UNIVERSIDAD EUROPEA DE MADRID

ESCUELA DE ARQUITECTURA, INGENIERÍA Y DISEÑO

DEGREE IN AEROSPACE ENGINEERING

FINAL PROJECT REPORT

DESIGN OF A DRONE AND ITS PRODUCTION SYSTEM

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YEAR 2022-2023

TITLE: DESIGN OF A PRODUCTION SYSTEM OF A DRONE FOR OIL&GAS REFINERIES

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DEGREE OR COURSE: AEROSPACE ENGINEERING

DATE: 2022-2023

ABSTRACT

The Oil & Gas sector is expanding, which will lead to the construction of refineries and pipelines. These industrial establishments have hard-to-reach areas which present risks for maintenance operators. The main objective of this project is to design a drone that can operate in these areas and design a production system optimized for it.

The production rate and the release date of the initial batch were obtained by means of a market analysis.

A compact and optimized drone was designed with reduced dimensions, with 360-degree sensor protection, allowing operation in tight spaces.

By applying a product structure methodology, the complete drone production system was designed, specifying SOI, jigs and tools and machinery for each production step.

A quality plan was designed for the production system that involved preventive and corrective actions.

The design of a Mode Analysis and Effects of Process Failures validated the critical production steps.

Lean methodology tools such as Poka Yoke or VSM were implemented to optimize drone production and add value to the system.

RESUMEN

El sector de Oil & Gas se encuentra en expansión, lo que dará lugar a la construcción de refinerías y oleoductos. Estos establecimientos industriales poseen zonas de difícil acceso que presentan riesgos para los operadores de mantenimiento. El objetivo principal de este proyecto es diseñar un dron que pueda operar en estas zonas y diseñar un sistema de producción optimizado para el mismo.

La tasa de producción y la fecha de lanzamiento del lote inicial se obtuvieron mediante un análisis de mercado.

Se diseñó un dron compacto y optimizado con dimensiones reducidas, con protección de sensores de 360 grados que permitía la operación en espacios reducidos.

Mediante la aplicación de una metodología de estructura de producto se diseñó el sistema de producción completo del dron, especificando SOI, útiles y herramientas y maquinaria para cada paso de producción.

Se diseñó un plan de calidad para el sistema de producción que implicaba acciones preventivas y correctivas.

Mediante el diseño de un Análisis de Modo y Efectos de Fallas de Proceso se validaron los pasos críticos de producción.

Se implementaron herramientas de metodología Lean como Poka Yoke o VSM para optimizar la producción del dron y agregar valor al sistema.

ACKNOWLEDGEMENTS

I want to extend my sincere gratitude to everyone who helped with and contributed to the completion of this final project. First and foremost, I want to express my sincere gratitude to my project supervisor for all his support, encouragement, and insightful advice. I also want to express my gratitude to my friends and family for their unfailing support and compassion throughout this journey. I'm also appreciative of all the people who shared their knowledge and resources with me so I could do in-depth study and analysis. Finally, I want to thank the academic community for its significant contributions, as their work served as the basis for our initiative.

Contents

Figures

Tables

Chapter 1. INTRODUCTION

As the Oil & Gas sector is currently expanding, there is a market opportunity for the drone visual inspection of refineries and pipelines. The main objectives of the project are to design a fully operational drone capable of operating in difficult access areas as well as a production system that follows a product structure architecture. The added value of the drone is its 360-degree proximity sensors system as well as its reduced dimensions and weight plus the Poka Yoke design decisions. The added value of the production system is the optimized number of stations to avoid overproduction and delays, adapted carbon fiber manufacturing processes in function of the shape of the part and a Quality Plan system that prevents and corrects possible deviations. The subjects related to the drone design will be Aeronautical Structures, Resistance of Materials and Mechanical Elasticity, Aircraft Design, Flight Mechanics, Propulsion Systems, Mechanical and Graphic Design, Aerospace Technology and Production Systems. The main technical knowledge used in the drone design was 3D modelling, structures calculations, deformation and stress analysis, mesh creation and sizing, material selection, weight estimation and product architecture. In the production system design the technical knowledge that will be applied are product structure architecture, composite materials manufacturing, drilling strategies, drilling scheduling , shimming policy, sealant architecture , assembly build process steps, Quality Plan design, PFMA methodology and Lean manufacturing.

Chapter 2. Market Study, Economic Viability and Similar Drones Comparison

In this section of the report a market study will be done by comparing the different competition the drone will face. Additionally, an economic viability study will be done to confirm the viability of the production system. The main goal of this section is to determine the number of drones the first production batch will deliver and the delivery date.

2.1 Market Study

Oil and natural gas have played a very influential role in the global economy in terms of primary fuel sources. As technology became more sophisticated, the demand of these fuel sources increased, which led to a struggle for resources, and they became high valued. Over the 19th and 20th centuries, Canada, Mexico, Iran, Trinidad, Saudi Arabia, and Venezuela occasionally joined the United States and Russia as the top oil-producing nations. [1]

In 2021 different studies [2] [3]showed that the Oil&Gas market estimated value rounded the $ 620 billion and is expected to grow at over 6% (CAGR) by 2030. Just to put in context how influential this sector is for the worldwide economy , let it be compared with the aircraft manufacturers market. According to a research report [4] , the global aircraft manufacturing market share valued around $ 395 billion and was predicted to grow at over 3.01% by 2028. This implies that both markets do possess high influence at global economy scale and hence they can be compared. The reason behind this comparison is that an approximation will be done by analysing how Airbus introduced itself in the aircraft manufacturers market and hence by which percentage of units they delivered their first batch. This will estimate how many drone units will be manufactured and this will highly influence the production system and the market approximation as depending on the number of units, the competitive advantage of this production system will vary.

2.1.1 Airbus Market Strategy Proposal

Boeing owned most of the aircraft manufacturing market from 1916 to 1974[5]. Airbus, founded in 1970, launched its first aircraft in 1974. The aircraft model was the A300B2, a two-class 266 passenger aircraft configuration with a range of 1850 nautical miles. Its direct competitor was the Boeing 727. The first batch of the Boeing model was of 91 aircrafts per year[6]. In the case of the Airbus model, as it was a market entry aircraft, the deliveries and orders were lower. They were estimated in 4 aircrafts per year[7]. This implies that if Boeing was assumed to have the complete control of the market, Airbus launched a first delivery of the 4.39 %. By assuming this percentage, lets analyse the number of possible drone deliveries the production system could fit.

2.2 Economic Viability

2.2.1 Production Rate Calculation

As mentioned earlier, the drone's main missions are to execute surveillance and daily inspections of Oil&Gas refineries and pipelines. After some research, it has been concluded that there are 316 Oil&Gas refineries worldwide[8]. In terms of Oil&Gas pipelines, the most influential ones can be seen in Table 1 [9].

Oil Pipelines	
Name	Length (Km)
Druzhba	8.900
Kazakhstan-China	2.228
Baku-Tbilisi-Ceyhan	1.768
Gas Pipelines	
Name	Length (Km)
Sila Sibiri	4.800
Southern Peruvian	1000
Megdaz	210

Table 1. Oil&Gas Pipelines Data

With this information it is enough to deliver an estimation of how many possible drones should be delivered by the competition for these missions. Firstly, it will be assumed that a single drone cannot individually perform the whole daily refinery inspection and hence the number required per daily inspection is 2. By this assumption, at least 632 drone deliveries opportunity emerge.

