ir būtinas algoritmas, reglamentuojantis prietaiso veikimą. Darbe taip pat yra reikalingų dalių.

Struktūra: Įvadas, analoginių konstrukcijų apžvalga, konkrečių mazgų apžvalga, projekto skaičiavimas, statybos ir eksploatavimo principo aprašymas, darbo sauga, ekonominis skaičiavimas, išvados ir literatūros sąrašas.

Disertaciją sudaro: 51 p. tekstas be priedų, 27 paveikslėliai, 5 lentelės ir 18 bibliografinių įrašų.

Pridedami priedai: Komplektavimo specifikacija ir prietaiso brėžiniai.

Brėžiniai: Bendras vaizdas, surinkimas, 1 detalioji dalis, 2 detalioji dalis, 3 detalioji dalis, kontrolės algoritmas, kontrolės struktūra ir ekonominės schemos.

Raktažodžiai: kamera, džiovinimas, ventiliatorius, drėgmė, temperatūra, jutiklis, šiluma

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INTRODUCTION

In the field of biopolymer processing, drying control is a critical factor in ensuring the quality, stability, and performance of the final material. The focus of this project is about designing a drying chamber optimized for *κ-carrageenan* films, a seaweed-derived biopolymer with applications in biodegradable materials and flexible sensors. With the increasing demand for sustainable alternatives against conventional polymers, optimizing the drying process for such materials is essential to enhance their mechanical properties, durability and functional reliability to ensure the best results.

Carrageenan exhibits a highly hydrophilic nature, meaning its mechanical and electrical properties are influenced by its moisture content. Inadequate drying can result in shrinkage, brittleness or loss of flexibility, leading to compromised material's practical applications. Also, inadequate drying conditions can lead to non-uniform material properties, causing inconsistencies in performance. To address these challenges, a controlled drying system is required, allowing precise regulation of temperature, humidity, and airflow to ensure a uniform and efficient drying process.

Recent researches highlight the significant impact of controlled drying on carrageenan-based films. It has been observed that when dried under ambient conditions with optimized humidity control, the resulting films maintain flexibility, structural integrity, and stability for extended periods. Additionally, scanning electron microscopy (SEM) analysis has shown that uncontrolled drying can lead to an uneven distribution of iron oxide (Fe_2O_3) particles due to viscosity differences and gravitational effects. This irregular distribution can affect the material's mechanical properties and electrical conductivity in a way we are not interested.

Moreover, the electrical resistance of carrageenan varies significantly depending on its drying state. As is typically known, water is an electricity conductor, so without sufficient moisture regulation, resistance fluctuations between 1.2 MΩ and 13 MΩ have been observed. This demonstrates the instability of the material when dried under uncontrolled conditions. Additionally, long-term durability tests indicate that improper drying can reduce the material's elasticity by up to 25%, leading to premature aging and mechanical degradation. A well-regulated drying process is therefore essential for maintaining consistent electrical properties, preventing brittleness, and ensuring the longevity of the final product.

This study aims to design a drying chamber that optimizes the drying conditions for carrageenan films, ensuring consistency in their physical and mechanical properties to ensure the results align with was discussed before. The chamber will be designed to provide precise thermal control, regulated airflow, and optimal humidity levels to prevent structural defects and improve the overall quality of the dried material. By stabilizing the drying process, it will be possible to enhance the film's flexibility, improve additive distribution, and maintain its functional integrity for extended periods.

Although the focus will be carrageenan, the findings of this study will contribute to the general field of biodegradable polymer processing, offering insights into efficient and sustainable drying methods. By establishing a well-regulated drying environment, this project seeks to advance the practical usability of biopolymer-based materials, supporting their adoption in industrial and technological applications. The development of an optimized drying chamber represents a step forward in the advancement of environmentally friendly materials while addressing the technical challenges associated with their processing and lifetime capabilities.

The purpose of this project will be to produce the device capable of achieving the necessary conditions. To ensure that the design is withing the standards and the results successful, it is necessary to make an analysis of different types of devices that are available on the market as well as any type of home-made solution that although being rough could present decent results on the final product.

In the next chapters, different solutions are exposed and at the end, the final justification of the design will be analysed.

1. OWERVIEW OF ANALOGIC CONSTRUCTIONS

1.1 Microwave-Assisted Drying Technology for Sample Preparation

Microwave-assisted drying has emerged as a promising technique for the efficient and uniform removal of moisture from various materials, including polymers, bioplastics, and piezoelectric composites. Unlike conventional drying methods, which rely on conduction and convection to transfer heat from the surface to the inside, microwave drying heats materials volumetrically. This is achieved by the interaction of microwave radiation with polar molecules such as water, which absorb the energy and convert it directly into heat. This process not only accelerates drying times but also ensures a more uniform moisture distribution along all of the material´s structure, making it an attractive alternative to traditional methods like hot air, vacuum, and infrared drying.

Recent studies have highlighted the effectiveness of microwave drying for carrageenan-based materials and algae-derived polysaccharides, showing that microwave-assisted drying can significantly preserve bioactive compounds and functional properties compared to conventional methods. For instance, the use of microwave-assisted spouted bed drying (MSBD) for carrageenan resulted in reduced drying times and improved moisture diffusivity without significantly altering the material's structural properties (Serowik et al., 2018). In a similar way, microwave drying of green algae demonstrated enhanced retention of antioxidants and bioactive compounds compared to air-frying and other traditional drying methods (Montolalu et al., 2024), this may give us some insight into our study field.

In the context of drying piezoelectric materials, such as biodegradable carrageenan combined with iron oxide, which are sensitive to thermal gradients and require a controlled environment to preserve their functional properties, microwave-assisted drying offers a promising approach. This chapter explores the principles of microwave-assisted drying, its benefits over conventional methods, and its potential applications, particularly in preserving the integrity of piezoelectric composites and enhancing their final mechanical behaviour.

Microwave drying operates on the principle of dielectric heating, where electromagnetic waves in the microwave frequency range (typically in the range of 915 MHz and 2.45 GHz) interact with polar molecules in the material. The two primary mechanisms responsible for heating are dipole rotation and ionic conduction:

Dipole Rotation: Water molecules, which are polar, align themselves rapidly with the oscillating electric field of the microwaves, generating heat through internal friction.

Ionic Conduction: Free ions in the material move under the influence of the electromagnetic field, causing collisions that convert kinetic energy into heat.

The efficiency of microwave heating is influenced by the material's dielectric properties, particularly the dielectric constant and dielectric loss factor. Materials with high dielectric loss factors absorb microwave energy more efficiently, making them ideal candidates for microwave-assisted drying. Having this insight on how microwave technology works it seems to be a very attractive field to develop the drying chamber.

In the study by Serowik et al. (2018), the microwave-assisted spouted bed drying system was shown to achieve moisture levels as low as 0.01% for carrageenan, demonstrating both precision and efficiency in moisture removal without significantly affecting the material's structural properties. This precision is partly attributed to the uniform heating characteristic of microwave energy, which prevents the formation of thermal gradients that are common in conventional heating methods. As was discussed before, microwave technology heats volumetrically giving a better distribution of drying.

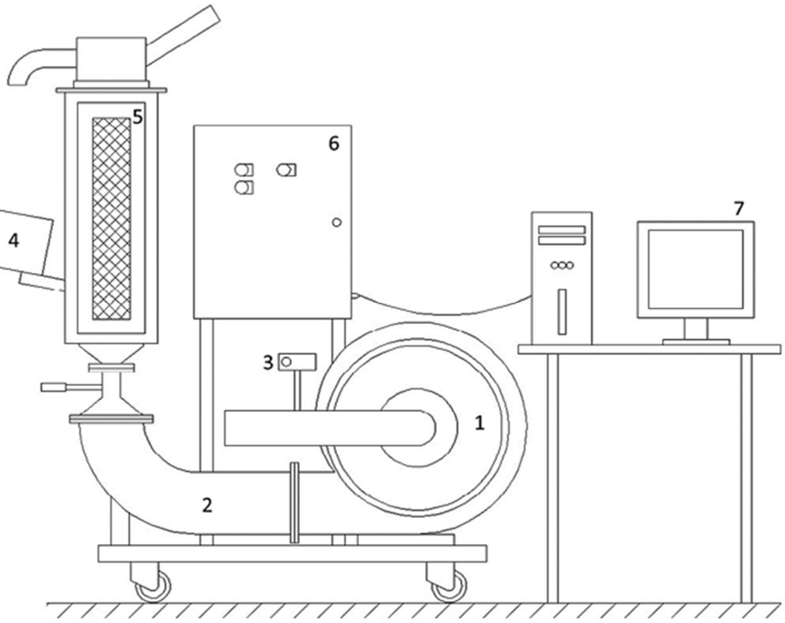

Figure 1 Scheme of microwave dryer (M. Serowik)

One of the most significant advantages of microwave-assisted drying is its ability to reduce energy consumption substantially. Traditional hot air-drying methods require prolonged heating to raise the temperature of both the material and the surrounding air, resulting in ae higher energy usage. In contrast, microwaves directly heat the water molecules within the material, leading to faster drying times and lower energy requirements.

For piezoelectric materials, which are sensitive to thermal stress and moisture, this rapid and controlled drying process minimizes the risk of cracking or delamination. The uniform heating provided by microwaves ensures that moisture is evenly removed, preventing localized overheating that could degrade the piezoelectric properties of the material.

Microwave drying ensures uniform moisture removal by heating the material from a whole, preventing the surface from becoming overdried while the interior remains moist. This uniform heating is particularly beneficial for drying piezoelectric composites, where uneven moisture distribution can lead to defects such as warping, stress cracks, or loss of piezoelectric properties. As was discussed before, electrical resistance depends on water content, producing an uneven distribution would affect its conductivity creating different values through the material. This aligns with the purpose of this study where we are looking to improve the characteristics of our samples.

The application of microwave-assisted spouted bed drying for carrageenan demonstrated that the technique could maintain the material's structural integrity and prevent thermal degradation, which is crucial for preserving the piezoelectric performance of biodegradable composites (Serowik et al., 2018).

Conventional drying methods, which involve prolonged exposure to elevated temperatures, can degrade the functional properties of piezoelectric materials, such as dielectric constant, piezoelectric coefficient, and mechanical strength. Microwave-assisted drying minimizes this risk by rapidly removing moisture at relatively lower temperatures.

Microwave drying of carrageenan-based materials was shown to preserve antioxidant, antidiabetic, and antiobesity properties effectively, suggesting that the method could similarly preserve the functional properties of piezoelectric composites that rely on the structural integrity of carrageenan and iron oxide (Montolalu et al., 2024).

Recent research has demonstrated the potential of using natural biopolymers such as carrageenan combined with iron oxide to create biodegradable piezoelectric sensors. These materials are sensitive to moisture and thermal gradients, which can affect their electrical properties and sensor performance. The uniform heating ensures that the piezoelectric response of the material remains consistent, which is crucial for applications in flexible sensors and wearable electronics.

Given the application of microwave drying in preserving bioactive compounds in algae, it is reasonable to hypothesize that similar mechanisms could help maintain the active sites necessary for piezoelectric effects in carrageenan-iron oxide composites (Montolalu et al., 2024).

This technology may have it drawbacks though. Not all materials interact in the same way with microwave energy. As it was discussed before, differences on dielectric behaviour exist as piezoelectric composites with low dielectric loss factors may require additives to enhance microwave absorption. Additionally, care must be taken to prevent thermal runaway, where certain regions of the material absorb more energy and overheat. Given this, we would be looking at the necessity to study in detail every material object of the treatment to ensure its limits aren’t surpassed.

Talking about its implementation possibilities, while the operational cost of microwave drying is lower due to reduced energy consumption, the initial investment in microwave generators, waveguides, and control systems can be substantial. Ensuring uniform field distribution and preventing reflections within the drying chamber also adds to the system's complexity.

To conclude, microwave-assisted drying represents a transformative approach to moisture removal in both polymer processing and piezoelectric applications. Its ability to reduce energy consumption, ensure uniform drying, and preserve the functional properties of piezoelectric materials makes it an attractive alternative to conventional methods.

The successful demonstration of this technology in projects such as microwave-assisted spouted bed drying for carrageenan and the preservation of bioactive compounds in algae underscores its potential for scaling in industrial applications, including the drying of piezoelectric composites for sensors.

Future developments should focus on enhancing material compatibility, reducing equipment costs, and integrating microwave drying more seamlessly into existing manufacturing workflows. By addressing these challenges, microwave-assisted drying can pave the way for more efficient and sustainable industrial processes, particularly in the preservation of piezoelectric materials for sensor applications.

1.2 Sun drying

Drying is a crucial post-harvest process for biopolymers such as carrageenan, derived from seaweeds like *Kappaphycus alvarezii*. Traditional sun drying has been widely employed in coast regions due to its low cost and simplicity. However, this method presents significant challenges, including dependence on weather conditions, contamination from dust and microorganisms, and variability in the final product quality (Lakkala et al., 2023). To address these issues, advanced solar drying technologies have been developed, optimizing the process through precise control of temperature, humidity, and airflow, thereby significantly enhancing the properties of carrageenan (Fang et al., 2020).

This chapter explores the use of solar energy as an effective drying technology for carrageenan, evaluating both traditional methods and modern solar dryers. Additionally, it examines the effects of drying temperature on the properties of carrageenan, based on recent studies that highlight the importance of maintaining controlled conditions to preserve the quality of the final product (Hadi et al., 2023). Although it may not be apparently aligned with our purpose for piezoelectric materials, this technology could provide a new study path given its low complexity and interesting results.

Sun drying is one of the oldest and most cost-effective methods for processing seaweeds. In this technique, seaweeds are lied directly on open surfaces under sunlight for several days. According to a study conducted in Brazil, sun drying of *Kappaphycus alvarezii* requires approximately 1,400 minutes (about 1.5 days) to reduce the moisture content to 30% (Bhagia et al., 2021). While effective in terms of cost, this process faces several challenges, such as its climate dependence, where the efficiency of drying is directly influenced by factors such as temperature, humidity, and wind speed (Adhikary et al., 2008). Prolonged exposure increases the risk of contamination by dust, insects, and microorganisms. Inconsistent quality may occur because variations in environmental conditions can significantly affect the viscosity and gel strength of carrageenan (Zhang et al., 2021). Despite these limitations, sun drying remains popular due to its low cost and simplicity in rural areas with limited resources. However, the need to improve quality and efficiency has driven the development of controlled solar drying technologies (Andreozzi et al., 2024).

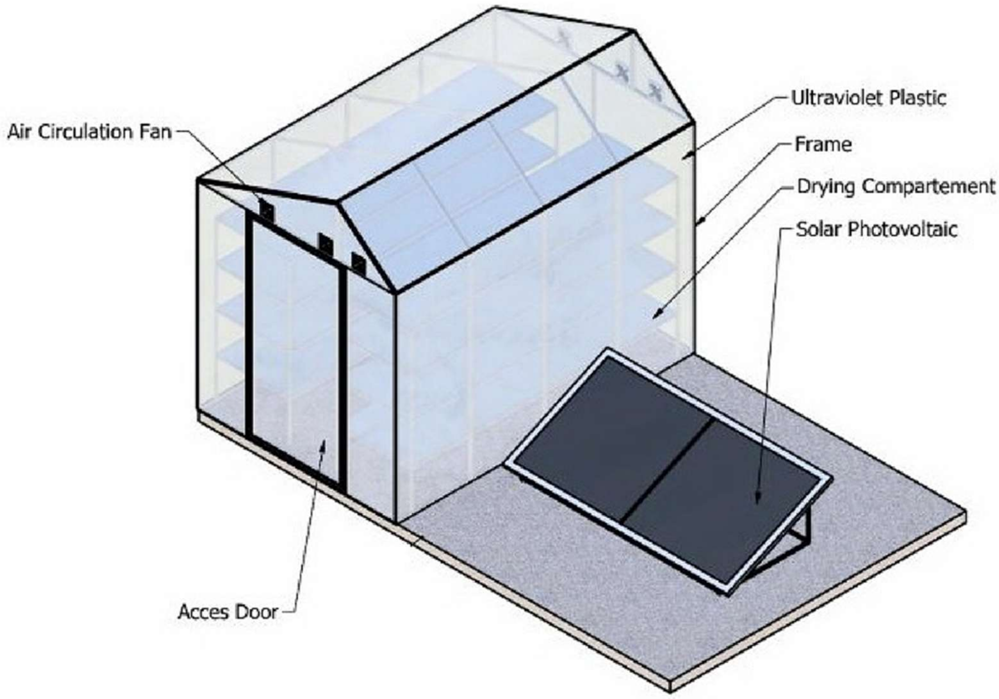

Figure 2 Scheme of proposed solar drying (Nizar Amir)

Forced convection solar dryers combine solar energy with ventilation systems to enhance drying efficiency. These devices use fans powered by solar panels to circulate hot air evenly through the trays containing the material. A recent study on the drying of *Eucheuma cottonii* seaweed demonstrated that a forced convection solar dryer reduced the moisture content from 92% to 35–40% in two days, whereas open sun drying required up to four days (Gunasekaran et al., 2021). Some of its advantages include a significantly reduced drying time by enhancing heat and mass transfer, a lower contamination risk due to being enclosed, preventing direct contact with dust and other contaminants, and precise control of the process allowing regulation of temperature (typically between 40°C and 60°C) and humidity (Senthilvel et al., 2023).

The use of materials such as black gravel for storing heat during the day helps maintain elevated temperatures at night, ensuring continuous drying. Studies indicate that these materials can keep the temperature of the dryer 5 to 20°C above the ambient temperature during the night (Comino et al., 2023). This strategy is particularly effective in regions with significant temperature fluctuations between day and night, which may be an important characteristic depending on the region we will be working in.

Drying temperature has a direct impact on the rheological properties of carrageenan. A study evaluated the effects of drying *Kappaphycus alvarezii* at 40°C, 60°C, and 90°C, concluding that 60°C is the optimal temperature for preserving both viscosity and gel strength (Boonmee et al., 2016). The results showed:

- Highest viscosity: 271 mPa·s at 40°C and 233 mPa·s at 60°C.
- Lowest viscosity: 175 mPa·s at 90°C due to thermal depolymerization.
- Optimal gel strength: 1,727 g cm^2 at 60°C compared to 1,324 g cm^2 at 90°C.

The degradation of viscosity and gel strength at temperatures above 60°C is attributed to depolymerization and the breakdown of bonds within the carrageenan structure. This highlights the importance of maintaining a controlled temperature during the drying process to preserve the functional properties of carrageenan (Raj et al., 2021).

Regarding the effect on syneresis and carrageenan yield, syneresis, or the release of water from the gel, is also influenced by drying temperature. At 90°C, syneresis was significantly lower (9.8% for semi-refined carrageenan and 10.3% for refined), suggesting a higher water retention capacity of carrageenan. However, this is related to the formation of more compact structures due to depolymerization, negatively affecting the gel quality for applications that require flexibility and high viscosity (Wang et al., 2023).

Regarding carrageenan yield:

- Semi-refined (SR): Ranged from 39.8% to 43.9% across different drying temperatures.
- Refined (R): Increased to 29.8% at 90°C but at the cost of reduced quality.

The results indicate that drying at 60°C provides an optimal balance between yield and quality, maintaining the structural integrity of carrageenan (Hadi et al., 2023).

To give us an overall comparative with other methods, the following table:

Table 1 Comparison of drying methods

Method	Drying time	Viscosity (mPa*s)	Gel strength (g*cm^2)	Overall quality
Open sun drying	1.5 days	271	1,685	Medium (risk of contamination)
Controlled solar drying (60ºC)	170 minutes	233	1,727	High (precise control)
Microwave drying	Few Minutes	Variable	Variable	High (but costly)
Convection drying (90ºC)	100 minutes	175	1,324	Low (depolymerization)

This comparison highlights that controlled solar drying at 60°C offers an optimal balance between drying time, quality, and operational cost, making it the most effective option for preserving the properties of carrageenan (Limpadapun & Sukmanee, 2023). The use of solar energy as a drying technology, particularly through advanced solar dryers with forced convection and thermal storage, presents a viable and efficient alternative for processing carrageenan. The optimal temperature identified (60°C) allows for the preservation of both viscosity and gel strength while avoiding the negative effects of depolymerization. Additionally, controlled solar drying reduces contamination risks and enhances the overall quality of the product compared to traditional sun drying and other methods such as microwave and high-temperature convection drying (Aniskevich et al., 2023).

The development of efficient solar drying systems not only improves the properties of carrageenan but also contributes to a more sustainable and cost-effective production process, especially in coastal and rural regions with limited access to advanced technologies (Andreozzi et al., 2024).

1.3 Oven drying

After studying some innovative alternative, we may describe a technology that it almost accessible to anyone and could offer results with high standards. We are here talking about the use of ovens, not only conventional ones for domestic use, but also the market offers some alternatives focused on drying. These devices are designed to reach very precise temperatures as well as multiple sensors to ensure the conditions inside the oven remain stable. The drying chambers presented below could serve with our purpose of heat-treat carrageenan samples as well as being simple and accessible compared with other technologies such as microwave.

Figure 3 Model ED 23 (Binder catalogue)

Binder offers some solutions, not specifically designed for our purpose but its function and operating characteristics may make them very attractive for us. The product shown on Fig. 1.1 is an oven or more specifically a drying chamber, in this model natural convection is used. Its measures make it ideal for the small samples that would be typically worked on the laboratory. The temperature operation window sits between 5ºC and 300ºC which is wide for any type of applications. More technical characteristics are shown on their web page which can be consulted on the bibliography.