Figure 1. Shell Convent Refinery

Additionally, an estimation will be done for the Oil&Gas pipelines. After comparing similar drones for pipelines inspection, it has been estimated that the average endurance of this mission is around 50 mins. Besides, the average flight speed for these drones is around 20 m/s.

With this information a calculation will be done to estimate the number of drones required to cover the whole pipeline length for inspection.

$$Range_{avg} = Endurance * Speed = 50 * 60 * 20 = 60000\ m = 60\ km$$

An average inspection drone can cover 60 km before needing to recharge. Hence, for completing all the pipelines inspections mentioned before:

$$Range_{Total} = 8900 + 2228 + 1768 + 4800 + 1000 + 210 = 18906\ km$$

$$Drones = \frac{18906}{60} = 315$$

By adding the number of drones required for both missions, it has been found that for a worldwide supply the required number of drones is 947. By applying the reasoning of Airbus entry in the market analysis, the initial batch of the project's drone should be a 4.39%. Then, the estimated number of drones for the initial batch is **42 drones per year**.

2.2.2 Drone's Life Cycle Degradation

Now that the production rate has been calculated, the following factor that will influence the production system is the first delivery date. In order to analyse this number, two main considerations need to be made. The first one is to estimate the life cycle of an Oil&Gas drone and the second one is the average time a new drone model is launched into the market of refineries inspection. This will provide an approximated time to deliver the initial batch.

Firstly, some research has been done related to Oil&Gas drones' life cycle. The main factors that contribute in the drones' life cycle degradation are[10][11][12]:

2.2.2.1 Usage

Drones, like aircrafts, suffer from operation. This degradation varies from the level of stress they are subjected to. The main parts of the drone that may degrade the most are the shell, propellers, and arms.

Figure 2. Damaged DJI Shell

The shell of a drone has commonly the main mission to hide the group of chaotic cables and components that enable the drone's correct operation. For this reason, some drone manufactures produce the shell with holes that drain the hot temperature atmosphere that may form due to the hardware operational heat. Consequently, the shell structure is not commonly stiff and is generally thin and light. This implies that the shell is not designed to support loads. In the event of a hard landing or accident the drone's shell may crack or fracture. This will eventually degrade the drone's life cycle. Focusing on propellers, they are also prone to suffer cracks due to fatigue as they are subjected to high speeds. Nevertheless, they are usually designed to be easily interchangeable. Last of all , arms may also be damaged as they transmit the loads from the weight of the rotors to the drone's chassis and due to continuous deflection fatigue may appear. Additionally, refinery drones are subjected to highly dense atmospheres with dust particles. These elements may accumulate in different parts of the drone, like in the propeller or on the hardware components, which might deteriorate the drone's life cycle.

2.2.2.2 Storage

Another aspect that needs to be considered is storage time while the drone is inoperative, whether it is receiving inspections, battery charging, or it is being stored for future operations. This storage needs to be studied as the components of the drone may deteriorate faster than expected if the UAV is subjected to extreme temperature fluctuations or high humidity.

2.2.2.3 Transportation

Drones may be transported between several locations to provide versatility to the customer. During this transportation time it is highly probable that the drone may suffer damage or deteriorate if the manufacturer transport recommendations are not followed.

2.2.2.4 Hardware Degradation

In order to operate autonomously and provide its design capabilities drones possess an enormous amount of integrated hardware. This hardware goes from sensitive sensors up to OBC or IMU. As mentioned before, this kind of components are prone to environment degradation so unexpected levels of humidity, temperature or water may degrade or even permanently damage these essential components. Additionally, the operation in Oil&Gas refineries is commonly under elevated levels of dust density which may infiltrate into the drone's shell and impregnate the internal components worsening them.

2.2.2.5 Battery Degradation

Most cutting-edge drones carry Lithium Polymer (LiPo) batteries. These types of batteries need very special and delicate care as they are very fragile. The maltreatment of this batteries by not following manufactures' instructions may lead to a shortening in the batteries' life and recharge cycles. Nevertheless, these expensive batteries can be replaced so in case of failure they will not be the ultimate root cause of an inoperative drone.

2.2.2.6 Drone Average Life Span

Extensive research was done in this field and several maintenance manuals from the most influential drone companies in this area like DJI [13] and Autel Robotics [14]. These companies recommend making "deep drone inspections" after a total flight time of 600 hours or if the product has been used for 18 months. Additionally, propellers are recommended to be disposed after 300 flight hours or 1 year of usage. By this estimation, a drone that is used at its maximum envelope operative capabilities is expected to have a life span from **2 to 3 years**. For this reason, the estimated time for a possible market opportunity for the developed drone in this project is for **2025-2026**.

2.3 Similar Drones Comparison

In order to design the drone, a comparison between similar drones will be done to obtain the common characteristics these drones possess that make them suitable for the Oil&Gas mission. Following this procedure, the different drones can be seen below.

2.3.1 DJI Matrice 300 RTK

It is the newest model of the Chinese leading edge drone company DJI. This drone is oriented to firefighting, search & rescue, security forces, tension lines inspections, Oil&Gas refineries inspection and geomatics[15].

Figure 3. DJI Matrice 300 RTK Possible Configurations

Some general characteristics of this model is that it has the water protection of IP45 which is very useful to operate in adverse flight conditions such as rain, fog, or highly dense areas like refineries. Besides, it possesses a self-heating battery for cold environments, an anticollision beacon and can operate in a temperature range from -20° C to 50 ° C.

More technical specifications can be seen in Table 2 .

Specification	Value
Dimensions	810 × 670 × 430 mm
Weight	6.3 kg
MTOW	9 kg
Max Climb Rate	6 m/s
Max Cruise Speed	23 m/s
Max Operating Altitude	5000 m
Max Operating Wind	15 m/s
Endurance	55 min

Working Temperature Range	-20° C to 50 ° C
Battery Type	LiPo 12S

Table 2. DJI Matrice 300 RTK Specs

Figure 4. DJI Matrice 300 RTK in-flight depiction

As Figure 5 shows, depending on the payload that is used, in this case the different RGB/Thermographic cameras, the flight time varies. It gradually decreases as the payload is increased. This will be a key factor to keep in mind in the drone's design phase as a heavy drone will have flight time limitations.