The next product shown on Figure. 1.2 is another product from the company shown before. The difference with this model is the use of forced convection which will result int better heat propagation inside the oven as well as less time to reach the operating temperature. As was previously metntion on the solar drying option, forced convention offers lower time of exposition as well as it is useful to ensure the conditions inside the chamber stay withing the correct values.

It´s indeed very useful to analyse the different solutions that this brand offers. Their catalogue contains more kind of devices upgrading its size as well as incorporating more technology with different operating programmes. This added characteristic may be very important if in a future, the device purpose may open to new material where temperature and humidity conditions could be different to carrageenan so a wider window of configuration can be very optimal.

This brand is the only one on the market offering this kind of products. Although it would be interesting to look for other suppliers, the purpose of this analysis is to investigate the available solutions and justify the build this project is about. Given this, it is concluded that the use of conventional ovens as drying chambers can have a very optimistic outcome for the desire results.

To further deep in the use of ovens, research was taken by Universitas Negeri Yogyakarta, done by Angus Widyianto. This work described the modification of a conventional oven to fulfill the necessity of drying filaments for 3d printing. Although it may not seem the same application, similarities exist on the necessity of drying filaments and our heat treatment for carrageenan.

Printing filaments absorbs moisture, leading to degraded mechanical properties and printing capabilities. These characteristics align perfectly with the goal of this research for the treatment of biopolymers to remove moisture to preserve structural and bioactive properties.

Figure 4 Oven of the project

The filament dryer project demonstrated that drying PLA filaments at controlled temperatures improved their tensile and bending strengths. Likewise, drying carrageenan under optimized conditions can enhance its mechanical properties, such as viscosity and gel strength, which are crucial for its applications in sensors and biodegradable materials.

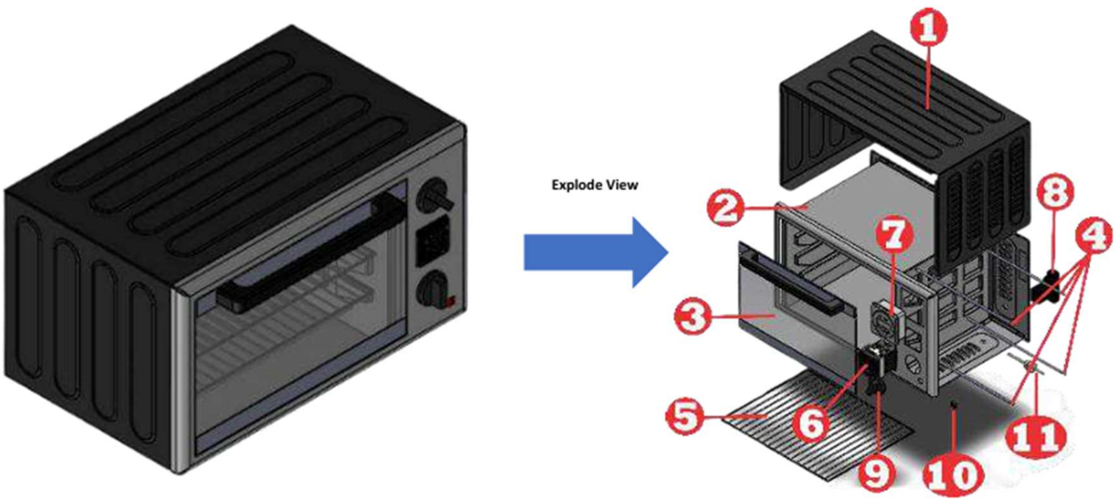

Figure 5 Filament dryer exploded view

This project found out that temperatures around 45°C for extended durations provided the best balance between moisture removal and mechanical strength retention for PLA filaments. In a similar way, my research suggests that maintaining moderate drying temperatures prevents the degradation of carrageenan's functional properties.

Table 2 Open storage moisture content testing

Conditions	Empty Watch Glasses	Sample + Watch Glasses Before Heating	Sample + Watch Glasses After Heating	Moisture Content (%)
Week 1	40.240 gr	45.242 gr	45.215 gr	0.539%
Week 2	40.240 gr	45.241 gr	45.210 gr	0.620%
Week 3	40.241 gr	45.242 gr	45.201 gr	0.820%
Week 4	40.249 gr	45.251 gr	45.209 gr	0.839%
Week 5	40.249 gr	45.252 gr	45.210 gr	0.839%

The similarities between this project are obvious and support firmly the idea of reusing old material as well as serving as an efficient technology for a small-scale drying process.

Next, a very rudimentary and DIY solution is proposed. Although being rough and basic, could serve as a temporary solution and with the necessary precautions, it may offer decent results.

Figure 6 Stanley Fan heater

Given that the quantity of samples on the department that will be produced won´t be at a high scale, to justify the purchase of a quality-built device may not be satisfied, the idea of building a home-made solution comes very attractive, especially if the achieved results become acceptable.

Since the temperatures we are talking about won´t be extremely high rounding up to 50ºC, the possibility of heating a whole room wouldn't be nothing very difficult. This option is extremely related with sun drying as was previously described. In this case, the heat source would be the heater instead of sun. This may be controversial but could solve the sun problem in countries where sun radiation is low or not very frequent which would be an important problem. However, as previously mentioned, the quantity of samples produced may not be as numerous to compensate the waste of building up temperature in a whole room.

An alternative to solve this drawback is proposed. Some kind of plastic box may be used for the purpose. To adapt it, a whole is to be done on one of the sides as well as some ventilation on the upper part as hot air tends to go up. A well seize joint must be made to ensure all the hot air produced by the device is introduced into the box and nothing gets lost, so its performance becomes maximise.

A thermometer should be placed on the inside of the box with the samples object of the heat treatment. To ensure the materials won’t be compromised, heating procedure must start from a low heat rate combined with a low fan speed. Speed of the air rate must not rise to prevent samples to deteriorate. Heat rate will be increased at a constant rate checking the thermometer for the inside temperature. Also, some silica composes or similar can be putted on the bottom of the box. This material could absorb the extracted moisture from the samples in a more efficient way.

This home-made solution could provide the expected results and as well as being rudimentary, its cost will be very low compared to other commercial products although providing decent results.

Studies may be made to check the veracity of this device.

1.4.Substantiation of the decision

The objective of this project is to design and construct a drying chamber specifically for carrageenan samples, ensuring optimal preservation of their functional properties while maintaining cost-effectiveness and practical feasibility. After a thorough analysis of three potential drying methods—microwave-assisted drying, solar drying, and conventional oven drying—it has been concluded that oven drying presents the most suitable solution for this project.

One of the primary reasons for selecting oven drying is its cost-effectiveness. Microwave-assisted drying systems, despite their efficiency, require a significant initial investment due to the need for specialized equipment such as microwave generators, waveguides, and control systems. In contrast, an oven-based system can be constructed at a relatively lower cost by utilizing readily available components like heating elements, temperature controllers, and insulation. Additionally, while microwave drying might offer lower energy consumption per session, the costs associated with maintaining and repairing such systems can be substantial. Ovens, on the other hand, use simpler and more durable components, which translates to lower maintenance and operational costs over time. The affordability of key components for ovens further strengthens their economic viability within the scope of this project.

From a practical standpoint, oven drying also proves to be a more feasible option. The design and construction of an oven are considerably more straightforward compared to the complexity of integrating a microwave-assisted system, which demands precise electromagnetic field distribution and shielding. The simplicity of an oven's design not only reduces potential technical challenges but also allows for easier customization based on the specific requirements of carrageenan drying. Furthermore, unlike solar drying, which heavily depends on consistent sunlight—a significant limitation in regions with variable weather—oven drying provides a controlled environment with consistent heating capabilities, ensuring reliable and repeatable results irrespective of external conditions. This independence from weather variations is a critical advantage, given that solar drying can be highly unreliable due to overcast days, rain, or seasonal changes that could lead to uneven drying and prolonged processing times.

The ability to control temperature precisely is another significant advantage of oven drying. Ovens can be equipped with programmable controllers that regulate temperature and drying time accurately, preventing overheating and ensuring uniform drying of carrageenan samples. Such a level of control is far more challenging to achieve with solar drying methods and even with microwave-assisted drying, which requires careful management of dielectric heating properties to prevent localized overheating or thermal runaway—risks that could degrade carrageenan's bioactive compounds. Additionally, solar drying presents the risk of contamination from dust, insects, and other environmental factors, which could compromise the purity and quality of carrageenan samples. Ovens, by providing a sealed and controlled environment, effectively mitigate these risks, ensuring that the drying process remains unaffected by external humidity and temperature variations.

Consistency and quality control are also crucial factors that support the choice of oven drying. An oven equipped with forced convection can distribute heat evenly, eliminating the issue of surface overdrying observed in solar methods. This uniform drying process is essential for preserving the mechanical properties of carrageenan, such as gel strength and viscosity. Moreover, the controlled environment of an oven reduces the risk of contamination, further ensuring that the dried carrageenan retains its desired functional properties.

The primary objective of this project is to design a drying chamber that is both feasible to construct and effective in maintaining the quality of carrageenan samples. An oven-based design aligns perfectly with this goal by offering precise control over drying parameters without the need for highly specialized components or infrastructure. Although microwave and solar drying methods were explored and presented, the choice of an oven strikes an ideal balance between cost, feasibility, and performance. This approach not only meets the project's objective but also ensures that the final system is accessible, manageable, and capable of preserving the functional properties of carrageenan effectively.

In conclusion, the decision to construct an oven for drying carrageenan samples is justified by its cost-effectiveness, practicality, and ability to provide consistent and controlled drying conditions. The challenges associated with microwave and solar drying methods—such as high costs, dependence on weather, and risk of contamination—further reinforce the suitability of an oven-based solution. This approach not only achieves the project's goal of designing an efficient drying chamber but also ensures that the system is accessible, reliable, and capable of producing high-quality dried carrageenan samples.

2. OVERVIEW OF SPECIFIC NODES

2.1.Chassis

This project will be based on an old and not functioning 3d printer. Its casing will provide a secure and flexible space for the construction of the chamber. Due to temperatures being relatively low around 50 ºC, precautions and special insulation won't be needed. The chassis, made from aluminum, will stand all the structure. The old 3d printer remains disarmed, with all its electronics and mechanism out of the way. Given this, space for a new control system is available as well as all the necessary moving parts. In the next chapters, a more detailed view of the casing will be explained.

Figure 7 Mass portal 3D printer

This solution, as well as providing a good performance for our purpose, will reuse some material for the laboratory. Taking advantage of this is very useful to keep costs very low as well as helping with waste. If it wasn't like this, a new case should be designed and built. Although this way its characteristics would be improved for the purpose, we've decided that it won't be necessary, and the solution taken will be enough to fulfill our purpose.

2.2.Heat mechanism

In conjunction with the old 3d printer, its heated bed is also available. The heated bed in 3D printers serves two main purposes: ensuring proper adhesion of the first layer and preventing warping. By maintaining a consistent temperature, it helps the material stick to the bed and cool evenly, reducing the risk of deformation. Typical temperatures range from 50-60°C for PLA, 90-110°C for ABS, and up to 120-130°C for more technical materials.

Figure 8 Heated plate

The reached temperatures we are talking about will be on the surface of the bed. Our intention is to have the temperature distributed on the whole atmosphere of the chamber. For this purpose some studies should be made to determine if with only the heated bed will be necessary, if some forced induction must be installed or also some electric resistors must be placed around the casing.

The surface of the bed is designed to reach temperatures up to 120ºC. As previously mentioned, a thermal analysis must be carried out to ensure the conditions are met.

These are some of the solutions that we will be studying for this research to ensure the temperature of the chamber reaches stable conditions in case the bed isn't sufficient as well as providing good preheating times.

One of the ideas for an extra heating method could be to use a silicone heating blanket. This device would be placed around the inside walls of the chamber. With adequate insulation preventing the heat to be lost by transfer to the exterior of the case, the produced heat could be used to rise uniformly the temperature on the interior meeting the needs of the project.

Figure 9 Silicone blanket

However, these devices are expensive and typically work on a higher temperature range, so our application doesn’t meet the expected purpose of this product.

After some research, PTC resistors appear to be a very convenient solution. These PTC (Positive Temperature Coefficient) are self-regulating heating elements designed for efficient and safe heating applications. They automatically adjust their resistance as the temperature rises, preventing overheating and ensuring stable operation. Featuring aluminium fins for enhanced heat dissipation, these heaters provide fast and uniform heating. They come in various shapes, such as rectangular and circular, and are available in different voltage options (12V, 24V, 110V, 220V) to suit a wide range of applications, including drying chambers, dehumidifiers, car defrosting systems, and small space heaters. Their durability and self-regulating properties make them a reliable and efficient heating solution.

Figure 10 Electrical resistors for fans

The market offers some built-in solutions where these resistors are combined with an electric fan. This device could serve as a perfect option for this project to use another type of heating system combined with the heating bed from the 3d printer.

Figure 11 Aluminum thermal foil

To ensure the temperature becomes uniform on the interior and power loses are minimized some type of insulation may be needed. Given the temperatures won't be a risk value, insulation won't be specific. For this purpose, aluminium film tape is proposed. The inside walls of the chamber will be covered with this foil tape which would reflect the heat of the inside ensuring heat doesn't scape as well as distributing the temperature very good.

2.3.Control system

For the control system of the chamber, the use of an ESP32 is studied here. The ESP32 is a powerful microcontroller with built-in Wi-Fi and Bluetooth capabilities, making it ideal for managing and automating systems like the drying chamber in this project. Its versatility allows it to connect to temperature and humidity sensors, enabling precise environmental monitoring and control. Additionally, the ESP32 can manage power outputs and control relays for the fans or the heated plate.

Moreover, the ESP32's memory and processing capabilities allow it to store multiple configuration profiles, ensuring flexibility for different drying needs. By integrating a display, it becomes possible to monitor real-time data and adjust settings directly providing an intuitive interface for managing temperature, humidity, and other parameters efficiently. This combination of connectivity, control, and user interaction makes the ESP32 an excellent choice for this application.

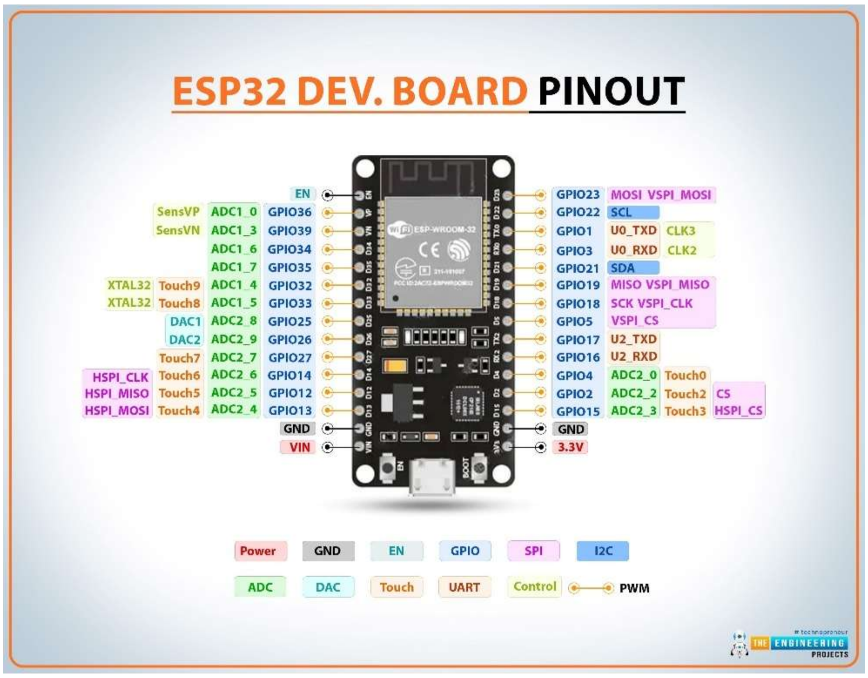

Figure 12 ESP32 scheme

In the next chapters, a more detailed view of this device would be explained as well as its functionality, electrical schemes and algorithm to ensure all the conditions are met.

2.4.Temperature and humidity control

In this study, the DHT22 will be used for ambient temperature and humidity measurements, even though the implementation of an AHT25, which is generally a more accurate and advanced sensor, was studied. The reason for choosing the DHT22 is simply due to its availability in the laboratory. Despite being slightly less accurate and slower than the AHT25, the DHT22 remains a very reliable option for this application.

The DHT22 offers a temperature range of -40°C to 80°C with an accuracy of ±0.5°C, and a humidity range of 0-100% RH with an accuracy of ±2-5% RH. While it is not as precise as the AHT25, it still provides adequate accuracy for the needs of the drying chamber application. The data update rate of the DHT22 is every 2 seconds, which, while slower than the AHT25 (~1 Hz), is still sufficient for the purpose of the application.

Moreover, the DHT22 communicates via a single-wire digital protocol, making it easy to interface with microcontrollers such as the ESP32. The sensor does require a pull-up resistor on the data line to ensure stable communication, but this is a simple and widely known step that can be easily implemented on the design.

Although the DHT22 might not offer the higher precision and faster data acquisition rate that the AHT25 would have provided, it remains a solid choice for this application due to its availability, ease of integration, and sufficient performance for the task at hand. Additionally, the implementation of the AHT25 in the future would be straightforward, as the communication protocol (I2C) is similar, and only minor changes to the hardware and code would be required to switch to the more advanced sensor.

In conclusion, while the DHT22 is not the best sensor in this context, it is still a very good option that can meet the requirements of the drying chamber. If the need for higher precision appears in the future, the transition to the AHT25 will be relatively simple.

2.5.Ventilation control

The implementation of an exhaust fan in the drying chamber is a key element to ensure the efficiency and consistency of the drying process. During operation, especially under high temperatures, moisture is released from the samples into the chamber's internal atmosphere. If it is not properly removed, this accumulation of humidity may lead to a oversaturated environment that significantly lowers the evaporation rate and consequently extends the overall drying time.

By incorporating an exhaust fan, the air saturated with water vapor is continuously extracted and replaced by drier ambient air which would be taken from the bottom part. This promotes a more effective removal of moisture, maintaining a lower relative humidity inside the chamber and enhancing the thermal gradient necessary for efficient drying. In doing so, the system not only accelerates the drying process but also helps preserve the structural and thermal integrity of the material.

Furthermore, active air extraction reduces the risk of condensation within the chamber, which could otherwise lead to non-uniform drying or potential rehydration of the samples. Overall, the exhaust fan contributes to maintaining stable and controlled environmental conditions, thereby improving the reproducibility, reliability, and quality of the drying process.

Moreover, to ensure a better and more uniform distribution of flow on the inside of the chamber, a horizontally placed fan will be placed on one of the walls. Without it, a tube-shaped flow will be produced which won't help the drying process and prevent the results to meet expectation. This additional flow will create a better distribution of the heat and air flow and as a result improving the drying characteristics of the device.

The selection of the fans has been made considering the existing options on the laboratory. This helps to the purpose of the project to reuse as much materials as possible, keeping low costs. These fans are taken from old computers and machinery and will work perfectly with the control system of the project.

3. CALCULATION OF PROJECT

The goal of this project is to dry samples. The device will be designed to be adjustable giving it the capabilities to adapt to various drying characteristics. As it is, the main aspects of consideration for this purpose are two, the calorific power transmitted from the heating source and the air flow. The first one will be primarily controlled by the heating bed as was previously discussed. After some calculations a decision will be made depending on whether the power of the plate is sufficient or not. The airflow will be dependent on the fan. As more air flow is required, the rotation speed of this fan can be increased rising the flow and extracting more humidity form the chamber.

3.1.Description of equations and principles

The drying system consists of a control volume where air enters in its initial conditions (temperature and humidity) and after interacting with the material inside, will exit the system with a higher temperature and humidity values due to the evaporation from the sample. The drying power can be defined as the amount of heat transferred to the air in order to rise its temperature and evaporate the humidity from the material. As was previously mentioned, this depends on the calorific power and the airflow.

To understand this we must start by making and energy balance to the air inside our control volume. This balance can be defined by two components, the necessary heat to rise the air temperature and the necessary heat to evaporate water. The general equation for this balance is show below.

$$\mathrm{Q} = \mathrm{q} \times \rho \times c_p \times \Delta T + \dot{m_w} \times Lv\ (W) \tag{1}$$

- Q is the total heat transferred to the air (W)
- q is the flow of air.
- ρ is the density of air (kg/m^3).
- C_p is the specific heat for air (approximately 1005 J/kg*K).
- T_{out} is the temperature of the air at the exit of the chamber (K).
- T_{in} is the temperature of the air at the intake of the chamber (K).
- m_w is the water mass flow (kg/s)
- Lv is the latent heat for water (approximately 2400 J/g)

As described, the first components refer to the trasnmited heat to the air inside the chamber. The second components consider the flow of water due to the evaporation.

To determine the power from the heat source is necessary to know how much the plate can generate. From the technical data is supposed to reach temperatures up to 120 ºC, but to make any calculations for our model it is a must to know its power in watts. As it is an electrical resistor, power can be determined by its internal resistance and the electric current it flows through it. To ensure the data recollection, further examination and experimental research must be made to the device.

$$R = \frac{\Delta V}{\Delta I}\ (\Omega) \tag{2}$$

$$P = I^2 \times R = \frac{V^2}{R}(W) \tag{3}$$

The electrical power will approximately transform completely into heat power. The following part will explain how the power of the plate was measured.