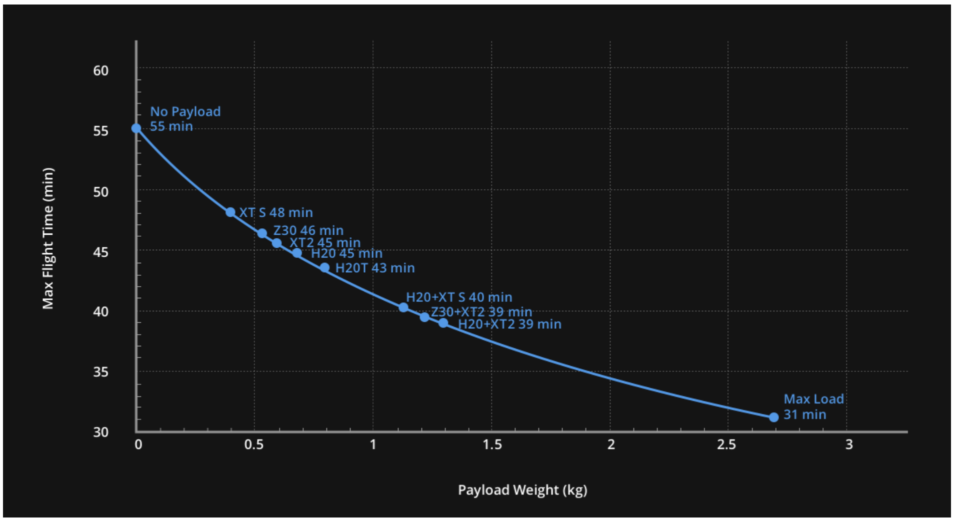

Figure 5. Payload vs Flight Time DJI Matrice 300 RTK

2.3.2 EVO Max 4T

This new model from Autel Robotics [16] which can take off in just 15 seconds, has an IP43 weather rating, 720 ° and 12.4 miles transmission range among other characteristics.

Figure 6. EVO Max 4T

One characteristic that this has is the system of cameras and sensors that provide safe flight operation with an autonomous in-flight correction system.

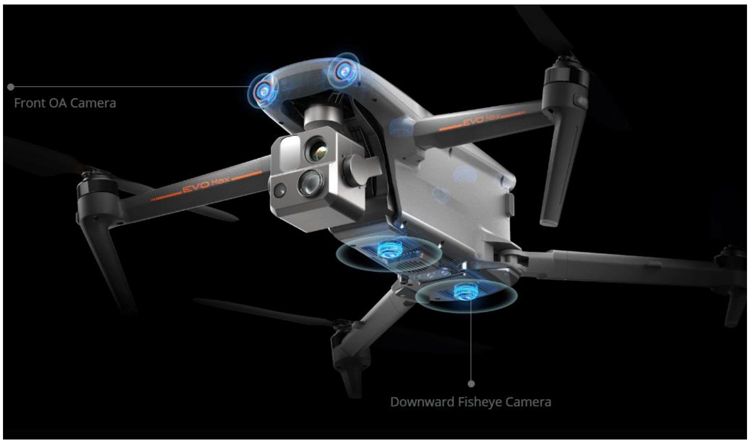

Figure 7. Obstacle Avoidance System

More technical specifications can be seen in Table 3.

Specification	Value
Dimensions	576 x 660 x 149 mm
Weight	1.6 kg
MTOW	2 kg
Max Climb Rate	8 m/s
Max Cruise Speed	23 m/s
Max Operating Altitude	7000 m
Max Operating Wind	12 m/s
Endurance	42 min
Working Temperature Range	-20° C to 50 ° C
Battery Type	LiPo 4S

Table 3. EVO Max 4T

2.3.3 Elios 3

This small drone from Flyability [17] can generate a 3D cloud of points that will create a topographic model of the drone's surroundings. It is a drone used for indoors difficult access zones and it possesses a plastic cage that protects the drone from external impacts. Besides, it possesses the IP44 certification.

Figure 8. Elios 3 Frontal View

Additionally, it possesses a system of LiDar sensors that provide stabilized flight that can be seen in Figure 9 .

Figure 9. LiDar Sensors Configuration

In Figure 10 it can be seen an example of the 3D maps this drone is capable of delivering.

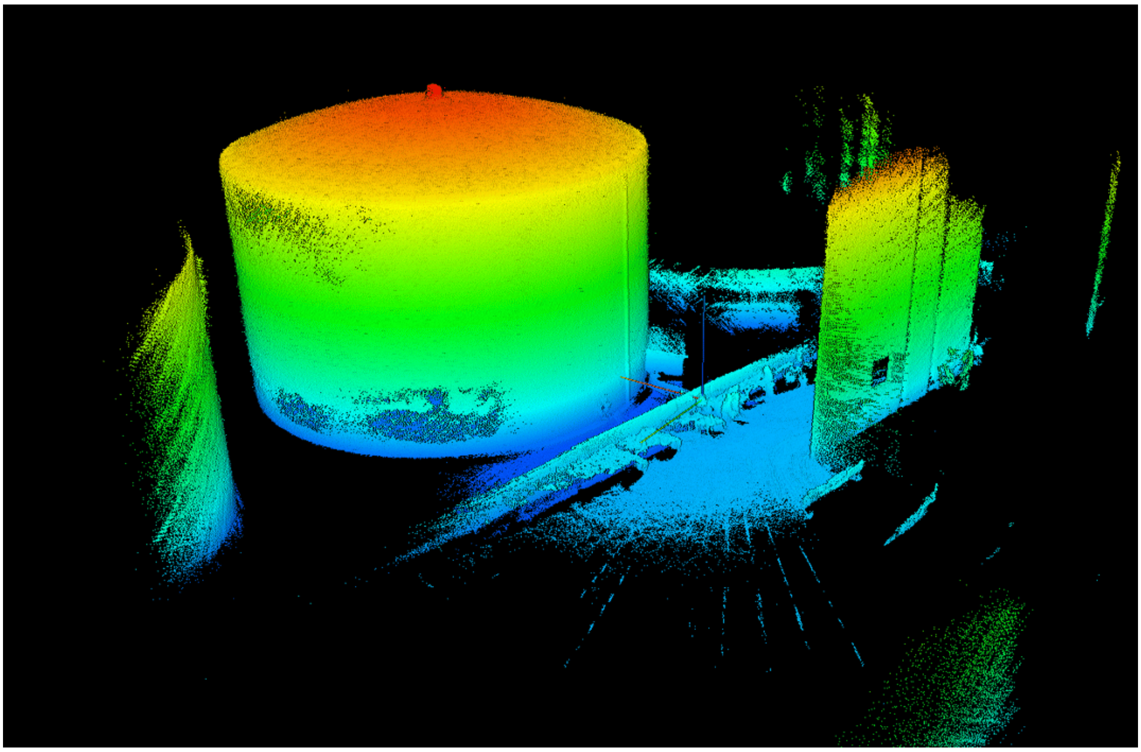

Figure 10. Elios 3 Cloud of Points Generation Example

More technical specifications can be seen in Table 4.

Specification	Value
Dimensions	480 x 380 mm (wide x high)
Weight	2.35 kg
MTOW	2.5 kg
Max Climb Rate	2 m/s
Max Cruise Speed	7 m/s
Max Operating Altitude	N/A
Max Operating Wind	7 m/s

Endurance	12.5 min
Working Temperature Range	0° C to 50 ° C
Battery Type	LiPo 6S

Table 4. Elios 3 Specs

Furthermore, in Figure 11 an Endurance vs Payload diagram can be seen. This drone carries a camera that has integrated in its shell both RGB and Thermal cameras which can be useful for the implementation to the drone of this project due to its reduced dimensions.

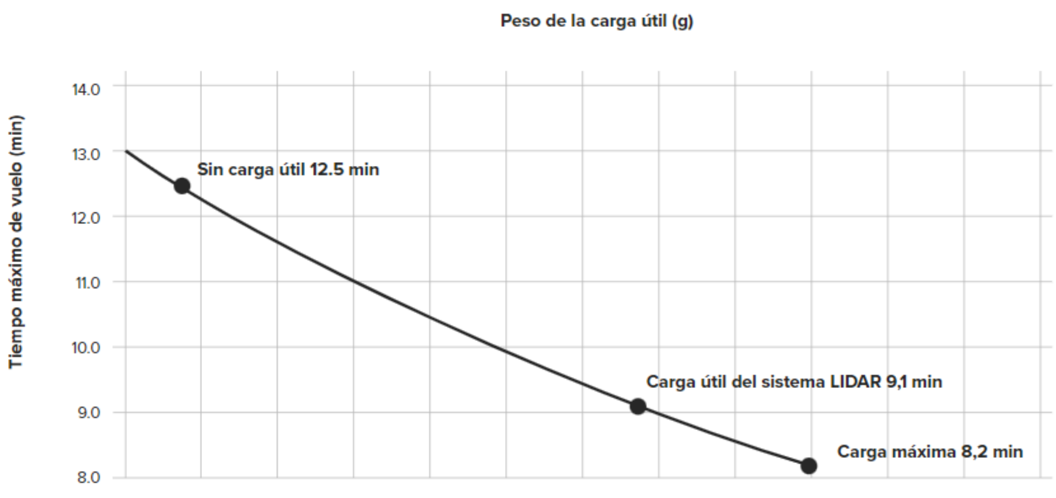

Figure 11.Endurance vs Payload Elios 3

2.3.4 ACECORE Neo

This new model from the company named Acecore [18] has produced its new drone for inspection. Between its most remarkable characteristics some that can be highlighted are that it is weatherproof, it is carbon fiber based and has 3 autopilots in order to increase the redundancy level in case of failure.

Figure 12. ACECORE Neo

More technical specifications can be seen in Table 5 [19][20] .

Specification	Value
Dimensions	1107 x 1107 x 635 mm
Weight	7.3 kg
MTOW	19 kg
Max Climb Rate	5 m/s
Max Cruise Speed	25 m/s
Max Operating Altitude	3000 m
Max Operating Wind	20.6 m/s
Endurance	25 min
Working Temperature Range	-15° C to 50 ° C

Battery Type	LiPo 6S

Table 5. ACECORE Neo Specs

Below there is a diagram that shows the interaction between the different batteries/flight time/payload configurations.

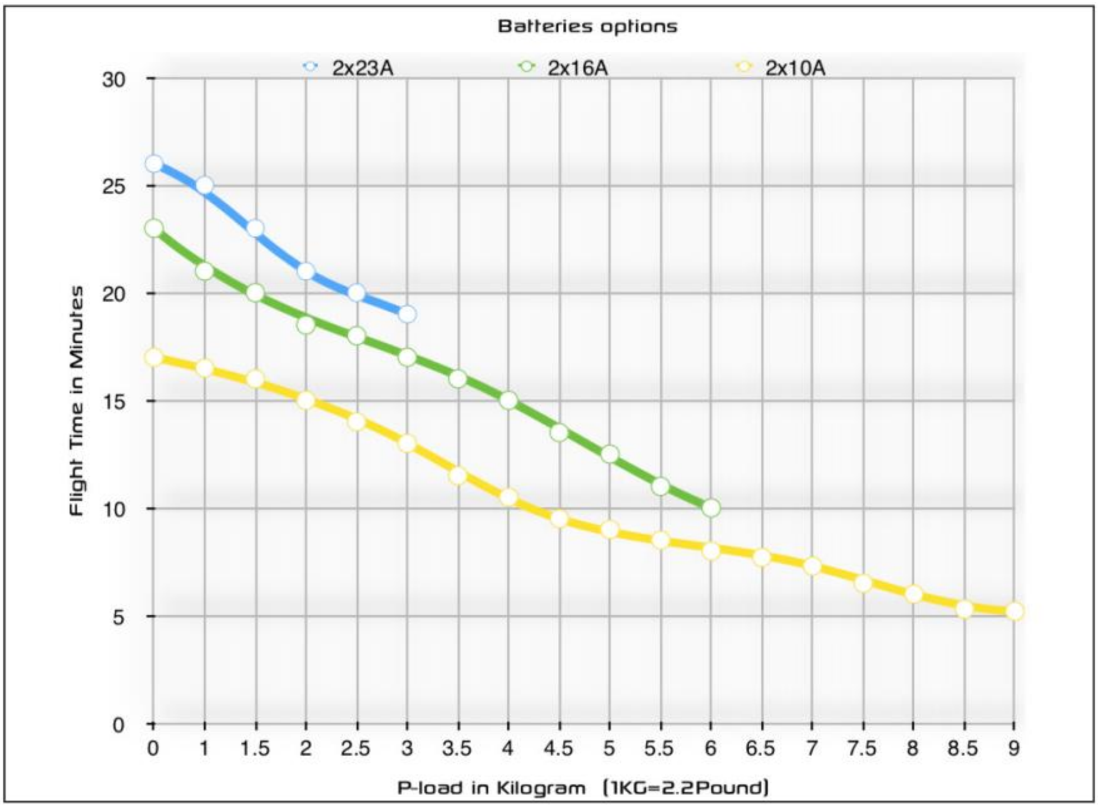

Figure 13. Endurance vs Payload ACECORE Neo

2.3.5 Conclusion and Requirements

As it can be seen in Table 6**Error! Reference source not found.**, the most relevant specs of the drones that were commented can be seen.

	Matrice 300 RTK	EVO Max 4T	Elios 3	ACECORE Neo
Dimensions (mm)	810 × 670 × 430	576 x 660 x 149	480 x 380 (w x h)	1107 x 1107 x 635
Weight (kg)	6.3	1.6	2.35	7.3
Payload (kg)	2.7	0.4	0.15	11.7
MTOW (kg)	9	2	2.5	19
MTOW/Weight	1.42	1.25	1.06	2,6
Endurance (min)	55	42	12.5	25
Batteries	LiPo 12S	LiPo 4S	LiPo 6S	LiPo 6S
Working Temperature (° C)	-20 to 50	-20 to 50	0 to 50	-15 to 50

Table 6. Drones' Specs Comparison

Several conclusions can be obtained from the previous table. Firstly, the drone should be capable of having a 30 min endurance with LiPo battery supply. A range of -15 ° C to 50 ° C operating temperature should be required to compete with the current market. The heaviest drone that was analysed is the ACECORE Neo with a weight of 7.3 kg so the drone should weight equal or less than this weight. But this is only for the structure, not taking into consideration the payload, so an additional 1,7 kg will be added for payload weight.. However, the Neo has the most efficient drone in terms of lifting power with the ability of lifting more than twice its weight. This may be attributed to the engines/propellers system which may be relevant to apply to the drone. In terms of dimensions, it seems clear that for higher lifting power higher dimensions are required. This may imply more space for batteries, bigger drone arms or larger engines and propellers. A range between 500 to 900 mm of width and 600 to 900 of height should be enough to manufacture an operative drone. In terms of payload, it will be fixed to 3 kg as it is the average between all the drones studied. In terms of design, all drones tend to be quadcopters. It has been studied that for different configurations like hexacopter or octocopter, the only added value is redundancy and lifting capabilities. It has been decided that payload is light enough to be lifted by a quadcopter. The next table covers the requirements in a schematic format for easier interpretation:

Requirement	Specification
REQ_01	The drone must at least deliver a flight time of 30 minutes.
REQ_02	The drone must have a at least a minimum standard empty weight of 7,3 kg or less or a total weight of 9kg or less
REQ_03	The drone dimensions must be in the range of 500-900 mm width and 600-900 mm height. Free margin is given for length to locate electronic components.
REQ_04	The payload must be 3kg or less. This includes the gimbal system, LiDar sensors and cameras.
REQ_05	The drone must be capable of operating in a temperature range from 15 ° C to 50 ° C
REQ_06	The drone must have a quadcopter configuration. Any other design feature has free design configuration.