To measure the resistance of the plate, an ohmmeter was used. These devices have the capabilities to measure resistance. The plate has two main power cables that can be identified by their thickness. Connect the terminals of the multimeter to the power cables and resistance of the plate will be measured. Given this, resistance of the plate was measured at 2 Ω. Considering the equations above and an electric supply of 24V, the power output will be approximately:

$$P = \frac{V^2}{R} = \frac{24^2}{2} = 288\ W \tag{4}$$

The drying chamber designed for this project operates by reducing the moisture content of samples through a controlled evaporation process, driven by heat and airflow. The chamber would maintain an internal temperature of approximately 50 °C, with the hot plate as the heat source, a fan to regulate and extract moisture-laden air, another fan to provide a better distribution of air on the inside and a humidity and temperature sensor to monitor the process. An explanation of the fundamental principles of evaporation will be presented as well as the physical phenomena involved, how key variables such as temperature and humidity evolve during the process and how these variables influence the drying efficiency.

Evaporation is the process by which liquid water transitions into water vapor, occurring when water molecules at the liquid's surface gain sufficient energy to overcome intermolecular forces and escape into the surrounding air. In the drying chamber, a sample is placed over a hot plate, which supplies heat to raise the water's temperature. At this temperature, evaporation occurs exclusively at the surface as it is well below the boiling point of water. Unlike boiling, where rapid phase change occurs throughout the liquid, surface evaporation will be a gradual process driven by the energy supplied by the hot plate.

The rate of evaporation will depend on several factors which are explained below:

- Water temperature: At approximately 40 °C, the water molecules have higher kinetic energy than at lower temperatures (e.g., 20 °C), resulting in a faster evaporation rate, though still slower than at boiling conditions.
- Relative humidity of the air: relative humidity represents the percentage of water vapor in the air compared to the maximum amount the air can hold at a given temperature. Lower relative humidity increases the evaporation rate as dry air has a greater capacity to absorb water vapor.

- Airflow: The fan in the chamber continuously removes humid air and introduces drier air allowing the control and maintaining evaporation at the desire rate.

Having a better understanding of this conditions, the evolution of the evaporation process will be explained. The drying process can be divided into three main stages each characterized by changes in temperature, humidity and the state of the sample:

1. Initial heating phase:
    - When the sample is introduced into the chamber, the water is typically at a lower temperature (room temperature about 22 °C). The hot plate transfers heat to the water, raising its temperature toward 40-50 °C which will be the equilibrium temperature of the chamber.
    - As the water warms, surface evaporation begins, releasing water vapor into the chamber's air. This increases the relative humidity, which is detected by the humidity sensor (DHT22).
    - During this phase, the water's temperature rises steadily until it stabilizes at the chamber inside´s temperature, assuming the hot plate's heat input is balanced by the chamber's temperature control system.
2. Constant evaporation phase:
    - Once the water temp reaches ambient inside, its temperature remains relatively stable, as most of the heat supplied by the hot plate is used to provide the latent heat of vaporization required for evaporation. This latent heat enables water molecules to transition from liquid to vapor without a further increase in temperature.
    - The evaporation process generates water vapor, which mixes with the air in the chamber, increasing the relative humidity. However, here the fan plays a critical role by extracting humid air and replacing it with drier air (from the room). This maintains a low relative humidity, ensuring that the air retains a high capacity to absorb additional vapor.
    - The humidity sensor typically shows a moderate relative humidity during this phase, reflecting a dynamic balance between the vapor produced by evaporation and the vapor removed by the fan. The evaporation rate remains relatively constant as long as liquid water is present.
3. Final drying phase:
    - When all the water in the sample has evaporated, no further vapor is produced. The relative humidity in the chamber decreases rapidly, as the fan continues to extract residual water vapor without new vapor being generated.

    - With no liquid water to absorb the heat from the hot plate, the energy may begin to heat the dry sample or the container, though the chamber's temperature control system is assumed to maintain the air temperature.
    - The humidity sensor indicates a low RH (approaching 0% if the incoming air is dry), confirming that the drying process is complete. The sample is now fully dehydrated. This is a situation we will avoid because full dehydration of the samples is not pursued.

Influence of Temperature and Humidity on Evaporation:

The efficiency of the drying process is significantly affected by the temperature and humidity conditions within the chamber:

- Effect of temperature:
    - At approximately 50 °C, the air in the chamber has a high capacity to hold water vapor. According to psychrometric data, air at 50 °C can contain up to 83 grams of water vapor per kilogram of dry air at 100% relative humidity. This is significantly higher than at lower temperatures (e.g., ~15 g/kg at 20 °C). The elevated temperature increases the air's ability to absorb vapor making for faster evaporation.
    - If the temperature were increased (e.g., to 60 or 70 °C), the air's vapor-holding capacity would rise further, potentially accelerating evaporation. Conversely, at lower temperatures (e.g., 40 °C), the air's capacity would decrease, slowing the process. However, the purpose of this study is to evaporate at a constant and uniform rate and not as fast as possible. Speed on the drying could affect the internal structure of the sample and that's not a desirable result. Considering this, a balance will be pursued.
- Effect of relative humidity:
    - Low relative humidity is critical for efficient evaporation. When RH is low (e.g., 10–30%), the air is far from saturation and can absorb significant amounts of vapor from the sample. For example, at 50 °C and 30% RH, the air contains approximately 24.9 g/kg of vapor, leaving a capacity of ~58 g/kg to absorb more vapor.
    - The fan ensures that relative humidity remains stable by controlling the renewing of the air. If the fan were absent or less effective, the RH could approach 100%, saturating the air and halting evaporation. The humidity sensor provides real-time feedback, allowing the system to maintain optimal drying conditions by balancing the speed of the fan and the heat applied by the plate.

Role of Psychrometric Data:

Psychrometric tables and charts are essential tools for understanding the behaviour of humid air in the drying chamber. These resources provide data on the air's properties, such as humidity absolute (g/kg), relative humidity, and saturation capacity, at specific temperatures. At 50 °C, psychrometric data indicate that the air's high vapor-holding capacity (~83 g/kg at 100% RH) makes it well-suited for drying applications. By maintaining a low relative humidity through the action of the fan, the system ensures that the air can continuously absorb vapor, as confirmed by the humidity sensor. In the simulation, psychrometric data are used to justify the efficiency of the drying process, demonstrating how the combination of 50 °C air temperature and low relative humidity creates optimal conditions for evaporation.

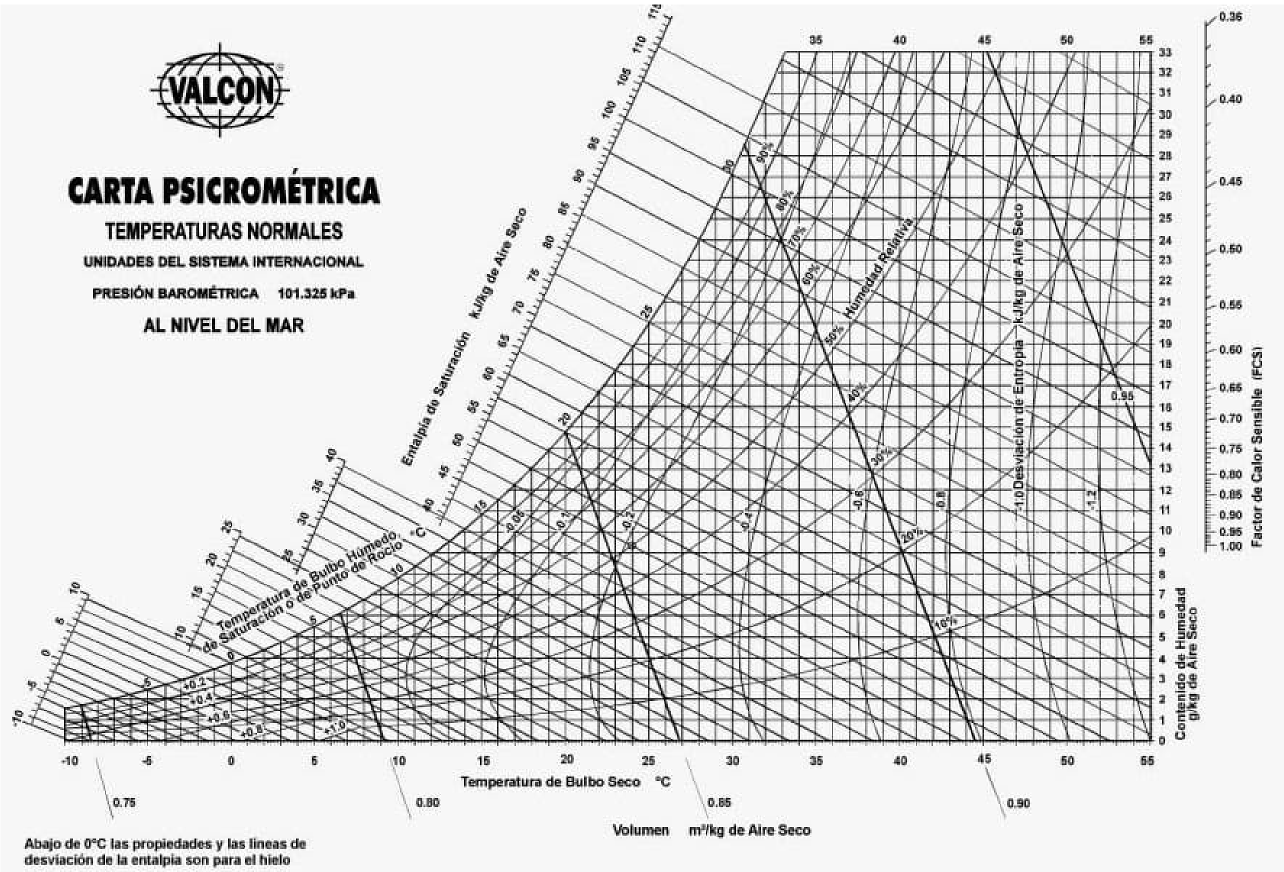

Figure 13 Psychrometric table (https://www.ingenieriaelemental.com/posts/es/carta-psicrometrica-online)

3.2.Simulation analysis

With the goal of evaluating and validate the thermal behaviour of our designs system, a simulation with the tool Flow Simulation from SolidWorks has been prepared. This tool allows the evaluation of the most important parameters un the drying process: the calorific power applied to the system and the airflow needed to extract the humid air. To make this, a simpler design of the chamber has been prepared. Although it won't be the exact same chamber, it has been considered that the approximation reflects very well the conditions of the real model so the data extracted from the simulation can be of substantial importance.

Based on the theoretical model that has been described before, the system is represented as a closed volume with inlet and outlet air streams and an internal heat source. The simulation allows observation of how the temperature and humidity of the air change as it passes through the chamber, depending on the values assigned to these actuators.

This approach enables analysis of whether the supplied heat is sufficient to reach the desired drying conditions and how the airflow influences the temperature distribution inside the control volume. It also helps identify potential dead zones, flow short-circuits or unwanted thermal gradients. According to results evaluated during this phase, the idea of using a second fan was introduced to ensure a better distribution of air on the inside.

These simulations are a key tool for understanding the system's behaviour prior to physical implementation and will serve as a basis for the subsequent experimental tuning of the prototype.

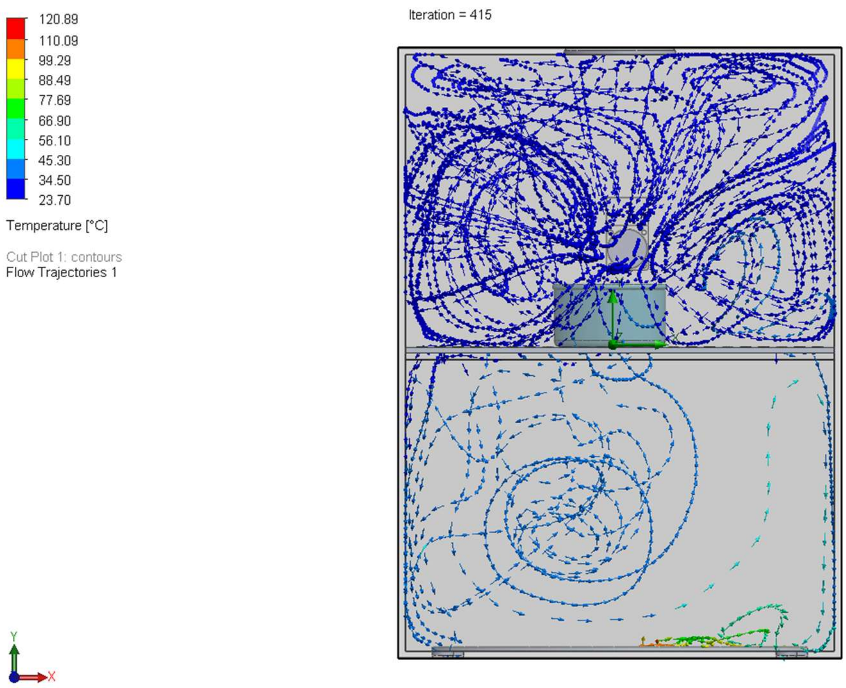

Figure 14 Front view, air flow

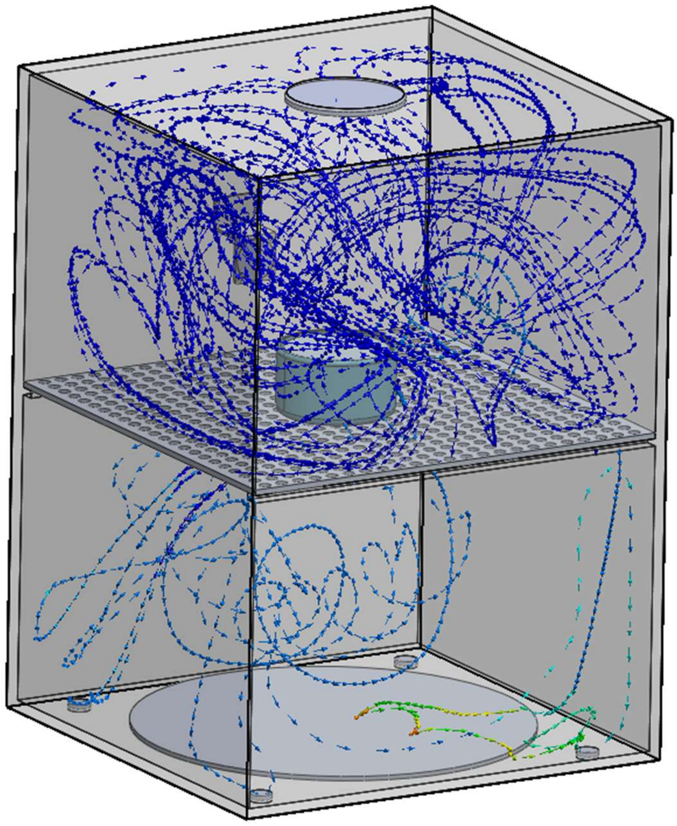

Figure 15 3D view of airflow, high speed

Looking at figures () and (), the results on the airflow stream can be appreciated. As was explained before, upper fan is used for extraction and its rate will be adjusted to keep the conditions in the chamber withing the desire operating window.

However, the second and smaller fan used for distribution would be functioning at a constant rate. As can be seen on the figures, the results are promising as flow becomes uniform and surrounds the sample allowing a better and more uniform drying process.

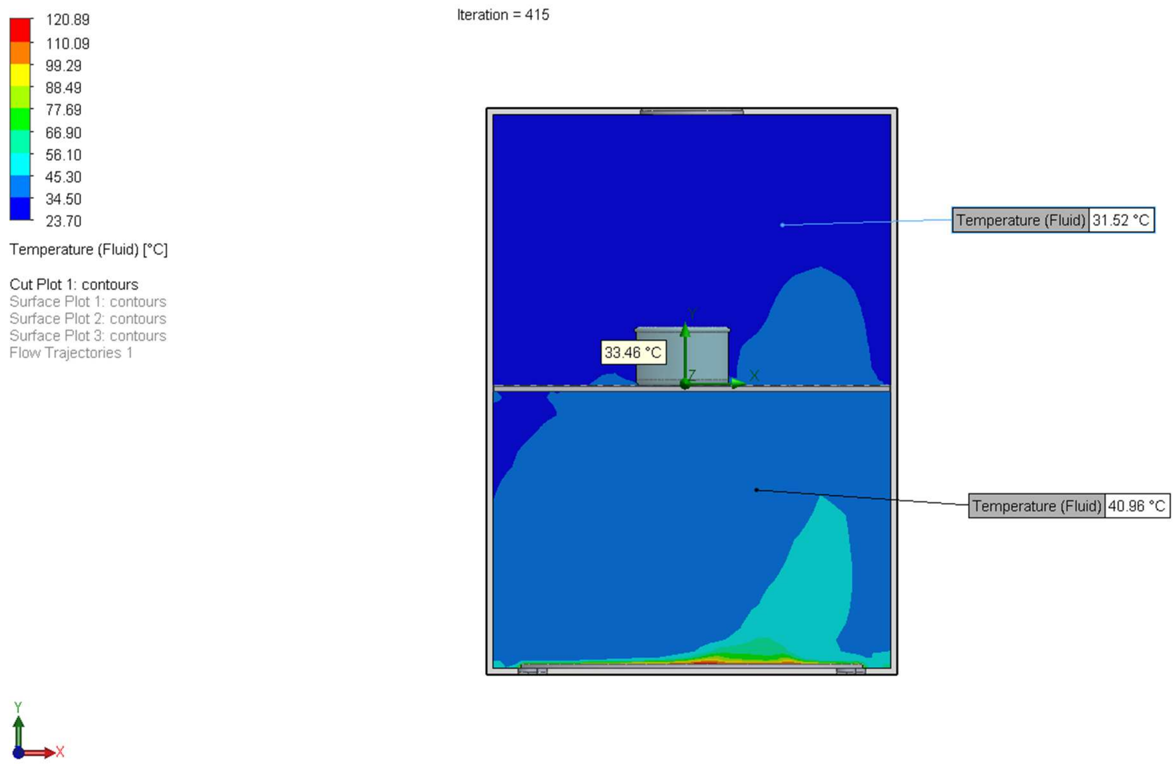

Figure 16 Temperature plot, High fan speed

Figure () displays a cut plot of the chamber. This view presents the distribution of temperature on the air volume inside the chamber. As can be observed, the temperature on the highest part of the chamber sits on approximately 32 ºC. This result is something lower than expected. However, this is primarily caused by the exhaust fan which extracts air from the chamber and prevents the air form reaching higher temperatures. In reality, speed of the fan will be regulated by the control system depending on the measurements taken from the input sensors. Given this, the results taken from the simulation can be taken as valid an as a confirmation that the actual design will meet the requirements.

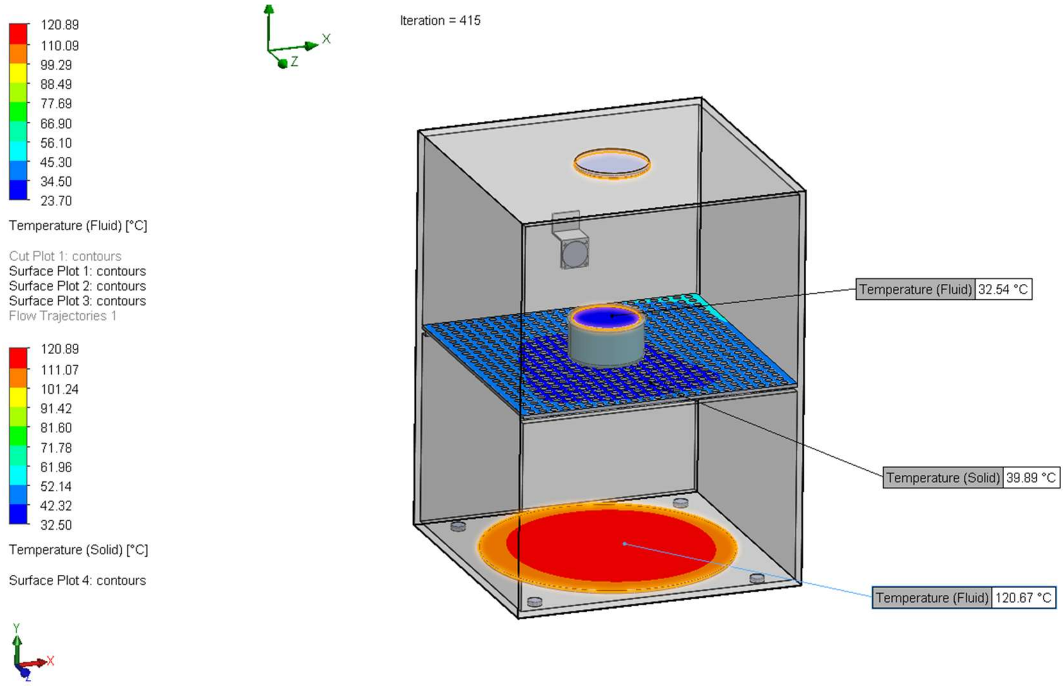

Figure 17 Surface temperatures, High speed

Figure () contains some surface temps taken from the same simulation. As was explained before, these values will be different when exhaust fan speed can be regulated rising the temperature on the chamber.