Table 7. Requirements

Chapter 3. Components Analysis and Weight Estimation

In this section of the report the components that will make the drone capable of flying will be chosen. By selecting specific components, a mass can be estimated which will be used in Chapter 4 .

3.1 Batteries

As commented in the *Similar Drones Comparison* section, the most common battery in the market with the current technology is the Lithium Polymer battery. The number of batteries generally required is **3**. The selected battery model is **HRB GRAPHENE 6S 6000 22.2V 100C LIPO BATTERY EC5** [21]. These batteries are commonly used in drone that range from 8-13 kg, so it is considered that these provide enough energy to uphold the estimated flight time of 30 minutes with standard operative conditions. Nevertheless, a future study should be done to estimate the actual power consumption of the drone.

Therefore, with this battery selection of 3 LiPo 6, the battery weight **2.62 kg.**

Figure 14. HRB GRAPHENE 6S 6000 22.2V 100C LIPO BATTERY EC5 Depiction

3.2 Flight Controller

The flight controller is an essential component in any drone. Its main function is to control every facet that affect the flight in order to operate safely and precise. The flight controller can be described more properly as a system. Inside this component reside several subcomponents that provide the aids that the flight controller needs to operate. These components are:

- GPS
- Accelerometer
- Gyroscope

- Magnetometer
- Barometric Sensor
- CPU

Instead of manufacturing and designing a new flight controller, it has been decided to select one that is already on the market to reduce costs. After some research it was decided that the **DJI A3** was a desirable option due to its precision and its new added feature to automatically calculate the best flight path and operation in case of rotor loss.[22]

The reduced weight of this flight controller makes it a great candidate as it only weighs **186 grams**.

Figure 15. DJI A3 Flight Controller Depiction

3.3 OBC

In order to use the drone apps, provided by the flight controller manufacturer, it is requested for the drone to possess an onboard computer (OBC). For this reason, a Raspeberri Pi 4 was selected. Firstly because of its reduced weight (**46 grams**) , and secondly, because it is a famous OBC there are a lot of sources from which troubleshooting information can be obtained and hence it will make the final user experience easier.

Figure 16. Raspberri Pi 4 Depiction

3.4 Radio Control RC

The drone needs a radio control system to be remotely controlled. This system is formed of a transmitter/receiver pair that enables communication between the drone and the user. The **DTXMX Flysky FS-i6X 2.4G Radio Transmitter** and **FS-iA10B 10CH RC Receiver** (**17.6 grams** both components) were selected as they possess 5 channels which is the recommended number of channels recommended by the industry as the minimum number of channels to operate a quadcopter is four. When selecting the antenna, it is crucial to determine its operative range as it can be a limiting factor of the drone.

Figure 17.DTXMX Flysky FS-i6X 2.4G Radio Transmitter & FS-iA10B 10CH RC Receiver Depiction

3.5 Proximity Sensors

A drone that is working in Oil&Gas refineries should possess proximity sensors to avoid impact with its surrounding. Specially in zones 1 and 2, as they tend to accumulate particles that are prone to ignition. The sensors that were selected are **LW20/C microLiDAR™** [23]. These sensors allow long range measurements of 100 meters and provide up to 388 readings per second. Although they are not as powerful as LiDAR Vu8 or LiDAR One, their reduced dimensions and weight (**19 grams**) makes them a great contribution to the drone. Additionally, it is important to mention that a sensor will be installed in every face of the drone providing 360 coverage.

Figure 18. LW20/C microLiDAR Sensor Depiction

3.6 Camera

Due to its operation atmosphere, it is essential for the drone to possess a thermographic camera that is able to detect changes in temperature and gas leakage. After some research of the camera market, the most suitable options in terms of quality, dimensions and weight for the drone were the cameras H20T and XT2. It was decided that the H20T camera had better specs that the XT2, so it was the one that was selected. Its weight is of **828 grams**.

Figure 19. H20T Camera Depiction

3.7 Engines

There are several options for drone engines. However, it was studied that the option of brushless motor is the best among the other as it is sparkles and hence, adds value to the drone for refinery operation.

A **TAROT-TL100B08-02** Brushless motor was chosen due to its reduced weight (**148 g**) and its power consumption.

Figure 20.TAROT-TL100B08-02 Brushless motor

3.8 Electronic Speed Controller (ESC)

This component is one of the most important parts of the drone apart from the flight controller. The main function of the ESC is to transform the continuous current that is provided by the batteries into triphasic AC to move the brushless motor. They are in charge of vary the engines' speed and direction. In order to avoid compatibility problems, a DJI ESC was selected. More specific, the **DJI E5000** [24](189 grams).

Figure 21. DJI E5000 Electronic Speed Controller

Chapter 4. Drone Design

In this section of the report the drone design will be explained. Every design decision that has been taken will be followed by a subsequent and thoughtful explanation. The main dimensions of the drone are also stablished in this section. Besides, in this section a structural analysis of the drone's parts which are more likely to be subjected to forces will be studied to determine the forces and stresses the drone may present.

4.1 Internal Architecture Design

The main idea of this internal structure is to locate the electronic components and support the loads. As it can be seen in the figure below there are several subcomponents in this structure. This chassis has been optimized to fit all the different components in a reduced volume so that the drone possess smaller dimensions that the other market choices.

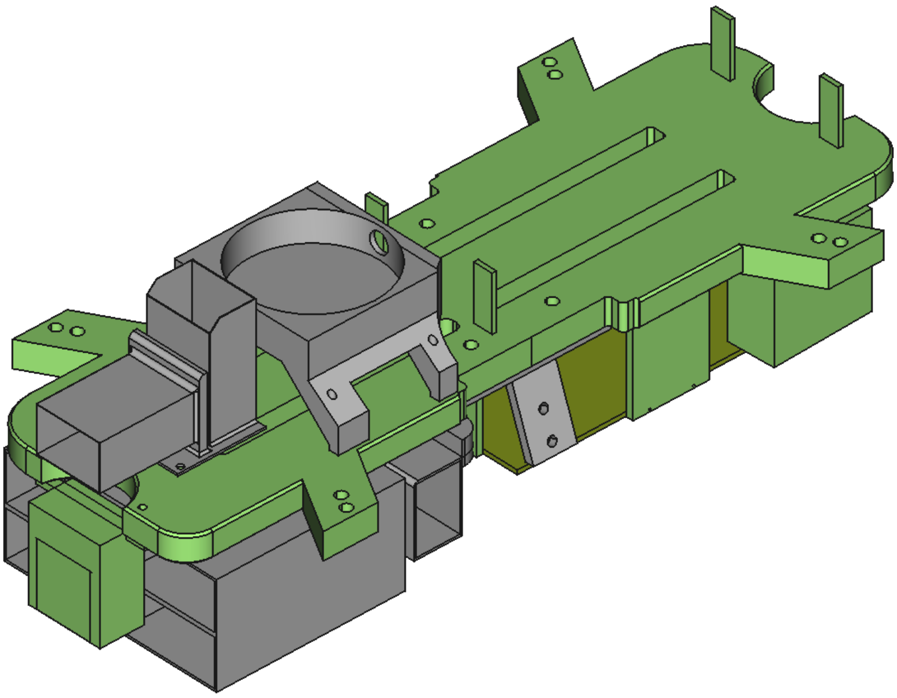

Figure 22. 3D Model of the internal architecture of the drone

Firstly, all the preforms that are shown in Figure 22 are made from carbon fiber. This will be latter explained in the manufacturing section. The reason why the structures have different colour is to have a better visual representation of the organisation and assembly of this architecture.

As mentioned before, one of the main missions of this structure is to support the loads that are subjected due to the weight of the drone and the lift of the engines. For this reason, four different elongations can be seen extruded in the main chassis. These elongations serve as an assembly support for both the upper and lower shells and the arm of the drone. An assembly image can be seen below.

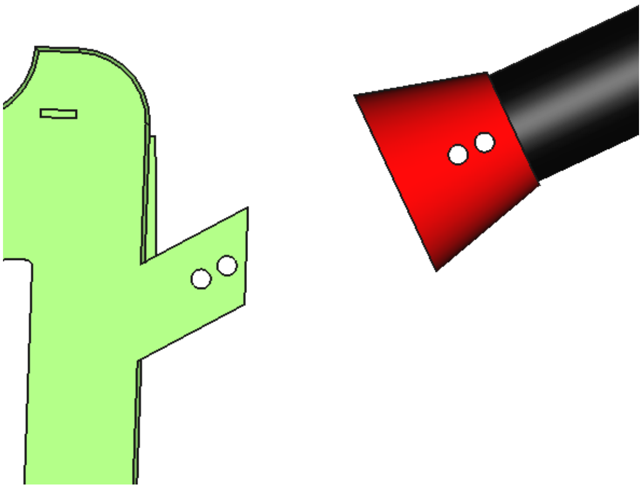

Figure 23. 3D Model Arm/Chassis Connection

These two elements are connected by the 2 screws that fix the arms' position relative to the chassis. The reaction generated by the lift of the engines will be transmitted to this elongation.

The legs of the drone, in which the landing rests is fixed by the following structure.

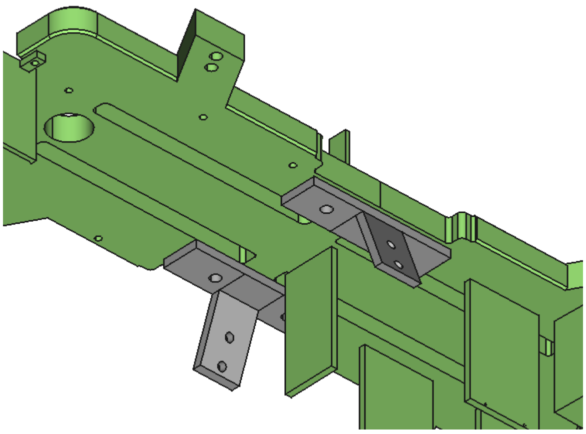

Figure 24.3D Model Landing Gear Connection

The grey preform is assembled by a permanent assembly to the main chassis. This connection has the same operating principle as the one of the legs, 2 screws secure the position of the landing gear legs to this point.

Now that the main structural supports are fixed, the internal components must be placed. Starting with the batteries, the next image shows the battery compartment.

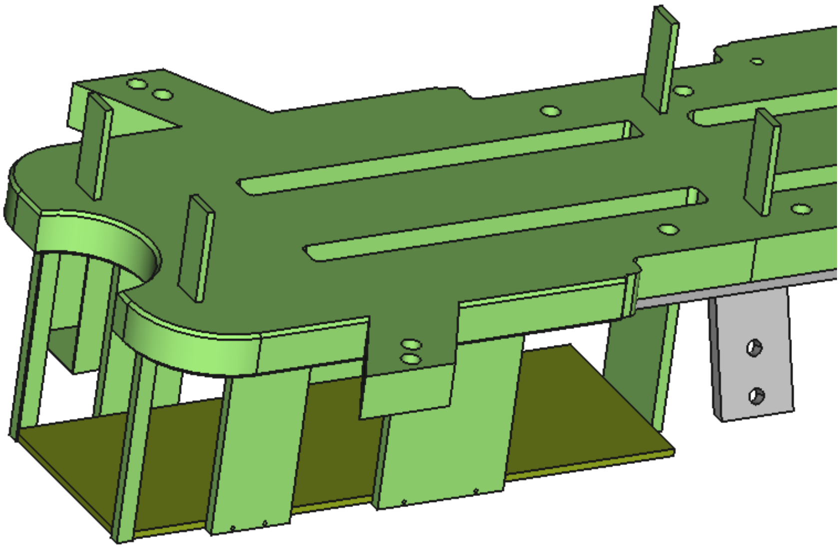

Figure 25. 3D Model Battery Compartment

Due to the dimensions of the batteries, they could not be placed at the same surface of the chassis as they collided with the external shells, and this would be a problem as the drone would not be able to be closed. For this reason, they were distributed along the two surfaces of the drone. Two batteries are place in the upper surface, which has those 4 elongations that perfectly fit the batteries and locks them in place, and a compartment was designed at the inferior surface to locate the remaining battery. This compartment possesses an internal shell that is connected with the structure with screws too. As it can be seen, the compartments are not completely enclosed as the batteries required space to locate the cables and wires.

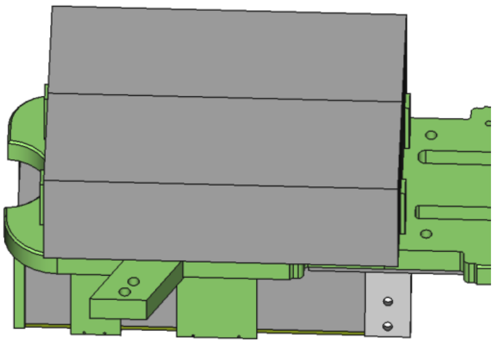

Figure 26. 3D Model Batteries Layout

For fixing the position of the LiDAR there are several structures that secure its placement.