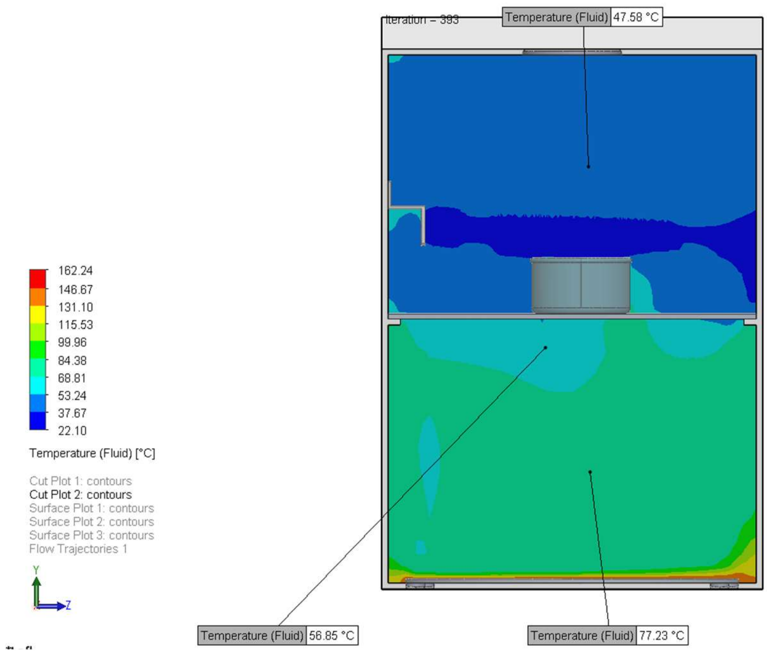

Figure 18 Temperature Plot, Lower fan speed

On figure 18, a lower fan speed was configured. As was explained before, the temperature inside the chamber will be regulated with the power applied to the plate and the fans speed. As can be seen on the images, a lower flow produces an increase in temperature. Figure 19 displays the air velocity at the new lower speed.

With these simulations we can conclude that the heated plate will be sufficient heat power for the application. Considering this, more evaluation and tests should be done on the real model to ensure the correlations with the simulations are within expected.

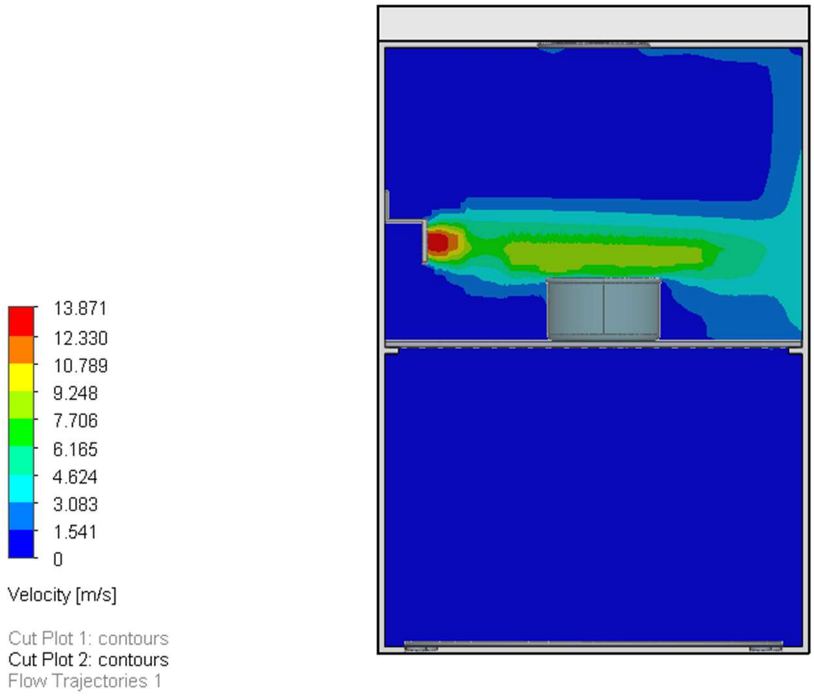

Figure 19 Velocity plot, Lower fan speed

On the following simulations, as can be observed, a less restrictive grill was used. The consequence was a better distribution of temperature and air flow. This new design aligns better with the final version of the grill which will be used.

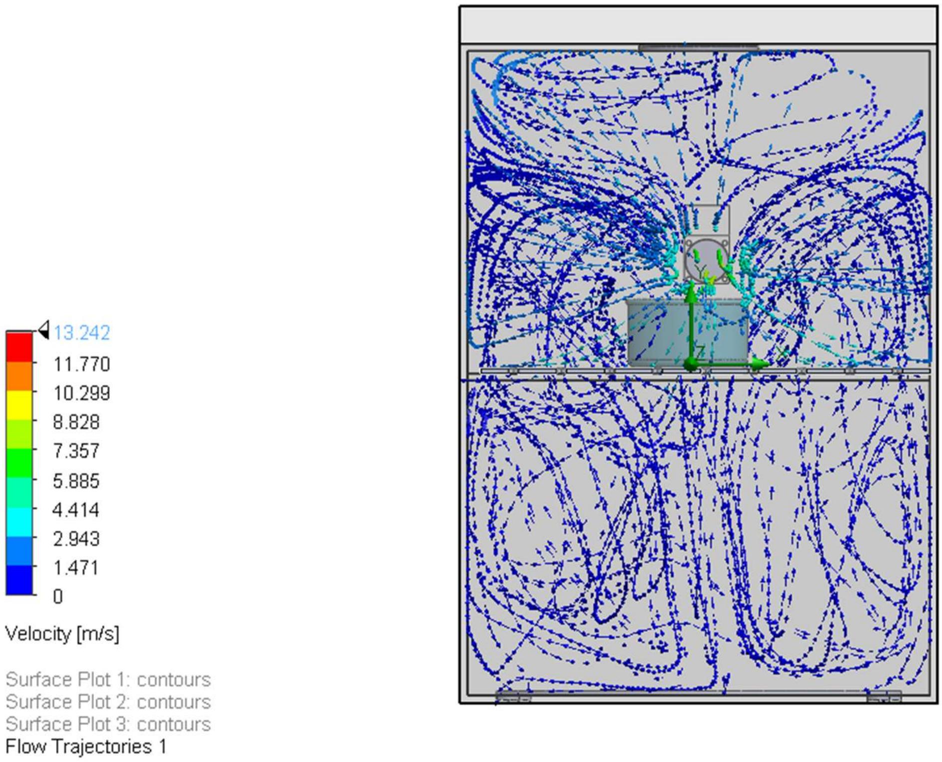

Figure 20 Air flow, less restrictive grill

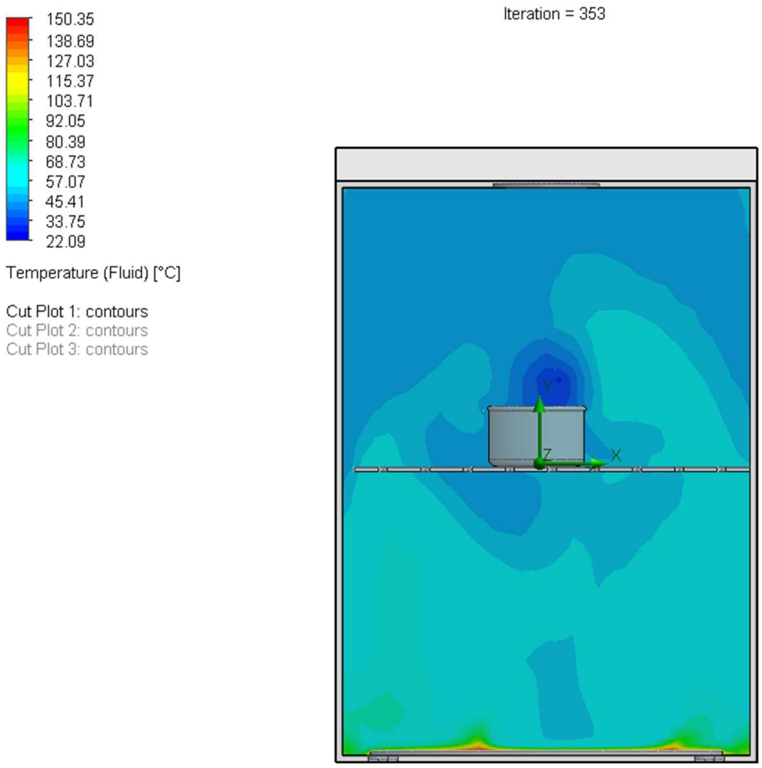

Figure 21 Temperature plot, less restrictive grill

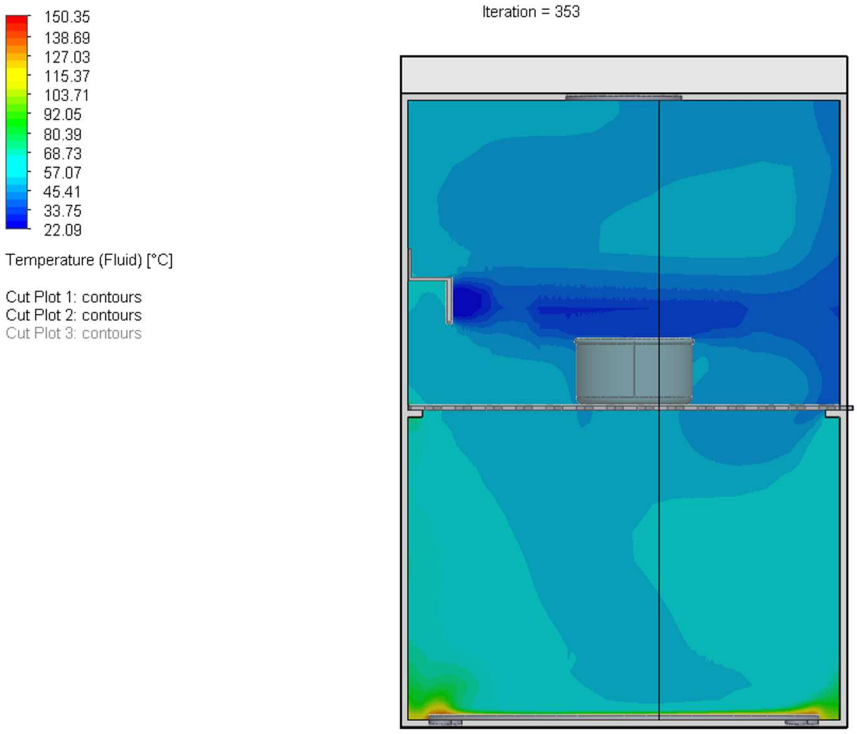

Figure 22 Temperature plot 2, less restrictive grill

After this analysis a conclusion was made. Flow simulation can´t simulate properly the evaporation because isn't designed to reproduce free surface or phase changes like the transition from liquid to vapor. Also, it isn't able to simulate water as a dynamic fluid that evaporates and lacks an integrated model to calculate the evaporation rate, which limits its ability to manage mass transfer processes. To cope with these drawbacks, results can be approximate using the data extracted from the previous simulations which were done without humidity. An empiric equation based on mass transfer principles will be used to estimate the quantity of vapor generated and extracted. This new point of view offers a practical solution to evaluate the performance of the chamber considering the limitations of the simulation program.

More advanced simulation programs such as Ansys or COMSOL offer this multi-phase interaction between fluids. However they are not accessible on the date of this study.

To solve this problem and provide an estimate calculation of how much water could be extracted, a theoretical model will be used to. The measurements taken from the simulation allow the data to be consistent and reliable.

To calculate the evaporation rate, a standard mass transfer equation is to be used, which describes the transfer on forced convection:

$$\dot{m} = A \times h_m \times (\rho_{sat} - \rho_\infty) \quad (5)$$

- A: describes the surface of the sample in contact with the air, given the diameter of the glass that was simulated. It may differ from the actual glass used but recalculation isn't a problem.
- h_m represents the ability vapor must be transferred from the sample to the air. It depends on the air speed because a higher flow rises convection. A typical correlation of 0,016*v is used as it is typical on many correlations.
- The differences on vapor densities are what creates evaporation. Sat represents the maximum concentration of vapor existing on the air near the sample. Infinite represents the water vapor concentration on the air entering the chamber. The difference reflects how much water the air can absorb on the evaporation process.

This equation should be valid due to the evaporation occurring due to the hot air flow recirculating inside the chamber. The process describes the mass transfer happening between the sample and the air.

First, some calculations are needed:

$$A = \pi \times \left(\frac{D}{2}\right)^2 = \pi \times \left(\frac{0{,}07}{2}\right)^2 = 0{,}0384845\ m^2 \quad (6)$$

$$h_m \approx 0{,}016 \times v = 0{,}016 \times 3 = 0{,}048 \frac{m}{s} \quad (7)$$

Is the mass transfer coefficient.

$$\rho_{sat} = \frac{P_{sat} \times M}{R \times T} = \frac{8270 \times 0{,}018}{8{,}314 \times 315} = 0{,}05684 \frac{kg}{m^3} \quad (8)$$

The air near the sample is at 42 ºC. Looking at saturated vapor tables we can approximate its pressure to 8270 Pa. (see figure 20)

Vapor pressure at 25 ºC is approximately 3170 Pa. Considering relative humidity of air in the room at 25%.

$$P_\infty = RH \times P_{sat} = 0{,}25 \times 3170 = 792{,}5\ Pa \quad (9)$$

So then we can calculate density at the entrance.

$$\rho_\infty = \frac{P_\infty \times M}{R \times T} = \frac{792{,}5 \times 0{,}018}{8{,}314 \times 295} = 0{,}0588162 \frac{kg}{m^3} \quad (10)$$

Now, every data from the general equation is known.

$$\dot{m} = A \times h_m \times (\rho_{sat} - \rho_\infty) = 0{,}03848 \times 0{,}048 \times (0{,}00197620) = 0{,}00000365 \frac{kg}{s} = 13{,}14 \frac{g}{h} \quad (11)$$

This value reflects the estimated value of vapor that is to be extracted from the conditions. However, on this study, a fully water sample has been considered. In reality, the samples won´t have 100% water content as they are not water. Considering this, contact with the air won´t be full.

According to these calculations, 13,14 grams will be the maximum rate that can be achieved by the device. For the design purpose rate will be something lower.

TABLA A-4

Agua saturada. Tabla de temperaturas

		Volumen específico, m^3/kg		Energía interna, kJ/kg			Entalpía, kJ/kg			Entropía, kJ/kg · K		
Temp., T °C	Pres. sat., P_{sat} kPa	Líq. sat., v_f	Vapor sat., v_g	Líq. sat., u_f	Evap., u_{fg}	Vapor sat., u_g	Líq. sat., h_f	Evap., h_{fg}	Vapor sat., h_g	Líq. sat., s_f	Evap., s_{fg}	Vapor sat., s_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9	0.0000	9.1556	9.1556
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1	0.0763	8.9487	9.0249
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2	0.1511	8.7488	8.8999
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3	0.2245	8.5559	8.7803
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.6291	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.3851	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.5953	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633

Figure 23 Vapor saturation table

On the table shown above, values for vapor saturation were taken for the equations 5-11.

3.3.Electric calculations

In this part, some electric calculations will be explained to acknowledge the system requirements. The most important and demanding component on the device will be the heated plate, which will use most of the power. Other devices will be the fans, illumination and control system. With these measurements the capabilities of the power supply will be studied to ensure requirements are met.

Heat plate power will be approximate to 250W. Considering the 24 V supply, a current of 10,4 amps is present. The mosfet used for controlling the plate, an IRF3205, has a electric resistance of 0,008 ohms. Due to the amps going through it, power losses can be calculated at approximately 0,86 W. That results on a total consumption of this part of 250,86 W and approximately 10,45 amps.

Nex calculation will be about the LED used for illumination. The power demand of the 12 LEDs built in the plate won´t be as significant as the heat but should be taken into consideration. On a moderate bright they should consume 0,15 W each, which sums up to 1,8 W (0,36 amps at 5V). On a higher bright they might demand double up to 0,3 W each, which will be 3,6 W (0,72 amps at 5V). Clearly is not much but it's important.

The 12 V fan consumes 0,24 amps which will be about 2,88 W. That was taken from the data written so might be on the worst-case scenario. The 5 V fan needs 0,1 amps so that will be 0,5 W, clearly a lower value.

The lcd screen typically will consume about 0,4 W, approximately 0,08 amps.

Now, an approximation of the power needed by the esp will be explained. It is important to note that wifi will not be used in this application. The peripherals connected to the device will be the plate, the 12 and the 5 V fans, the LEDs, I2C for display, the NTC sensor and the rotary selector. Typical demand on active mode for the CPU will be about 150 mA (0,5 W at 3,3 V), for devices will approximately be 20 mA (0,066 W at 3,3 V). That sums up a total of about 170 mA (0,51 W at 3,3 V).

Afert these considerations, it is believed that a power demand of 0,5 amps will be a correct approach and cope with any other loses that are not taken into consideration on this study. This leads to a 2,5 W power at 5 V, a secure and conservative margin.

All the powers calculated before sum up a consumption of 257 W. The power supply selected for the project will be Maitinimo šaltinis 24V, 14.6A, 350W and an efficiency of 88%. Considering its characteristics, 257 W will need approximately 293W given by the power supply, with power losses being up to 35 W. Although the device chosen might seem to exceed the needs, it has been considered its used in case the heat plate could need a bit more energy and to be conservative. It won't be an optimal decision to use almost 100% of the device characteristics. With this 350 W power supply, an approximately 85% of its capabilities will be used which will result in a better performance and useful life.

4. DESCRIPTION OF THE CONSTRUCTION AND OPERATIONAL PRINCIPLE

4.1. Electric-block scheme

The diagram shown below illustrates the drying chamber system designed for post-processing samples, with an ESP32 microcontroller serving as the central control unit. The system is powered from a 230V AC main supply, which is converted into lower 24 DC voltage by an appropriate transformer to supply the required power. However there are other components that need lower DC values. As a consequence, two converters are installed to provide 12 and 5 VDC, for the fan and the controller and the rest of the peripherals respectively.

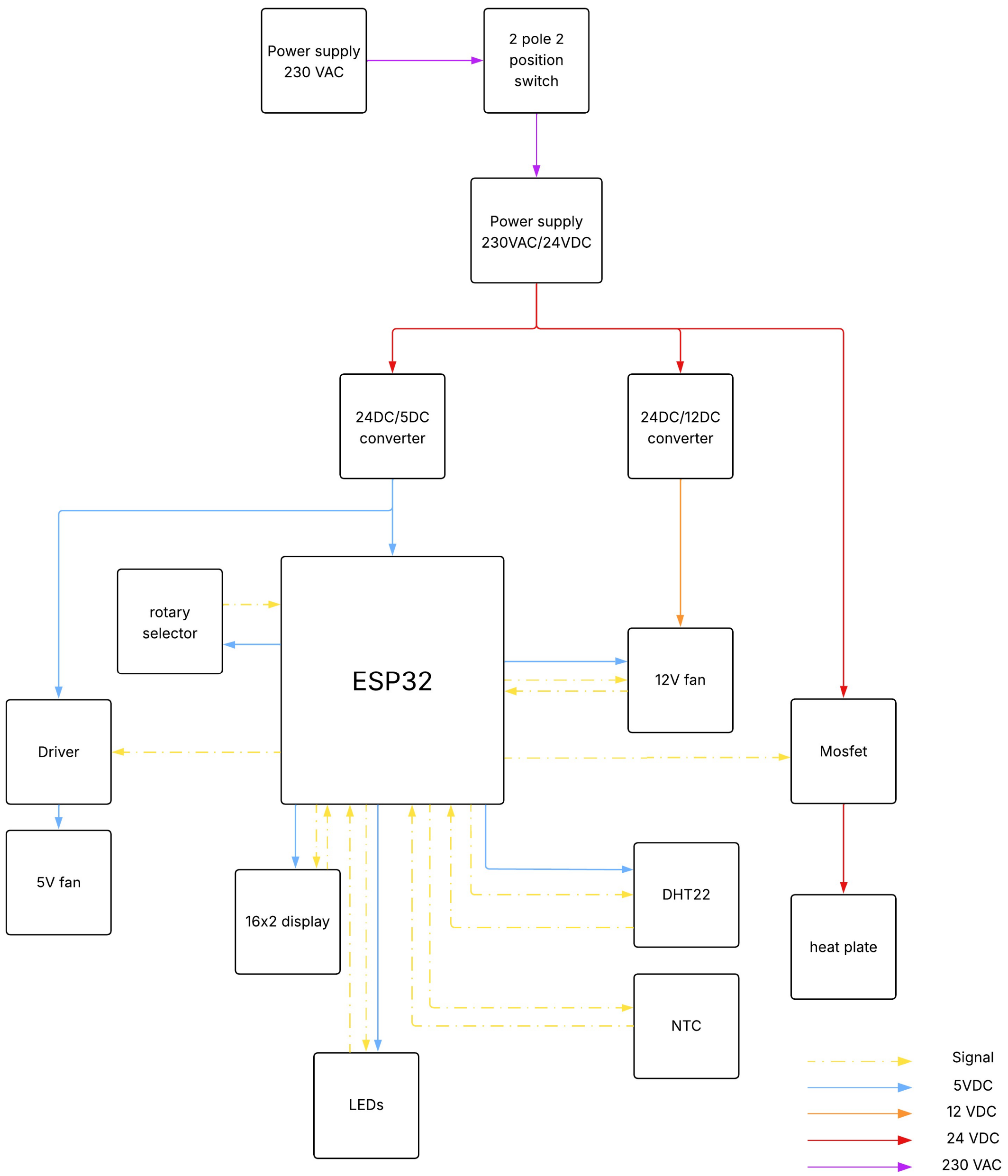

Figure 24 Electric scheme

The ESP32 coordinates all control and monitoring operations within the chamber. A DHT22 sensor is used to measure ambient temperature and humidity inside. It is connected digitally to one of the ESP32's GPIO pins and is powered through the controller’s 5V line. To further monitor thermal performance, a surface temperature sensor built in the heated plate is used as was explained before. This sensor has an analog input to the ESP32, allowing for direct thermal regulation of the platform and regulation of the control algorithm. It will be connected to one of GPIO pins with a pull up resistor to ensure optimal readings.

Airflow management is handled by two fans, a lower fan situated in the back wall of the chamber to distribute warm air throughout the volume and an upper fan to extract moisture in the air. The extraction fan is powered by a 12 V input voltage and has built in PWM regulation that can be managed through the ESP GPIO outputs. Additionally it has built in tachometer which could be easily connected to the ESP too. The other fan, used to distribute the air inside, is powered by a 5 V input. This fan won´t have any speed regulation but to control its operation a transistor will be used so it can be connected and disconnected when desired. The transistor will have its gate connected to one of GPIO pins to open and close the circuit.

User interaction is facilitated through a digital 16x2 LCD display which presents real-time data such as temperature and humidity, along with system status and different menu options. An encoder with a push-button function is employed to navigate the menu structure and select user-defined settings, also connected to GPIO to the ESP32. Additionally, a general power-on button controls the activation of the entire system cutting off power from main supply.

For internal visibility, a set of illumination LEDs is integrated under the heated base and controlled by the ESP32 through 5V digital output, providing appropriate lighting for monitoring the condition of the samples.

Overall, the system is designed to operate autonomously, responding dynamically to environmental conditions within the chamber, while also allowing manual user input for configuration and control for further experiments and checks.

4.2.Algorithm of management

The algorithm of management will be explained on this section. As was mentioned before, the microcontroller will be an esp32. This device will carry all the operations, readings and decisions for the system, creating outputs for the actuators depending on the actual state of the system. The information of the actual status will be provided by the sensors explained on previous chapters.

System Initialization and User Interface

Upong powering up the device, a menu of three options will appear; configure, initiate and status. The first step for the user will be to input the desire drying conditions via the “configure” menu. The setpoints will be selected via the rotary button and the feedback from the information shown on the display. The menu will ask the user to introduce the desire conditions on the chamber:

- Chamber Temperature: Adjustable between 20 °C and 60 °C, in 1 °C increments.
- Humidity: Adjustable between 20% and 90%, in 1% increments.
- Drying time: Configurable from 1 to 48 hours, in 1-hour increments.

The rotary encoder facilitates navigation, rotating selects values or menu options and pressing confirms the selection. Upon confirming all setpoints, the LCD displays "Setpoints Saved" and returns to the main menu.

The Status menu provides real-time information from the sensors, including plate temperature, chamber temperature, humidity and the remaining drying time. If no setpoints have been configured, selecting “Initiate” displays "No Configurations" and prompts the user to return to the Configure menu, preventing any error or unwanted previous configurations that could remain stored on the controller memory.

Drying Process Initiation and initial heating phase

With this information, the process will start. First of all, power must be sent to the plate in order to start heating and therefore the evaporation of the water contained on the sample. After some time, the plate would have reached a warm temperature and due to that air inside the chamber would have risen its temperature too. An umbral will be decided which would determine the start of the drying process. This will allow the chamber to rise its temperate faster, however, too much temperature isn’t desirable, so the samples aren’t damaged. After these conditions are met, the stable control will start.

Stable control phase

Readings from the sensors will be updated every ten seconds, a good time to ensure optimal readings and avoid stress on the CPU. Regarding to the smaller fan, its aim is to provide a better distribution of air inside the chamber, so the process is more uniform. Therefore its functioning speed won’t be controlled so it will work at a normal speed in a continuous way. As it isn’t capable of extracting air from the chamber, its effect on the actual conditions from the inside won’t be much affected by it.

After the plate has reached the umbral, stable control will start, powering up the 5V fan, giving more power to the plate and controlling the 12 V fan. In this section, conditions will be constantly measured in order to maintain the stablished conditions. Temperature will be on a +-5º C window and so for the humidity (+-5 % RH). If temperature passes that limit, power will be cut from the plate, in contrary, if its low, power must be sent to the plate. The same applies for humidity, if it exceeds the limit, fan will raise its speed to extract the humid air until the value is within the range. As both conditions are dependent from each other so constant comparison of the values is needed so the process stays in the correct operating window.

As explained, the lcd will display the status of the process, updating the values every 10 seconds to avoid any unnecessary corrections and being synchronized with the sensor readings.

Process termination

Once the duration has ended, system will stop power to the plate and the fans, gradually slowing down the temperature on the chamber. However, sensors will still be measuring so the user is aware always of the values and avoid possible risks.

Optionally, if the user wants to end the process manually, another option will be on the menu so it can force the stop the device. As a security method, a warning may appear on the screen to advise the user about possible hazards.

Safety Measures

- Plate Temperature Limit:

If the plate temperature exceeds 130 °C, the ESP32 immediately cuts power to the plate, 5 V fan, and 12 V fan. The LCD displays "Error: Plate Overheating". This prevents thermal stress on the power components and potential damage to the samples.

- Chamber Temperature Limit:

If the chamber temperature exceeds 60 °C, the plate is powered off, and the 12 V fan is activated to cool the chamber. The LCD displays "Error: Chamber Overheating". The process resumes automatically if the temperature falls below 55 °C.

- Sensor Failure:

If the NTC or DHT22 provides out-of-range readings (e.g., NTC: <0 °C or >150 °C; DHT22: <0 °C, >80 °C, or humidity <0%, >100%), the ESP32 powers off all actuators, displays "Error: Sensor Failure" on the LCD. This ensures the system does not operate under unreliable conditions.

- Manual Intervention:

As explained, the user can interrupt the process at any time by pressing the rotary encoder, ensuring flexibility and safety.

Conclusion

The described algorithm ensures stable and uniform drying conditions, prioritizing sample integrity over speed. The initial heating phase accelerates the temperature rise, while the stable control phase maintains setpoints within ±5 °C and ±5% HR. The user-friendly interface, with configurable LEDs and real-time monitoring, enhances operability. Safety measures protect the system and samples from extreme conditions, making the drying chamber reliable for laboratory use. Future improvements could include proportional control for finer humidity regulation or enhanced thermal insulation to further reduce energy consumption. Figure 25 will show the diagram of decisions for the control algorithm. Variables were used for better comprehension, so explanation is below.

Sensors:

- ctemp: temperature of the chamber, coming from the dht22.
- ptemp: plate temperature, coming from the built in NTC sensor.
- hum: relative humidity value, coming from the dht22.

Actuators:

- fan1: 12V extraction fan, controls its speed via PWM.
- fan2: 5V flow fan, controls its functioning via transistor.
- plate: heat power, controls its functioning via mosfet.

Targets:

- temp_trg: chamber temperature target set by the user.
- hum_trg: chamber humidity value set by the user.
- t_trg: time of drying value set by the user.

As was explained before, the main governor of the process is the time. After time is checked, precautions are revised to avoid wrong functioning, problems and damage to the sample. These measures are temperature and humidity limits, as well as it prevents wrong measurements from the sensors.

After precautions are taken, control of the conditions is carried out by comparing temperature and humidity values with the setpoints marked by the user. As explained, some margins are necessary to avoid wrong functioning and better results for the system control.

Following this decision route would result in an optimal result of the device developed on this thesis. Although some upgrades and adjustments could be optimized, conclusions will be at the end.

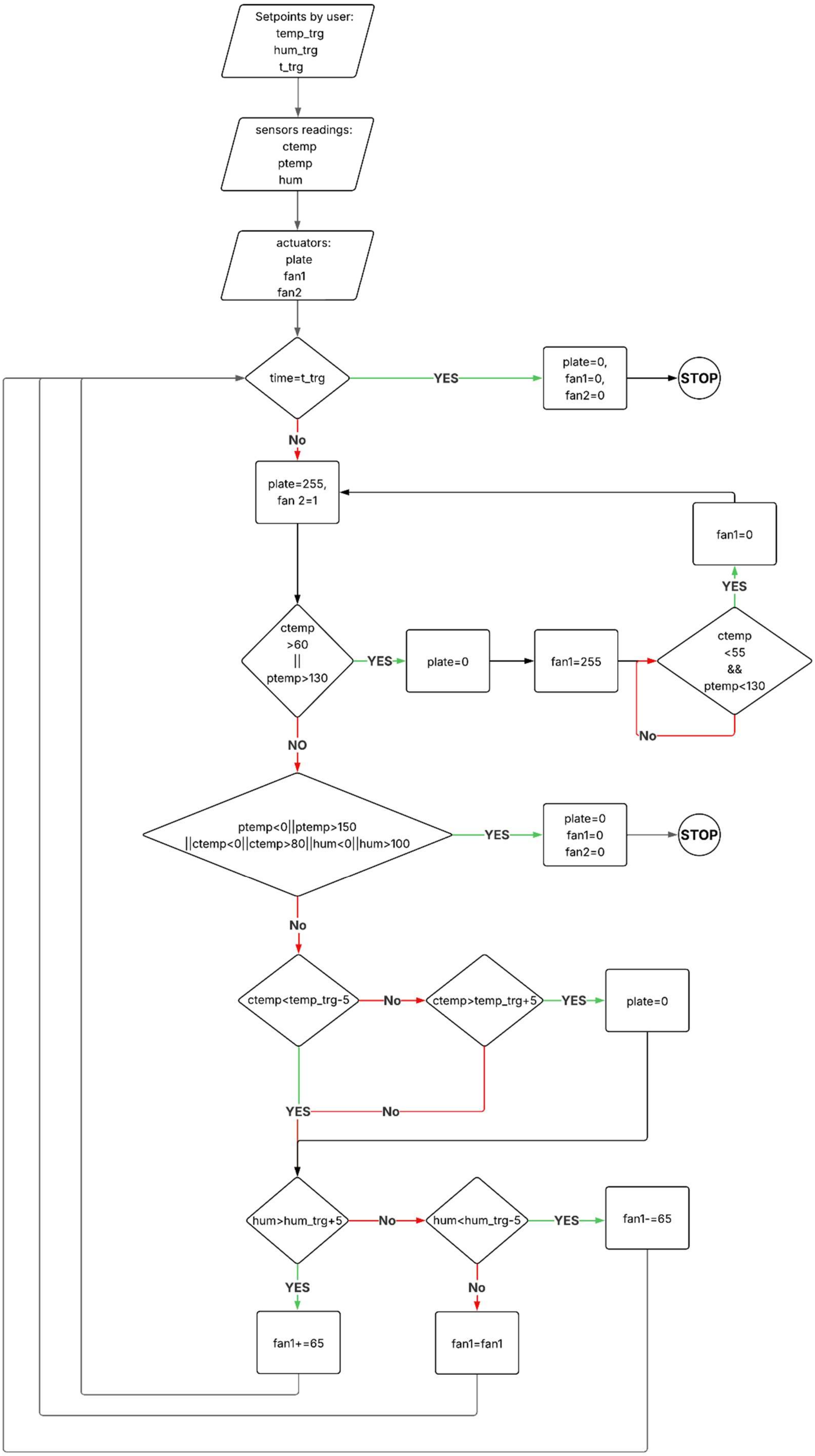

Figure 25 Algorithm of control

5. WORK SAFETY

5.1. General provisions and requirements for safe working and environmental protection

The development and operation of the drying chamber designed for this project involve various mechanical, thermal, and electrical components that pose potential hazards to the user. Consequently, ensuring the safety of both the operator and the equipment has been a key consideration throughout the design phase. This section outlines the main risks identified in the system and presents the corresponding preventive measures implemented to ensure safe operation. Particular attention has been given to hazards associated with high voltage, high temperatures, moving parts, and control electronics.

5.2. Work safety and environmental requirements of drying chamber Electrical

Hazards and Safety Measures

The drying system will be powered by a standard 230 V AC supply, which will provide energy to the heated rotating plate as well as the electronic components. This voltage level is potentially lethal and requires strict adherence to safety guidelines and protective strategies.

1. Insulation and Electrical Enclosures:

All components operating at mains voltage are enclosed in protective housings made from flame-retardant and non-conductive materials. These enclosures comply with IP standards to prevent accidental contact and ingress of dust or moisture. Internal wiring will be double-insulated, and terminals will be fully covered to prevent any risk of electric shock.

2. Separation of Power and Control Circuits:

To prevent interference and reduce the risk of cross-voltage incidents, the high-voltage components will be physically and electrically isolated from the low-voltage control electronics based on the ESP32 microcontroller. The separation will be achieved using opto-isolators and relay modules rated for 220 V AC switching.

3. Overcurrent and Short-Circuit Protection:

The system will be protected with appropriately rated fuses and circuit breakers to avoid overheating and fire hazards caused by accidental short circuits or excessive current draw. The selection of protective devices follows guidelines from IEC 60269.

These safety measures are crucial in environments were embedded systems interface with power electronics. In line with best practices, all connections and terminations will be labelled, and the wiring layout will follow a logical and easily traceable scheme to facilitate inspection, maintenance and avoid possible short circuits.

Thermal Hazards and Preventive Strategies

The heating components of the drying chamber, including the resistive heaters and the rotating plate, can reach temperatures exceeding 80°C. Such levels are sufficient to cause burns or to ignite nearby flammable materials under certain conditions. Therefore, thermal safety is a priority.

1. Thermal Insulation and Heat Containment:

The internal chamber will be lined with aluminium foil. This material will help contain the heat within the drying compartment, prevent heat loss, and reduce the temperature of external surfaces.

2. Active Temperature Monitoring and Control:

A DHT22 humidity and a temperature sensor and the one embedded in the rotating plate will continuously monitor ambient and surface temperatures, respectively. These sensors will feed data to the ESP32, which will use PWM signals to regulate the power delivered to the heating elements. This closed-loop control helps prevent overheating and ensures the internal temperature remains within safe and predefined limits.

3. Visual Warnings and Safety Labels:

Labels indicating "Hot Surface" and "Caution – High Temperature" will be affixed near heating elements and the rotating plate. If an LCD interface is implemented, it will also display warning messages when the temperature exceeds a certain threshold (e.g., 50°C).

4. Ventilation Strategy and Moisture Management:

The inclusion of forced convection using strategically placed fans will allow for homogeneous temperature distribution. Additionally, an exhaust fan located at the upper end of the chamber will expel humid air, reducing internal humidity and preventing steam-related pressure buildup or condensation near electronics.

In line with existing literature, temperature control and humidity evacuation are essential in preventing thermal runaway and preserving the durability of embedded sensors and actuators.

Mechanical Risks from Moving Components

The system will include rotating and ventilating components that may represent a risk of mechanical injury. These include the heated rotary platform and axial-flow fans.

1. Fan Safety and Physical Guarding:

Each fan could be equipped with a protective mesh or grille to prevent fingers or foreign objects from coming into contact with the blades while in operation. These guards should comply with IEC 60335 safety requirements for rotating machinery.

2. Design for Mechanical Reliability:

Wear-resistant materials and bearings with appropriate temperature ratings will be used for all moving assemblies. Periodic inspection guidelines will be included in the system documentation to detect mechanical fatigue, vibrations, or misalignments early.

General Safety Measures and Compliance

Beyond specific risks, the overall system will incorporate broader safety principles:

1. Emergency Shutdown:

An emergency stop button will be installed on the main control panel, cutting all power to the heating and motor systems. The emergency stop will conform to the ISO 13850 standard for safety of machinery.

2. Access Restriction During Operation:

The main access door of the drying chamber will be fitted with a mechanical or magnetic interlock that prevents opening while the system is active or above a safe temperature threshold. This measure is intended to avoid exposure to hot air or moving components.

3. User Interface and Status Indicators:

The system will provide a clear and intuitive interface (either via buttons and LCD or touch screen) for setting parameters and visualizing current operating conditions. Status on the screen will indicate when the system is heating, ventilating, rotating, or in standby mode.

4. Training and Safe Use Documentation:

A safety manual will be provided, including start-up, shutdown, and emergency procedures. The manual will include a checklist for initial inspections and maintenance intervals. Users will be advised to avoid direct contact with internal surfaces and to use heat-resistant gloves when removing or placing samples.

5. Environmental and Material Considerations:

All selected materials comply with RoHS and REACH directives, ensuring the device is safe for indoor laboratory use. Ventilation ports will be designed to avoid creating pressure zones that could affect measurement accuracy or component durability.

6. ECONOMIC CALCULATION

The economic cost and profitability of the drying chamber developed throughout this thesis are studied. For this purpose, a table has been made with all the elements that make up the system. It shows the identification of the elements together with the quantity necessary for the production of one unit and the price of the element.

6.1.List of materials and components

Table 3. Material cost

Number	Entity	Quantity	Price per unit (eur)	Sum (eur)
1	Mean Well LRS-350-24	1	28,8	28,8
2	ESP32	1	16,6	16,6
3	SPRR93 Round Rocker	1	5,25	5,25
4	LM2596	2	3,4	6,8
5	Rotary Encoder	1	4,5	4,5
6	2N7000	1	2,24	2,24
7	5V 60x60x15 fan	1	3,04	3,04
8	AUB0712MB 7015 12V 0.24A	1	10,79	10,79
9	16x2 LCD	1	8,29	8,29
10	DHT22	1	3,95	3,95
11	IRF3205	1	1,41	1,41
12	HEATED PLATE 25x25 cm PCB heated silicone 12V 250W	1	48,8	48,8
13	NTC surface sensor	1	5	5
14	Hex Socket M4x30mm (pack of ten)	1	5,89	5,89
15	Mushroom head Allen bolt - M4 x 8mm (pack of 10)	1	2	2
16	Multiblock (pack)	1	5	5
17	15 amps fuse	1	3	3
18	Grill	1	0,5	0,5
	Total			161,86

The table above shows the components needed to fabricate the drying chamber developed on this thesis. The selection was done based on the materials available on the laboratory, spare parts and online shops on Lithuania. Considering this, different options with similar characteristics could be chosen if fabrication was to be done elsewhere.

However, the basis of this device is the chassis. Through the development of the chamber, a reused structure of an old 3D printer was used. Considering this, costs regarding this aspect are not taken into account being only the necessary parts needed to adapt it to its new purpose. With this in mind, the study focusses on description of the components as well as the associated costs involved on the construction.

6.2.Cost of fabrication and assembly

The following is an analysis of the costs per unit produced. First of all, it is necessary to print three pieces that are designed to hold the new components in the chassis. For this a 3D printer capable of printing with the required precision will be necessary.

Although actually the laboratory is equipped with some of them, it is the object of this study to determine the cost involved in building from scratch and this takes into account the lack of the tools needed to build it. It has been estimated to cost approximately 790€. In case it will be used for some other purpose, this will have a payback time of 5 years and will be active during the working days of a year resulting in an amortization cost per unit of about 8 cents. A roll of ABS (Acrylonitrile Butadiene Styrene) filament is required for printing. It is possible to buy a 1Kg spool of this material in the market for 18€. Currently the cost per kilowatt hour in Vilnius is 0.08€. Taking into account that a printer consumes on average 0,3KW the cost per hour will be 0,024 €. Finally, an operator is needed to place the parts to be printed and to assemble them as well as any other modifications needed. It has been estimated that the preparation time needed to start printing, which may include small calibrations or adjustments of the printer, is 15 minutes.

On the other hand, the operator will need another 3 hours to complete the final assembly, since it is important to ensure everything is correctly placed and adjusted. Considering these times and the fact that the operator's salary is 15€/h, the cost associated with the worker's salary for each printed piece is 3.75€.

6.3.Fix and variable costs

Table 4 Fixed costs

ABS cost (€/kg)	18
Light cost (€/KWh)	0,08
Average consumption (KW)	0,3
Light cost per hour (€/h)	0,024
Operator hourly cost (€/h)	15
Preparation time for piece (h)	0,25
Postproduction time (h)	3
Cost operator per piece (€/piece)	63,75
3D printer cost (€)	786,8
Amortization time (years)	5
Active days per year (days)	250
Active hours per day (h)	8
Amortization cost (€/h)	0,07868

Once the costs have been defined, the calculation of the cost associated with each different part that makes up the system has been carried out. For this purpose, the weight of the part has been taken into account together with the estimated printing time. In this way it is possible to calculate the cost associated with ABS, electricity, labor and amortization of the machinery used. It should be noted that all the parts have been printed with 20% density, so this has not entailed any additional cost. As a final result, the cost of printing the three pieces and the preparation time needed to make up the system is 25,16€. If we add here the approximately 3 hours needed for the assembly of the device, with the price per hour for the operator, the final cost is of 70,16 €.