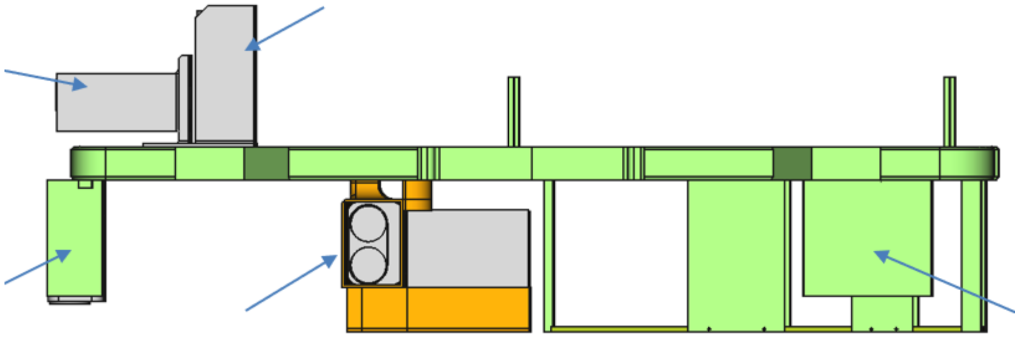

Figure 27. 3D Model LiDAR sensors layout

As it can be seen, at the left-hand side in the lower surface, the structure for the inferior face LiDAR can be seen. In the upper surface the preform that hold the frontal and upper sensors can be observed. The orange structure locates the two lateral sensors and the main controller as well. At the back of the main chassis (right-hand side) the sensor for the back face is placed.

The ESC has been located in an independent compartment (blue structure) that is permanently attached to the main chassis. They have not been completely enclosed again due to wiring limitations.

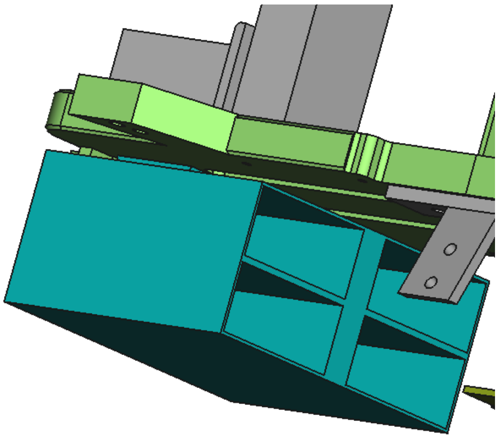

Figure 28. 3D Model ESC compartment

The Raspberry is drilled into the main chassis with replaceable nails and in the same holes which this one use, the structure to locate the GPS is placed (yellow figure) . As it can be seen in the picture below, the GPS is mounted in this structure which is above the Raspberry to optimize internal volume. Additionally, the GPS is elevated as DJI recommend locating their GPS with no obstructions above

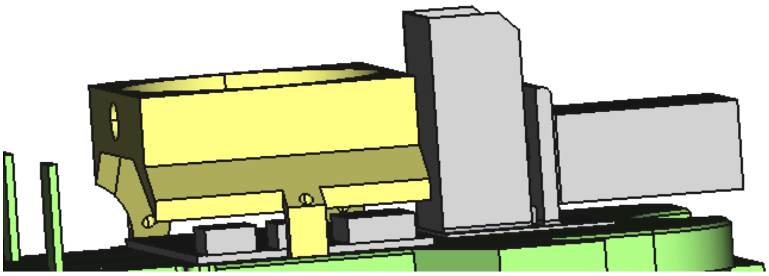

Figure 29. 3D Model GPS Support Structure

In the picture below, a final internal components layout can be seen.

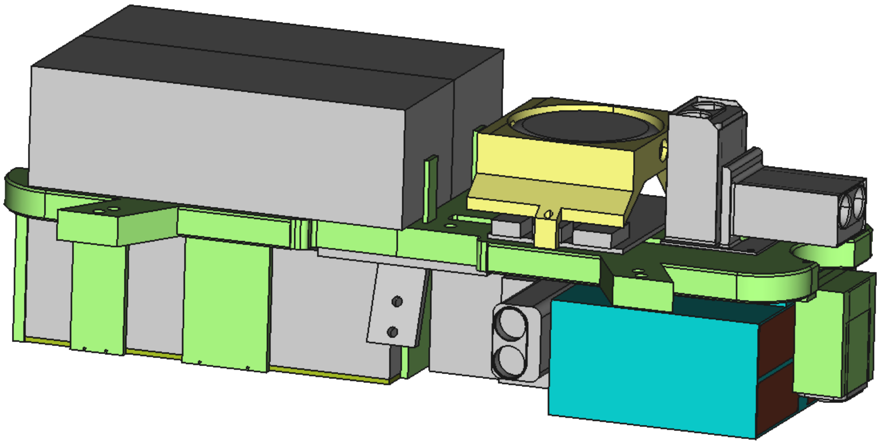

Figure 30. 3D Model Final Internal Component Layout

All these internal components are covered by two plastic shells that has a rubber joint to provide some level of water/dust resistance. This is especially important as dense dust particles tend to accumulate in the atmospheres at which the drone will operate.

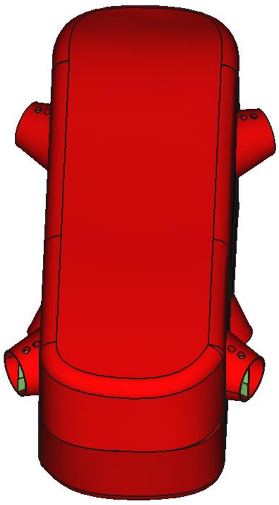

Figure 31. 3D Model Complete Shelled Drone

The connection between the arms, shells and chassis can be seen more in detail in the following picture.

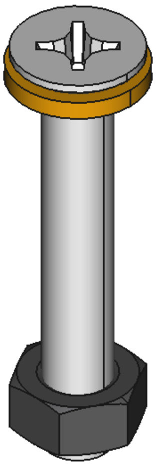

Figure 32. 3D Model of Arms, Shells and Chassis Connection

The screw is secured by a washer, that avoids deterioration to the shell, and a nut that fixes the screw in place. After doing this assembly the drone will have the following shape.

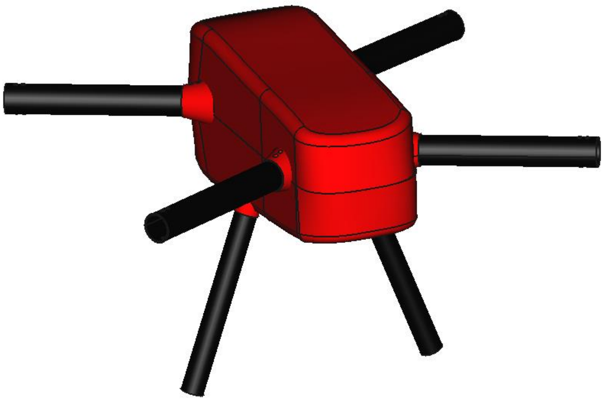

Figure 33. 3D Model of the drone with assembled arms

In terms of assembling, the upper shell will be detached first and then the bottom shell will drop, as the joint between these two shells is located at the arms. However, the landing gear arms are attached inside the upper and lower shells to the main chassis, as it was previously mentioned. This was intentionally done as in case of accident; the screws can hit a surface and produce sparks. For this reason, a reduction in the number of visible metallic objects will increase the overall safety of the drone in the refinery zones.

4.2 Landing gear configuration

The landing gear follows the next configuration.