Table 5 Printing and assembly costs

Printed pieces	Fan support	LCD and ESP support	Electric components support	Plate support x4	Grill support	Total (€)
Weight (g)	12	41	18,82	4	260	331,82
Printing time (h)	0,93	1,78	0,783333333	3,84	8,11	15,44333
ABS Cost (€)	0,216	0,738	0,33876	0,072	4,68	6,04476
Electric cost (€)	0,02232	0,04272	0,0188	0,09216	0,19464	0,37064
Workforce cost (€)	3,75	3,75	3,75	3,75	3,75	18,75
Sum (€)						25,1654
Assembly (€)						45
Total set						70,1654

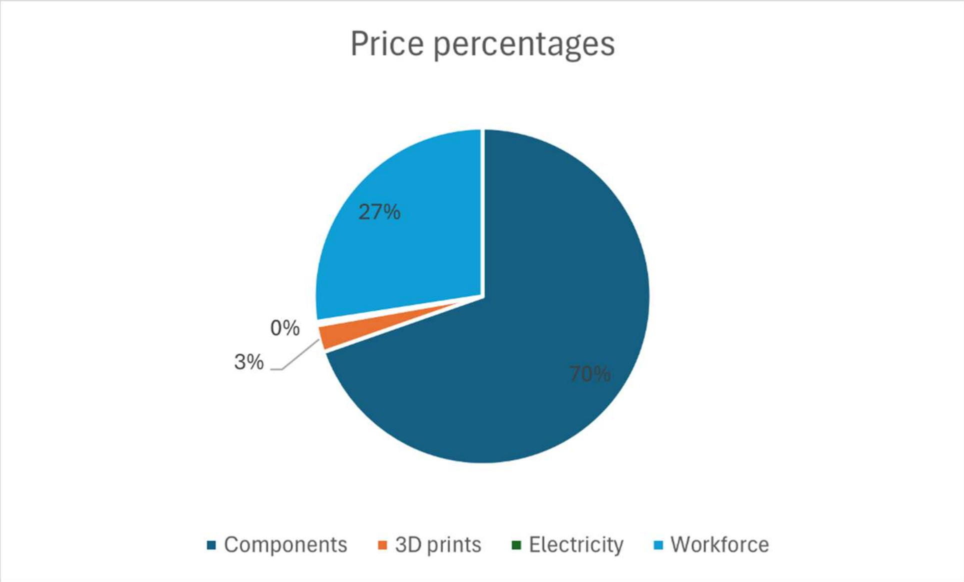

Figure 26 Price percentages comparison

The graphic above allows for better visualization of cost partitions.

6.4. Power usage

Considering the function of the device and since it has been designed for prolonged times of usage, an analysis of the estimated cost per cycle has been taken into account. For this study, various times were taken starting from a 6 going up to 48 hours. It is supposed that after heating up, the control system of the chamber will automatically control and maintain the temperature on the inside withing a determined range. With this in mind, an estimation that most of the power will be used at least 60% of the time has been taken. However, on lower periods of functioning, like for 6 hours, this percentage is higher due to warming times. The table below summarizes these costs.

Table 6 Power usage

Hours functioning	6	12	24	36	48
Power used (Watts)	340	340	340	340	340
Percentage of power (%)	70	60	60	60	60
Cost (€)	0,11424	0,19584	0,39168	0,58752	0,78336

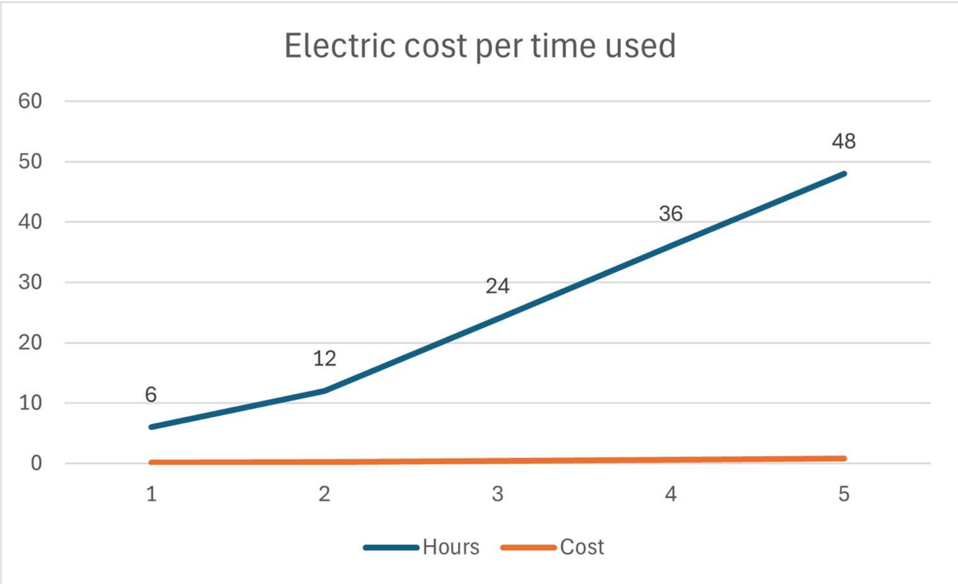

Figure 27 Electric cost per time used

The graph above shows the cost dependence on time of use. Although it’s understandable, visualization was considered of interest.

CONCLUSIONS

1. Potential Improvements with PID Control: The drying chamber currently employs an on/off control strategy with hysteresis to maintain the desired temperature and humidity levels over extended periods (12-48 hours), ensuring stability within tolerances of ±5 °C and ±5% relative humidity. This method, while simple and effective, results in abrupt transitions as the heater and extraction fan switch between fully on and fully off states, potentially causing minor fluctuations around the target conditions. These oscillations, though within acceptable limits for the current application, might affect sample uniformity in more sensitive scenarios. Implementing a Proportional-Integral-Derivative (PID) control approach could enhance the system's performance by providing smoother regulation. A PID controller adjusts the power applied to the heater and fan based on the error between the actual and desired conditions, factoring in the magnitude, accumulation, and rate of change of this error. This results in more gradual adjustments, reducing overshooting and maintaining conditions closer to the setpoints with minimal fluctuations. Consequently, the drying process would achieve greater uniformity, which could be beneficial for preserving highly sensitive samples. However, adopting PID control introduces complexity, as it requires careful tuning of its parameters to match the chamber's thermal and humidity dynamics, a process that can be time dependent. Additionally, the microcontroller would need to handle increased computational demands, though this is manageable with the chosen hardware. Compared to the on/off method, PID control offers superior precision and stability, making it ideal for applications demanding tighter control. Nevertheless, for the current system, where stability over long durations is prioritized and the existing tolerances are sufficient, the simplicity of the on/off approach remains advantageous, suggesting that PID might be more suitable for future iterations targeting stricter requirements.

2. An interesting new approach could be how the drying chamber designed could not only be used for treating the piezoelectric samples but also for other moisture-sensitive materials, such as PLA (polylactic acid) filament rolls. PLA is a widely used thermoplastic material in 3D printing, but one of its main drawbacks is its high moisture absorption from the environment. This moisture absorption negatively impacts the printing quality, as the PLA becomes more brittle, may form bubbles during extrusion, and loses precision in detail. The implementation of a controlled drying system, like the one designed in this work, could be an efficient solution to this problem. By providing precise control over temperature and humidity, the chamber could ensure that PLA rolls are kept in optimal conditions before being used in 3D printers, improving the material's quality and extending its shelf life. This type of application would not only be useful in professional or industrial environments but could also benefit home 3D printer users looking to improve their results without

the need for frequent purchases of new filament rolls. The flexibility of the drying system opens the door to a wide range of applications in the design and additive manufacturing industry.

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THE ANNEXES

ANNEX 1: BILL OF MATERIALS

Format	Zone	Position	Tag	Title	Qty.	Remarks
				<u>Documents</u>		
A1			MERS BM 25 AL 01 00 00 00 GV	General View	1	
				<u>Subassemblies</u>		
		1	MERS BM 25 AL 01 01 01 00 AD	Chassis	1	
		2	MERS BM 25 AL 01 01 02 00 AD	Heat plate	1	
		3	MERS BM 25 AL 01 01 03 00 AD	Circulation fan	1	
		4	MERS BM 25 AL 01 01 04 00 AD	Extraction fan	1	
A1		5	MERS BM 25 AL 01 01 05 00 AD	Electronics Assembly	1	
		6	MERS BM 25 AL 01 01 06 00 AD	Grill support	1	
				<u>Aditional components</u>		
		7	MERS BM 25 AL 01 01 07 00	Switch	1	
		8	MERS BM 25 AL 01 01 08 00	DHT22	1	
		9	MERS BM 25 AL 01 01 09 00	Rotary encoder	1	

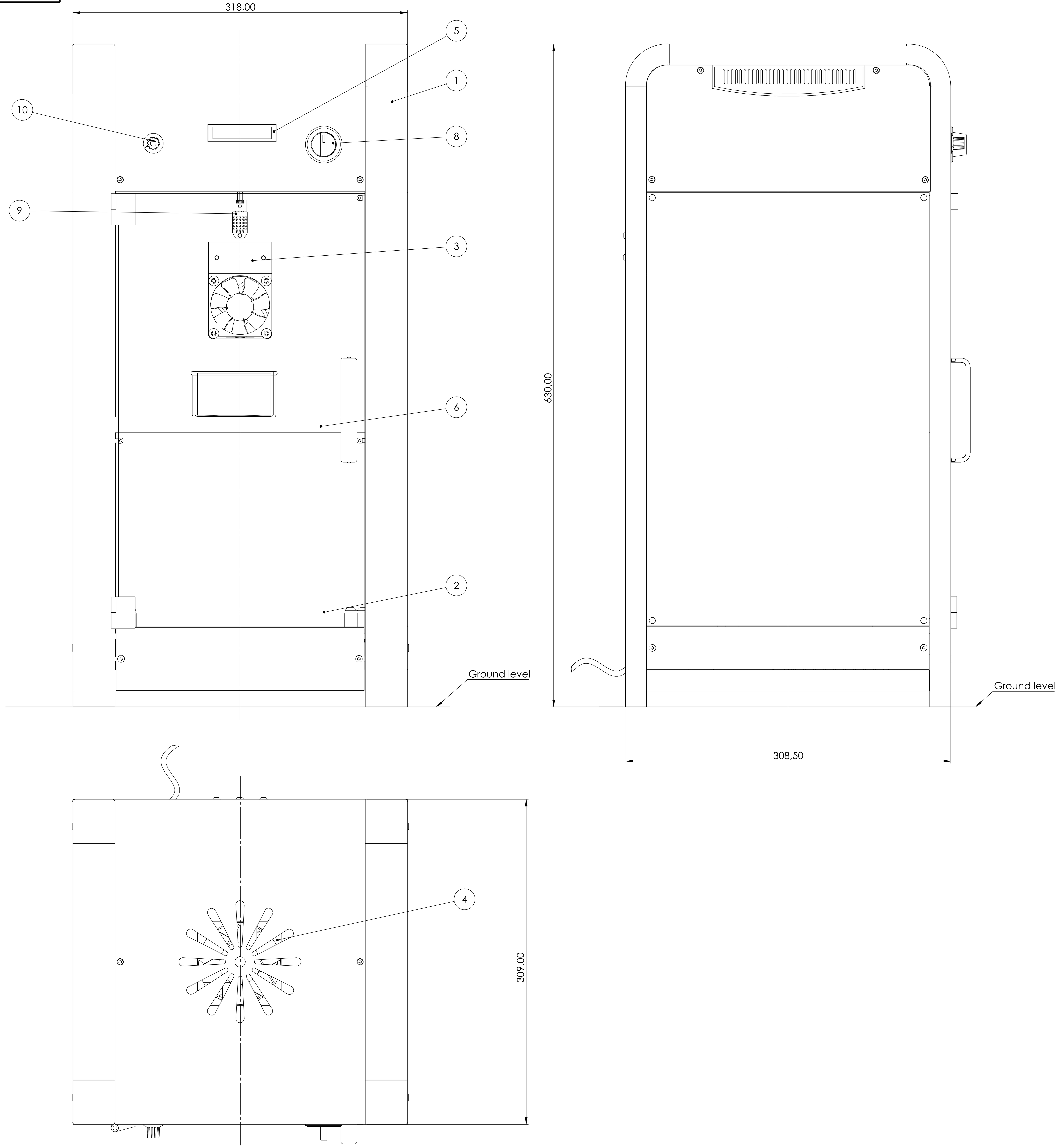
Respon.depart. Dep. of mech., rob, and dig. man.	Adviser	Document type Specification		Status of the document Educational		
Owner VILNIUS TECH MRfu-25	Prepared by Alejandro Lopez Perales	Title Design of drying chamber	Tag			
	Approved by		Issue A	Date 21/5/2025	Lang. En	Page 1/2

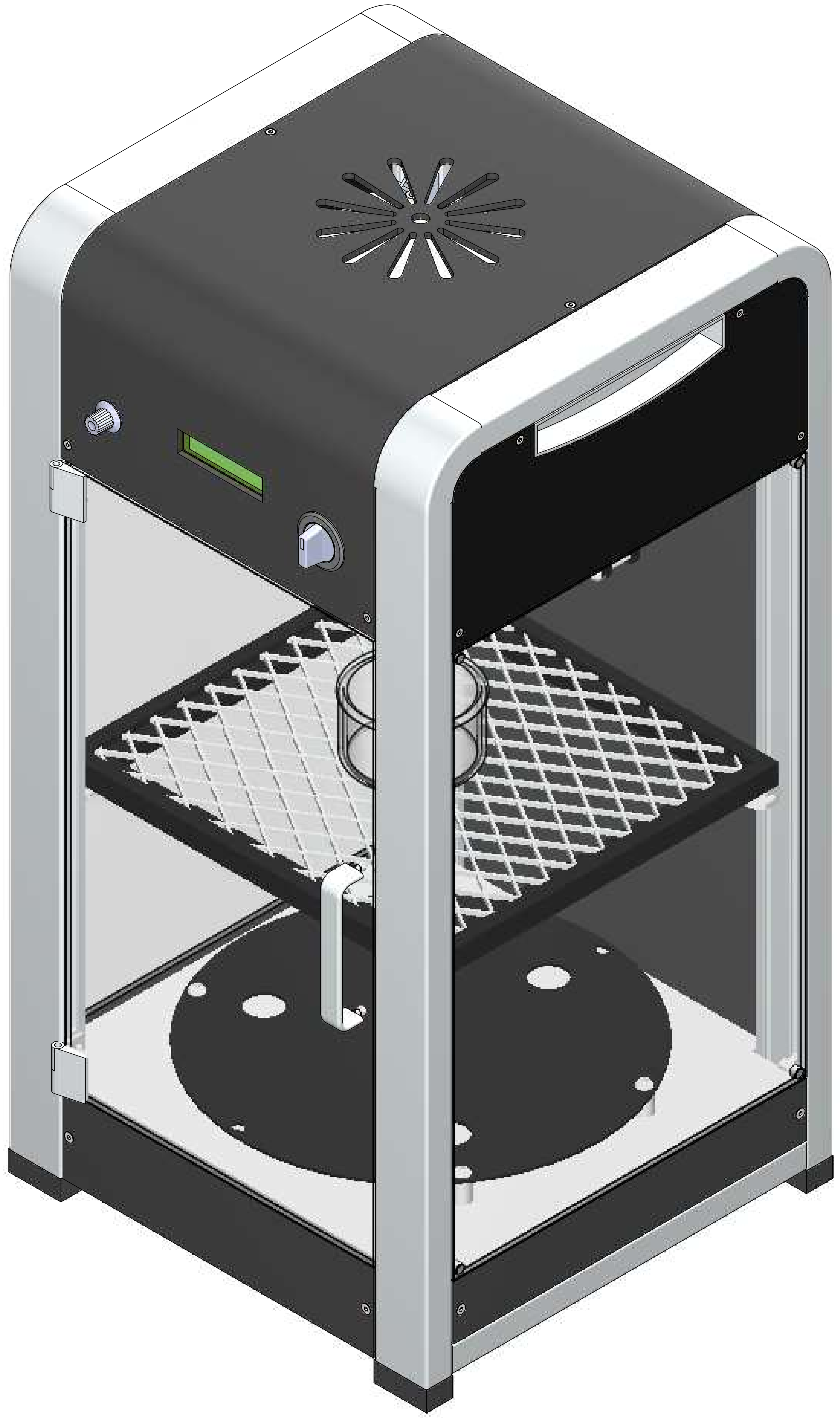
Format	Zone	Position	Tag	Title	Qty.	Remarks
				Documents		
A1			MERS BM 25 AL 01 01 05 00 AD	Electronics assembly	1	
				Parts		
A2		1	MERS BM 25 AL 01 01 01 00	Screen support	1	
				Standard components		
		2	MERS BM 25 AL 01 01 02 00	Hex bolts M3x12 (ISO 14581)	2	
		3	MERS BM 25 AL 01 01 03 00	M3 hexagon nuts (ISO 4032)	2	
		4	MERS BM 25 AL 01 01 04 00	Slotted bolts M2x3 (ISO 1207)	8	
				Electric components		
		5	MERS BM 25 AL 01 01 05 00	ESP32	1	
		6	MERS BM 25 AL 01 01 06 00	16x2 LCD screen	1	

Respon.depart. Dep. of mech., rob, and dig. man.	Adviser	Document type Specification		Status of the document Educational			
Owner VILNIUS TECH MRfu-25	Prepared by Alejandro Lopez Perales	Title Design of drying chamber	Tag				
	Approved by		Issue A	Date 21/5/2025	Lang. En	Page 2/2	

ANNEX 2: DRAWINGS

MERS BM 25 AL 01 00 00 00 GV



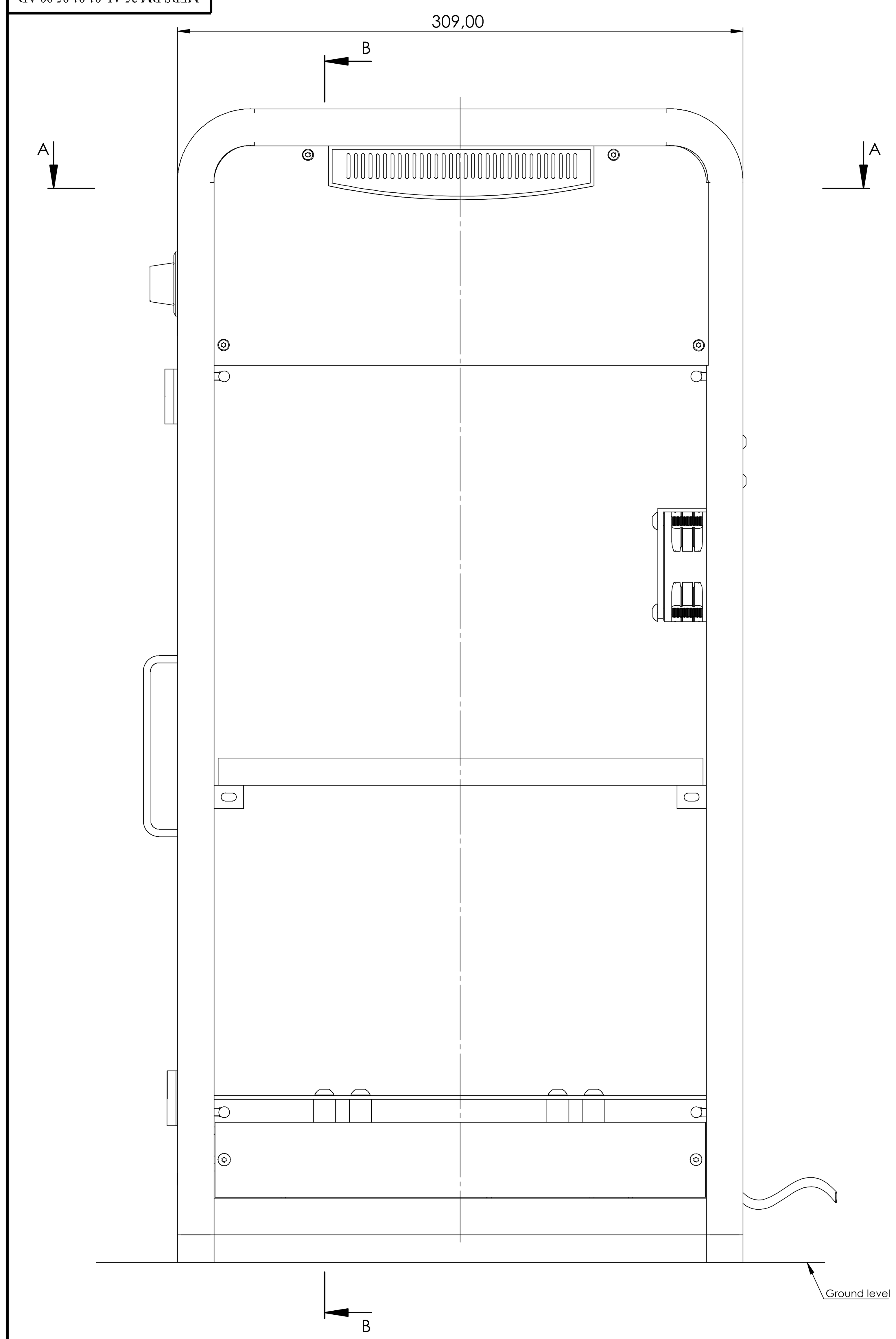


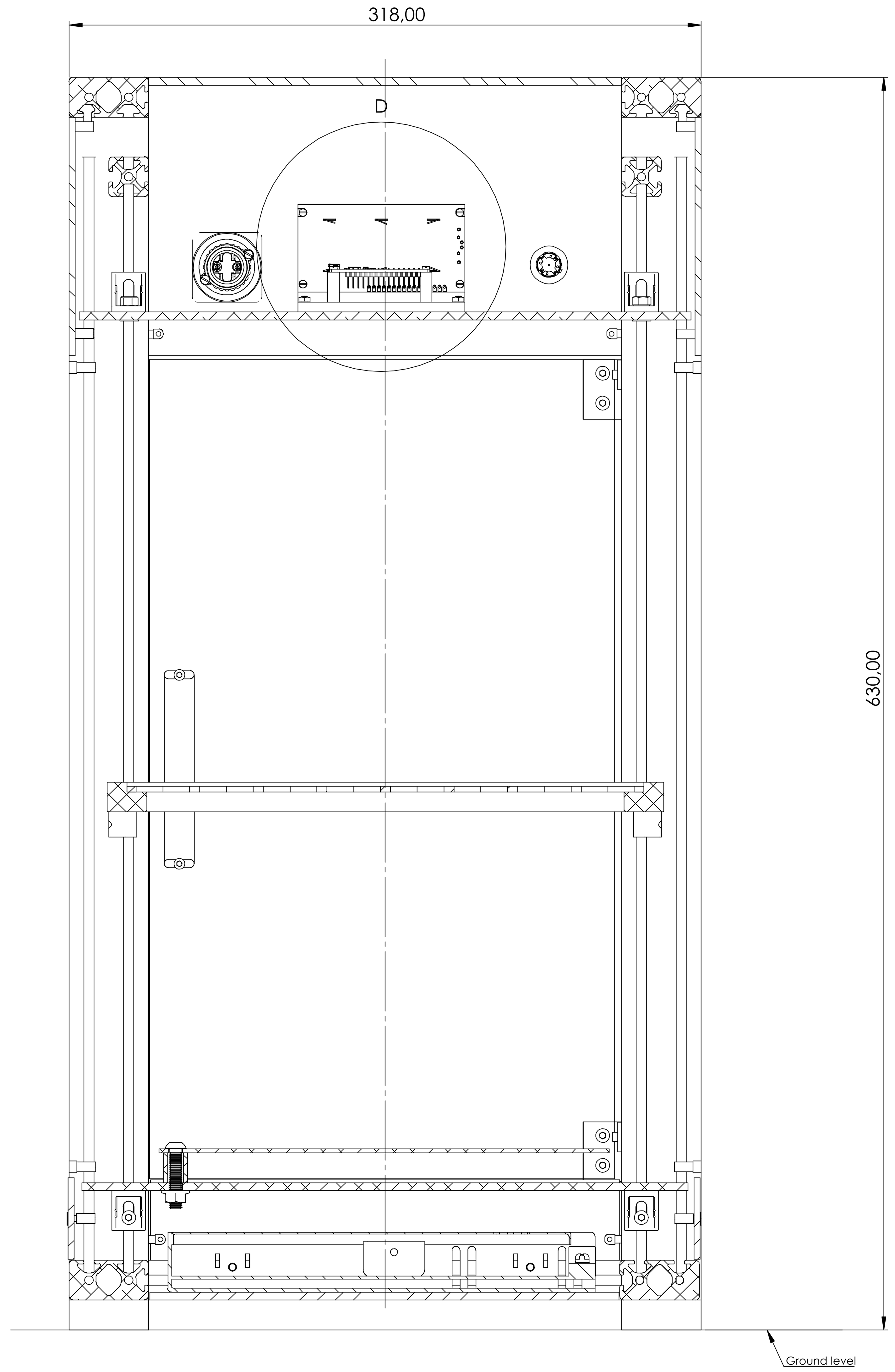
Structure material: aluminium
Walls materials: methacrylate
Door mechanism at front
Controlled by ESP32
Moving parts: two fans
Forced ventilation
Sensors: DHT22 & NTC surface
Input method: rotary button
Status visualization: LCD screen
Samples placed into the glass
Grill is adjustable in high

Working voltage: 230V, input from the back
Power supply: 350W
Working temperature: +20-60°C
Hot plate temperature: 120°C

File No.	Aditional information	Material	Scale 1:2
Respon. depart. Dep. of mech., rob, and dig. man.	Adviser	Document type	Status of the document Educational
Owner VILNIUS TECH MRfu-25	Prepared by Alejandro Lopez Perales; Approved by	Title General View	MERS BM 25 AL 01 00 00 00 GV; Issue 1; Date 21/5/25; Lang. Eng.; Page 1/8

MERS BM 25 AL 01 01 05 00 AD





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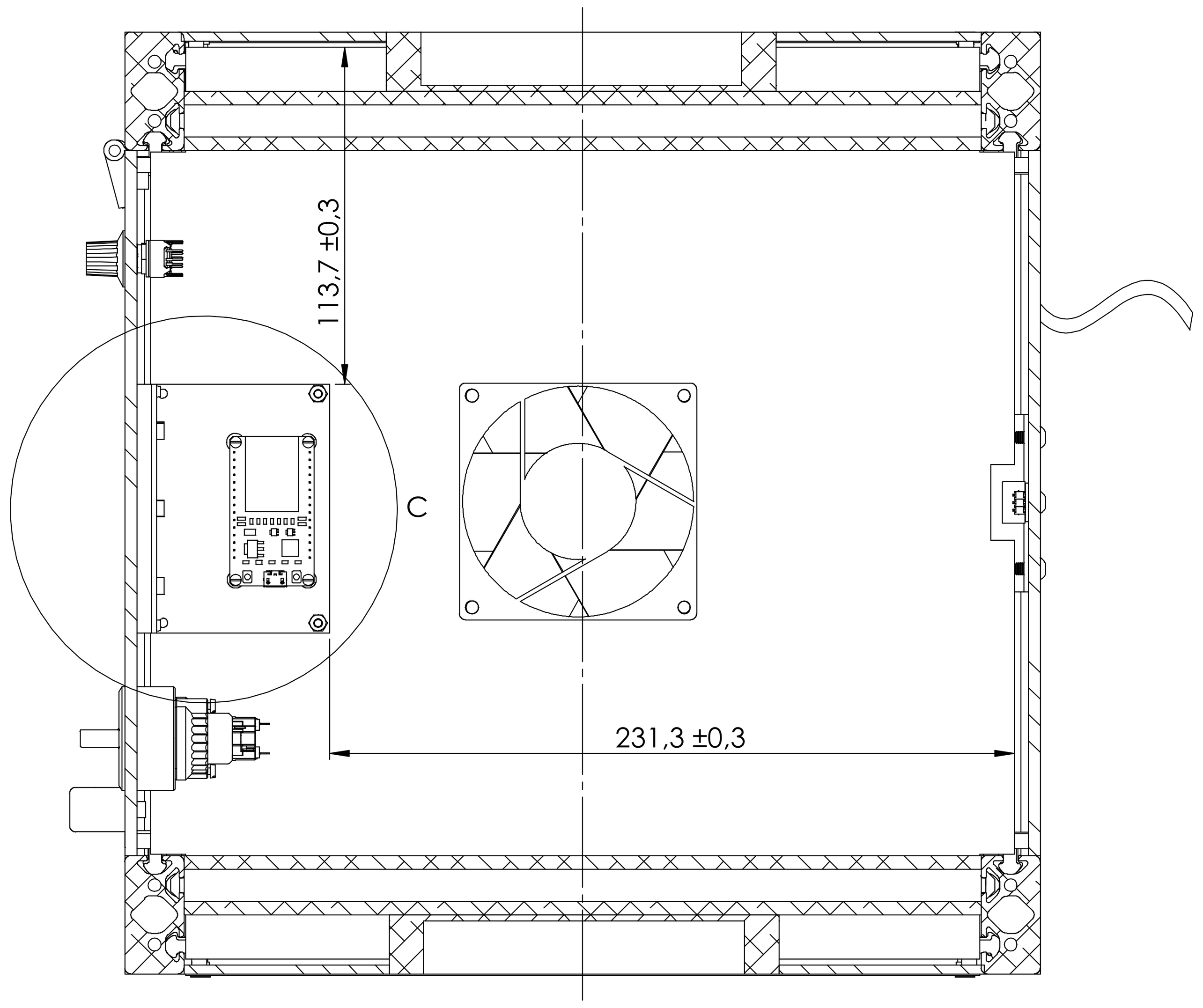

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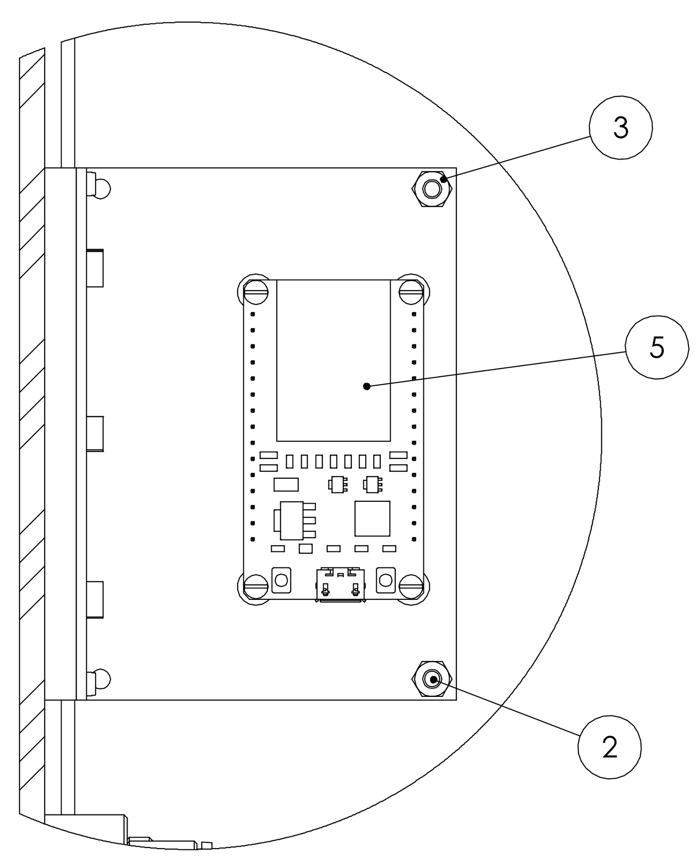
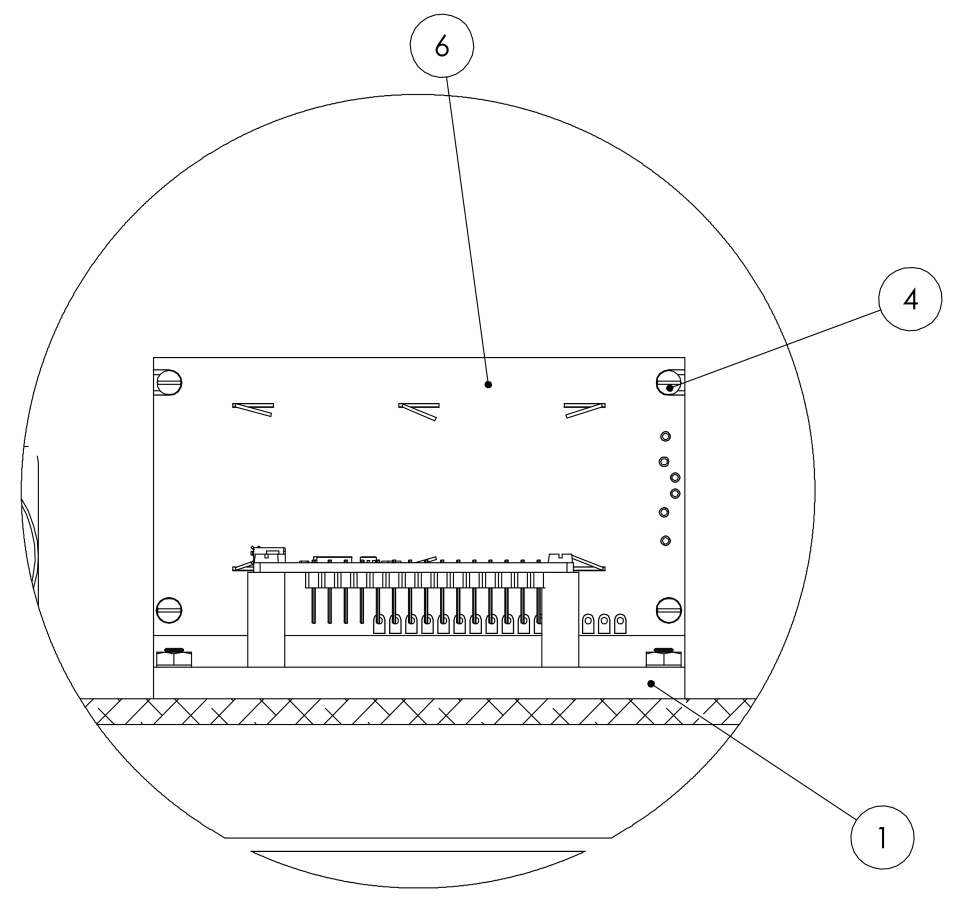


DETAIL C
SCALE 1 : 1



DETAIL D
SCALE 1 : 1

Screen and controller support are bolted to the top plate of the chamber by two flat head bolts. Bolts are tightened from the downside of the plate so they result flat with it.
Bolts: M3

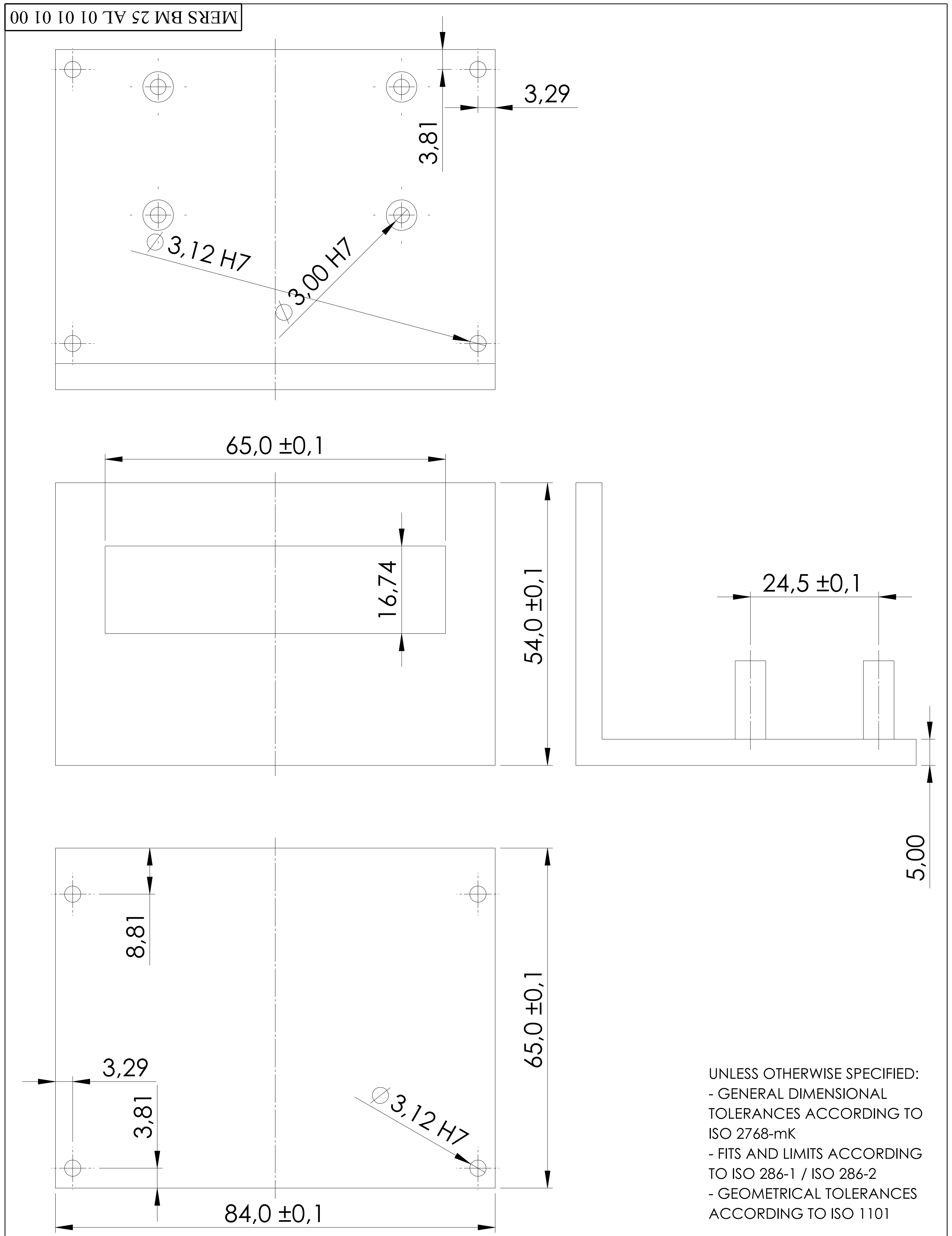
Controller is attached to the support by 4 raised and threaded supports. Bolted by four slotted head screws.
Bolts: M2

Screen is attached to the support by four slotted head screws. It will be prefirable to mount first the screen to the controller for better adjustment.
Bolts: M2

For installation of the assembly the top cover of the chamber needs to be disarmed to make access.

	File No.	Aditional information	Material			Scale 1:2
Respon. depart. Dep. of mech., rob. and dig. man.	Adviser	Document type		Status of the document		
Owner VILNIUS TECH MRfu-25	Prepared by Alejandro Lopez Perales	Title		MERS BM 25 AL 01 01 05 00 AD		
	Approved by	Electronics assembly	Issue 1	Date 21/5/2025	Lang. Eng.	Page 2/8

MERS BM 25 AL 01 01 01 00



UNLESS OTHERWISE SPECIFIED:
- GENERAL DIMENSIONAL TOLERANCES ACCORDING TO ISO 2768-mK
- FITS AND LIMITS ACCORDING TO ISO 286-1 / ISO 286-2
- GEOMETRICAL TOLERANCES ACCORDING TO ISO 1101

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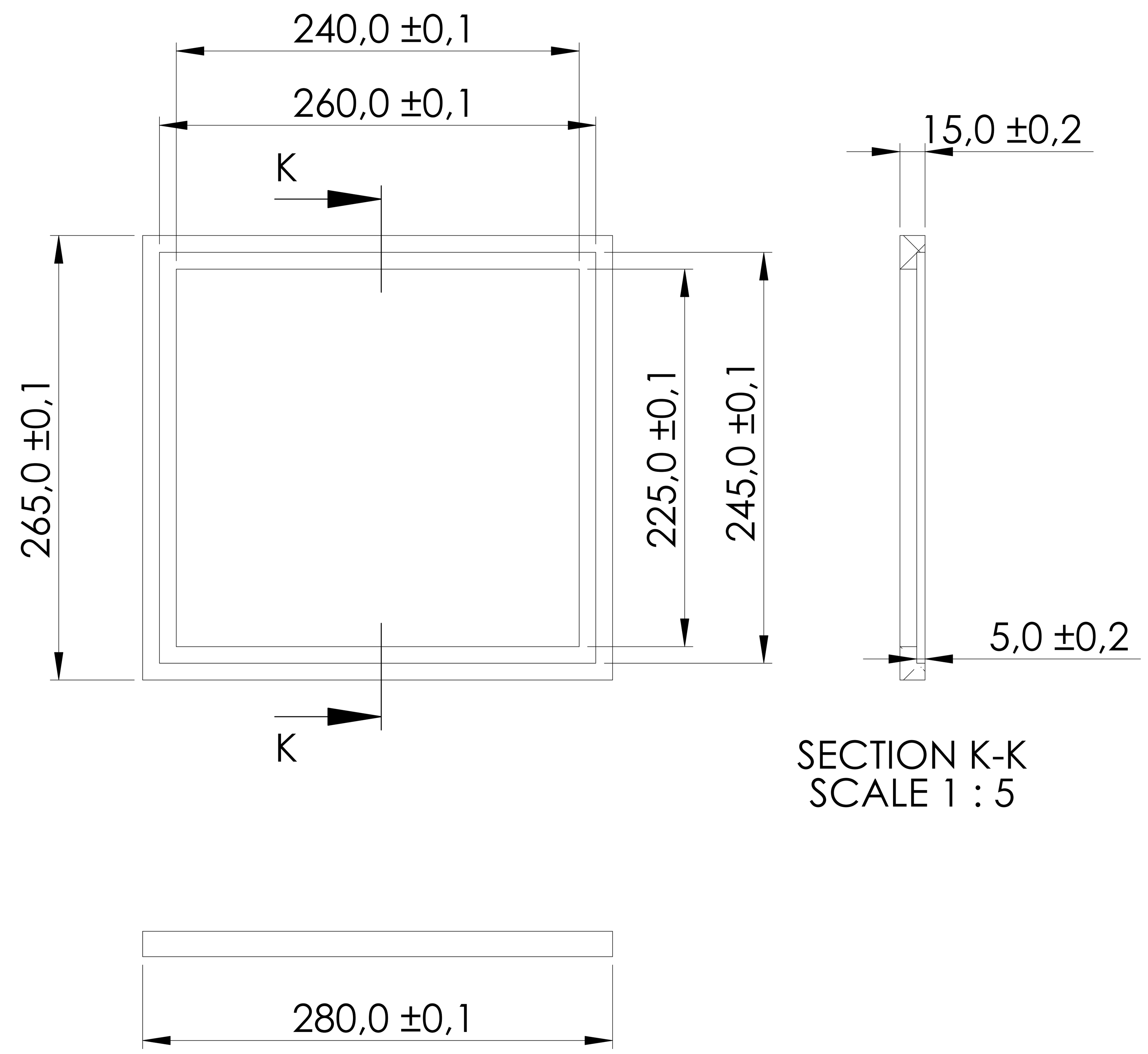
Respon. depart: Dep. of mech., rob, and dig. man.	Advisor	Document type		Status of the document: Educational drawing
Owner: VILNIUS TECH MRfu-25	Prepared by: Alejandro Lopez Perales	Title: Screnn support	MERS BM 25 AL 01 01 01 00	
	Approved by		Issue: A; Date: 21/5/2025	Lang.: Eng.; Page: 3/8

MERS BM 25 AL 01 00 00 00



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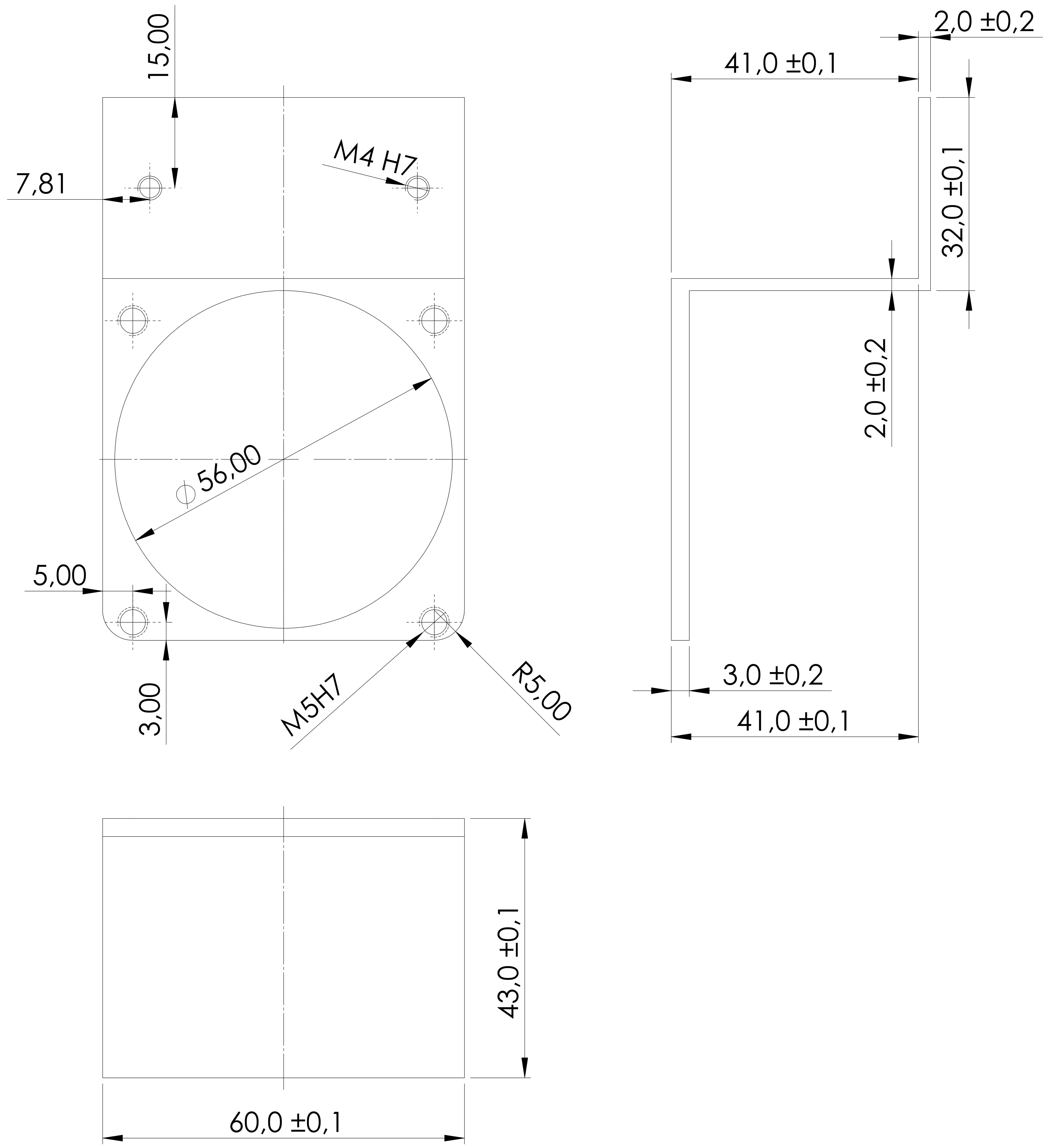
- FITS AND LIMITS ACCORDING TO ISO 286-1 / ISO 286-2
- GEOMETRICAL TOLERANCES ACCORDING TO ISO 1101

File No.	Additional information	Material: Acrylonitrile butadiene styrene (ABS)		Scale: 1:5
Respon. depart: Dep. of mech., rob, and dig. man.	Advisor	Document type		Status of the document: Educational drawing
Owner: VILNIUS TECH MRfu-25	Prepared by: Alejandro Lopez Perales	Title: Grill support	MERS BM 25 AL 01 00 00 00	
	Approved by		Issue: A; Date: 21/5/2025	Lang.: Eng.; Page: 4/8



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- FITS AND LIMITS ACCORDING TO ISO 286-1 / ISO 286-2
- GEOMETRICAL TOLERANCES ACCORDING TO ISO 1101

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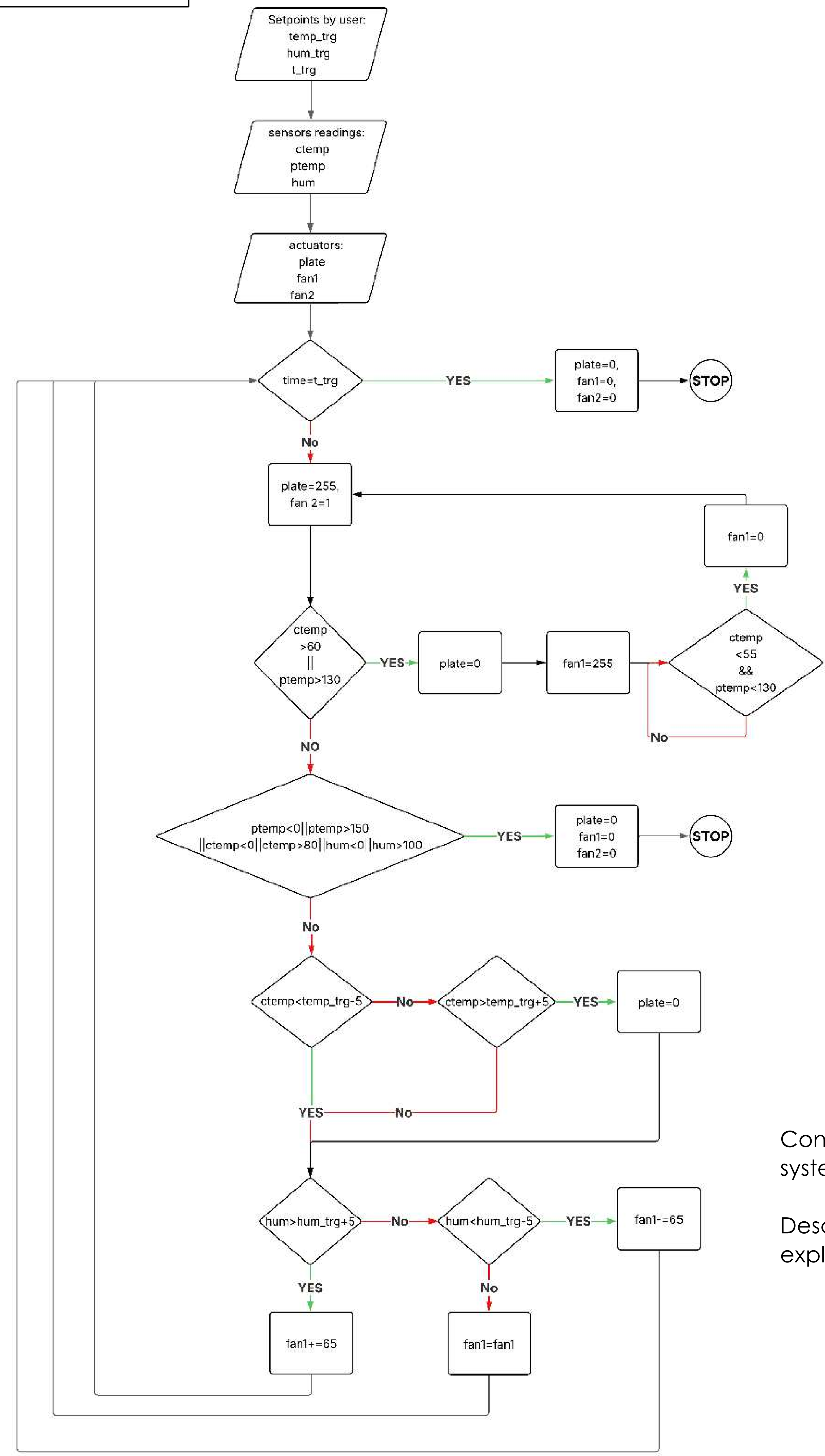
Respon. depart	Advisor	Document type	Status of the document
Dep. of mech., rob, and dig. man.			Educational drawing

Owner	Prepared by	Title	MERS BM 25 AL 01 00 00 00			
VILNIUS TECH MRfu-25	Alejandro Lopez Perales	Fan support	Issue	Date	Lang.	Page
	Approved by		A	21/5/25	Eng.	5/8



Controll algorithm for system management.

Description of variables is explained on thesis.

File No.	Additional information	Material	Scale

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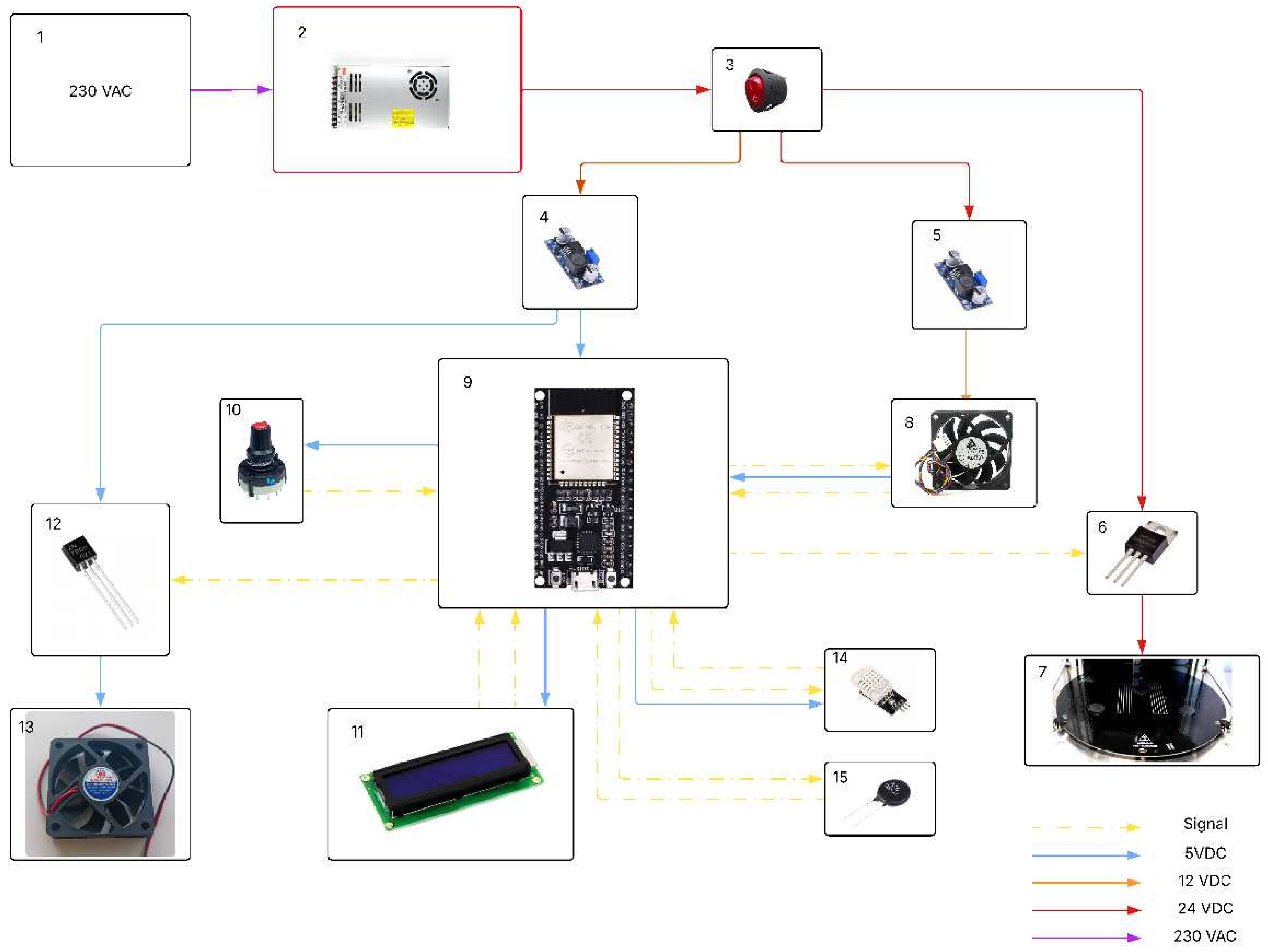
Dep. of mech., rob, and dig. man.			Educational drawing

Owner	Prepared by	Title	MERS BM 25 AL 01 00 00 00			
VILNIUS TECH MRfu-25	Alejandro Lopez Perales	Algorithm of control	Issue	Date	Lang.	Page
	Approved by		A	21/5/25	Eng.	6/8

MERS BM 25 AL 01 00 00 00

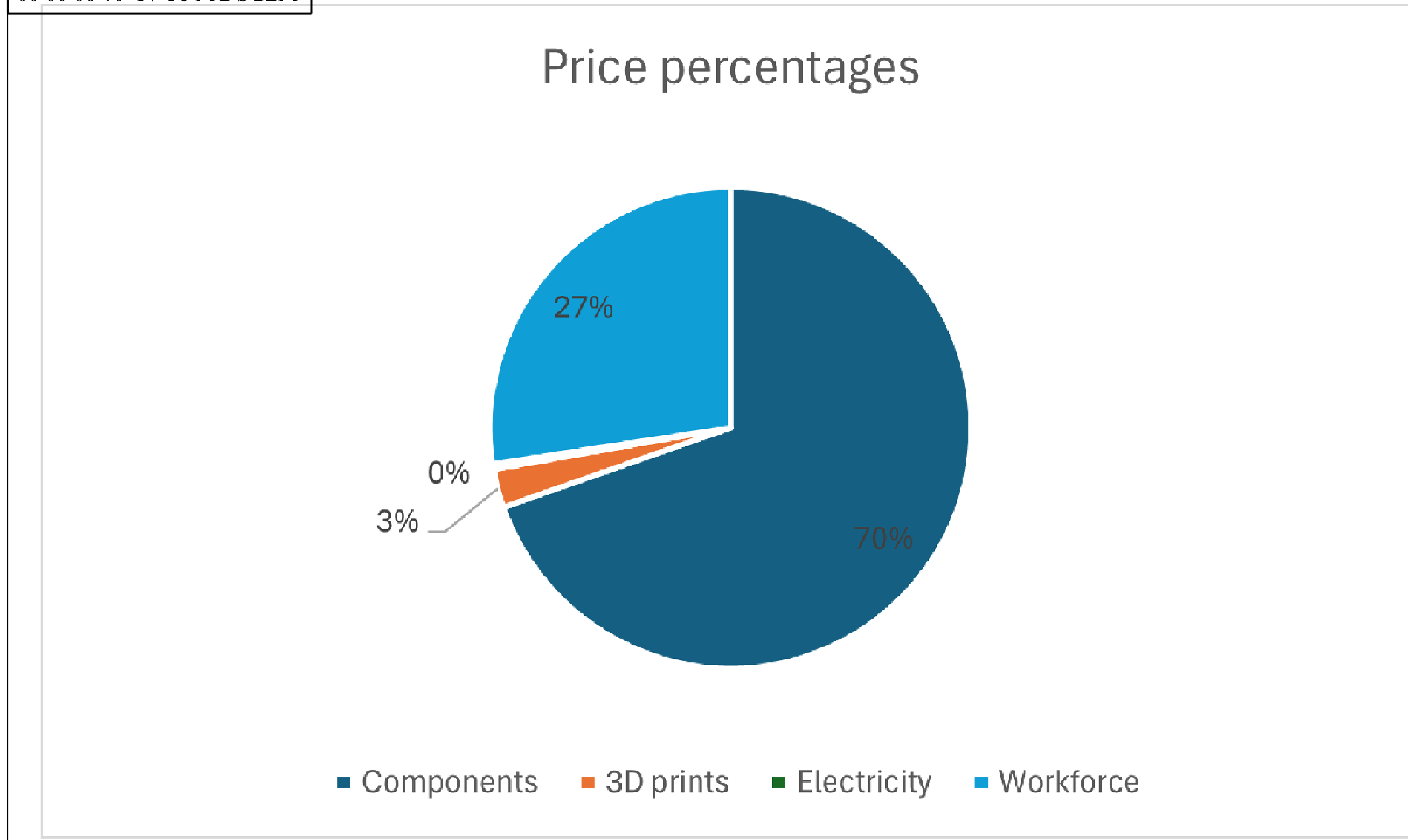


Part Nr	Component
1	230V supply
2	Mean Well LRS-350-24
3	SPRR93 Round Rocker
4	LM2596
5	LM2596
6	IRF3205
7	Heat plate
8	12 V fan
9	ESP32
10	Rotary Encoder
11	16x2 LCD
12	2N7000
13	5 V fan
14	DHT22
15	NTC surface sensor

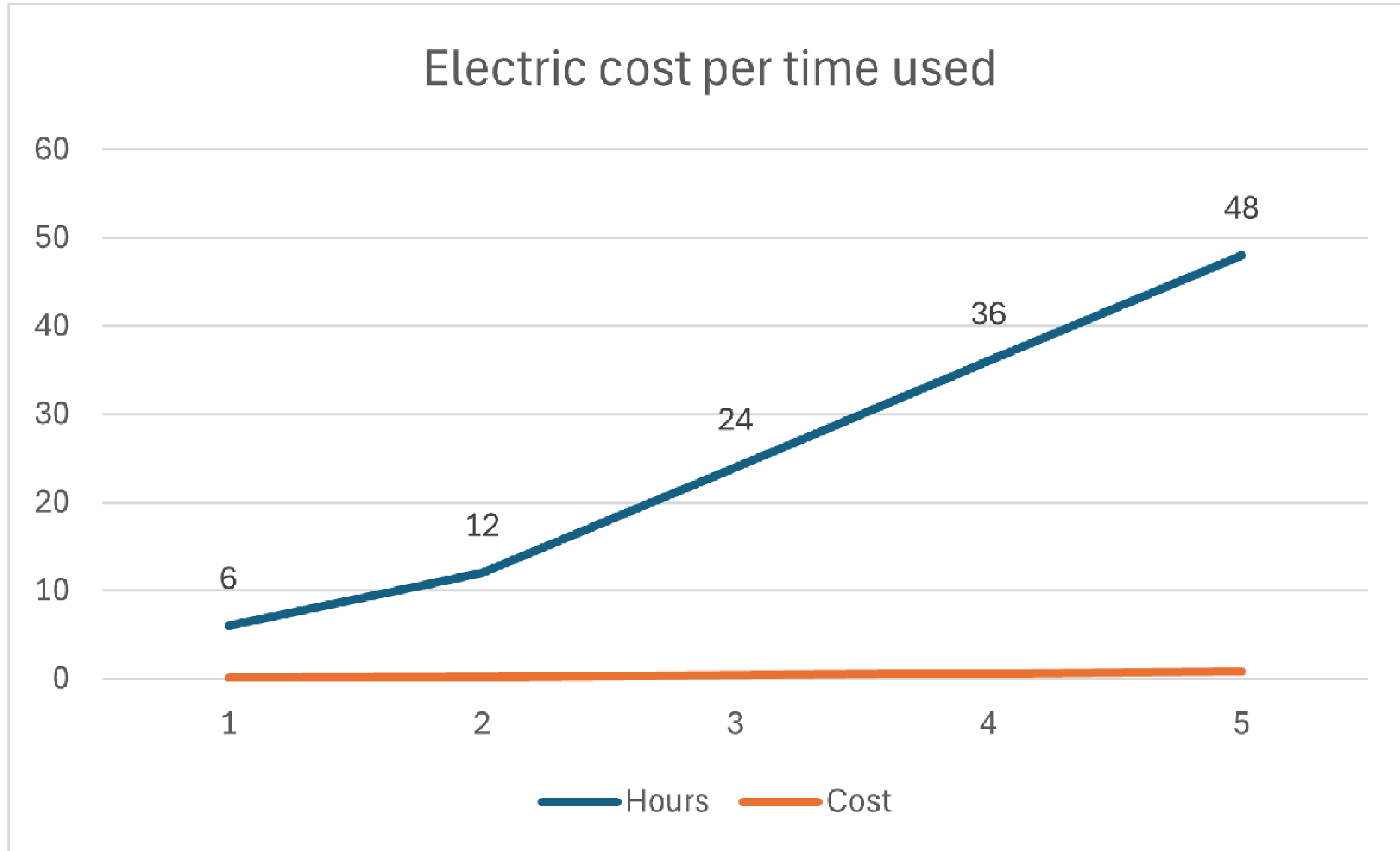
File No.	Additional information	Material	Scale

Respon. depart: Dep. of mech., rob, and dig. man.
Advisor
Document type
Status of the document: Educational drawing
Owner: VILNIUS TECH MRfu-25
Prepared by: Alejandro Lopez Perales
Approved by
Title: Electric scheme
MERS BM 25 AL 01 00 00 00
Issue: A
Date: 21/5/25
Lang.: Eng.
Page: 7/8

MERS BM 25 AL 01 00 00 00



Economic partition of cost for the project



Economic relation between hours used and cost incurred

File No.	Additional information	Material	Scale

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Advisor
Document type
Status of the document: Educational drawing
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Prepared by: Alejandro Lopez Perales
Approved by
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MERS BM 25 AL 01 00 00 00
Issue: A
Date: 21/5/25
Lang.: Eng.
Page: 8/8