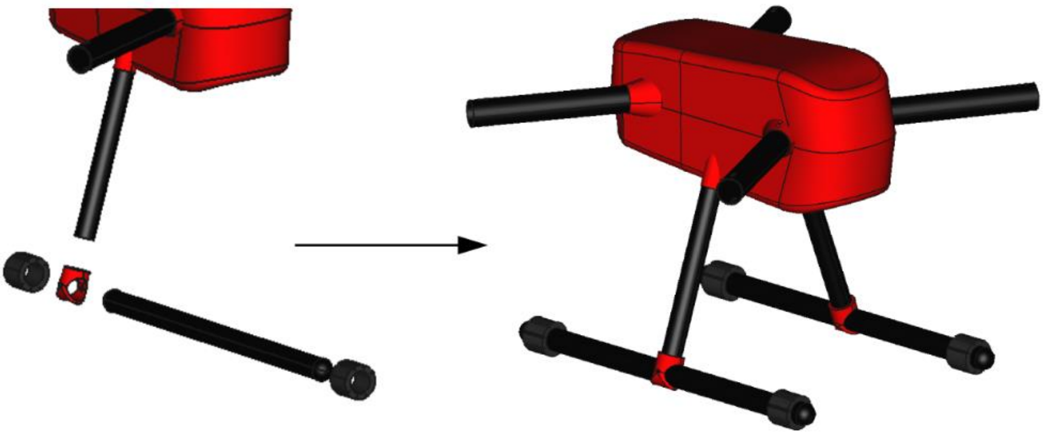

Figure 34. Landing Gear configuration

The landing gear legs are joined by a plastic piece that fixes the support leg by a screw-nut-washer system that follows the same principle as Figure 32. The leg that is fixed to the main chassis is joined to the plastic joint with aviation glue and the leg that is joined with the plastic piece that holds the shock absorbers possesses a screw-nut-washer system that fixes this arm. The shock absorbers are joined by aviation glue. The result of assembling the landing gear to the drone shows this result.

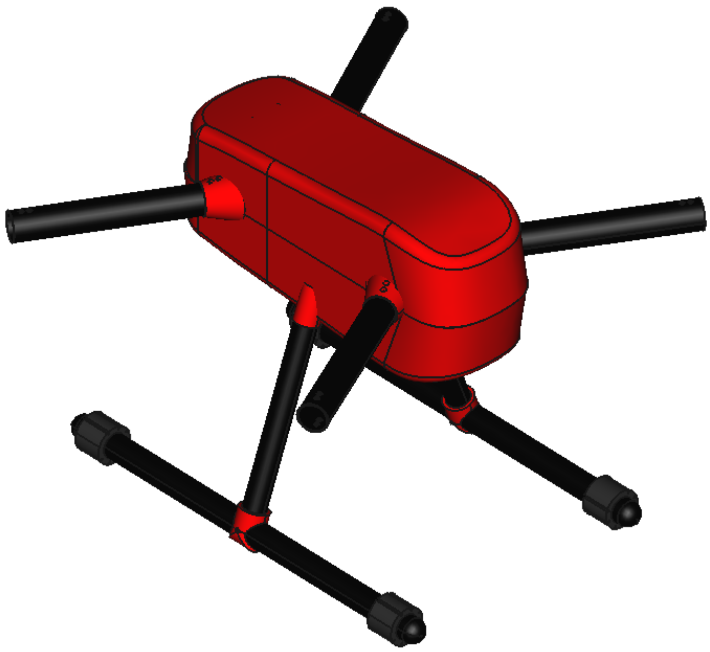

Figure 35. 3D Model of the drone with landing gear

4.3 Propulsion system configuration

The last group is the propulsion system. This group follows the next configuration.

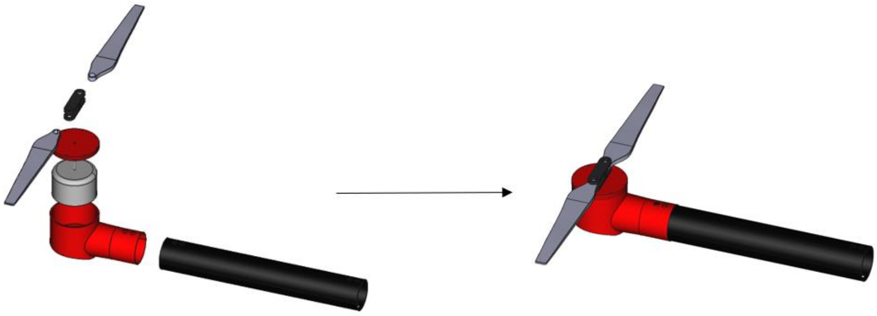

Figure 36. Propulsion System Configuration

Firstly, a shell for the brushless rotor was designed so that the engine received less dust pollution, and it could operate in adverse conditions. The engine is attached to a rotating cover that provides motion to the propellers. Although it is not modelled in 3D, the system is meant to have a rubber joint inside the shell that proved the IP waterproof rating to the drone. The propellers are joined by a screw-nut-washer system as explained before. Applying this system of joint, the propellers are correctly fixed, and they cannot rotate on their own axis.

A future study could be done to analyse how vibrations produced by the motion of the propellers affect the performance of the drone and a modal analysis could be done.

The material that was used for the shell is PEEK plastic due to its great performance at heat resistance. This is especially important in this piece as engines tend to heat while operating. The short-term heat resistance of this material is at 300 °C [25]which is more than the expected temperature that the engines will reach, which is 240 °C [26].

Additionally, this material possess a low friction coefficient which is desired as the support of the propellers will touch the upper surface of the engine shell. Besides, this helps to increase the life cycle of the shells as they wear they suffer is reduced due to the low friction coefficient.

Also, this material possess great chemical resistance as it is shown in the figure below.

	PI	PEEK	PTFE	PPS	PPSU	PEI	PVDF	PET	POM-C	PA 66 / 6
Acids - weak	+	+	+	+	+	+	+	+	(+)	(+)
Acids - strong	(+)	-	+	+	-	-	(+)	(+)	-	-
Alkalis - weak	(+)	+	+	+	+	-	(+)	(+)	+	+
Alkalis - strong	-	+	+	+	-	-	-	-	-	-
Solvents - alcohol		+	+	+	+	+	+	+	+	
Solvents - ester		+	+	+				(+)	(+)	
Solvents - ether		+	+	+			+	+	(+)	
Solvents - ketone		+	+	+	-	-	(+)	(+)	(+)	
Oils	+	+	+	+	(+)	(+)	+	+	+	+
Water - cold	+	+	+	+	+	+	+	+	+	+
Water - hot	(+)	+	+	+	+	(+)	+	(+)	+	-
Water - hot steam > 120 °C	-	+	+	+	+	(+)	+	-	(+)	-

\+ = resistant
(+) = limited resistance
\- = not resistant

Figure 37. Comparison of the chemical resistance of different plastic materials

4.4 Lenses installation

As the drone is designed with LiDAR sensors to provide a 360-obstacle detection, lenses should be installed into the drone's shell to have a translucent surface in which the sensor can operate. However, due to software limitations, the implementation of the drone lens was not possible. Nevertheless, an approximated sketch was designed to have a clear understanding of the layout of this hypothetical lenses. Additionally, in the case that these lenses were to be installed in the shells, they will have a rubber gasket to ensure the drone's tightness and silicone will be applied to seal the joint. The material of these lenses will be an explosion proof glass to comply with the ATEX regulation (Explosive Atmospheres European Regulation)

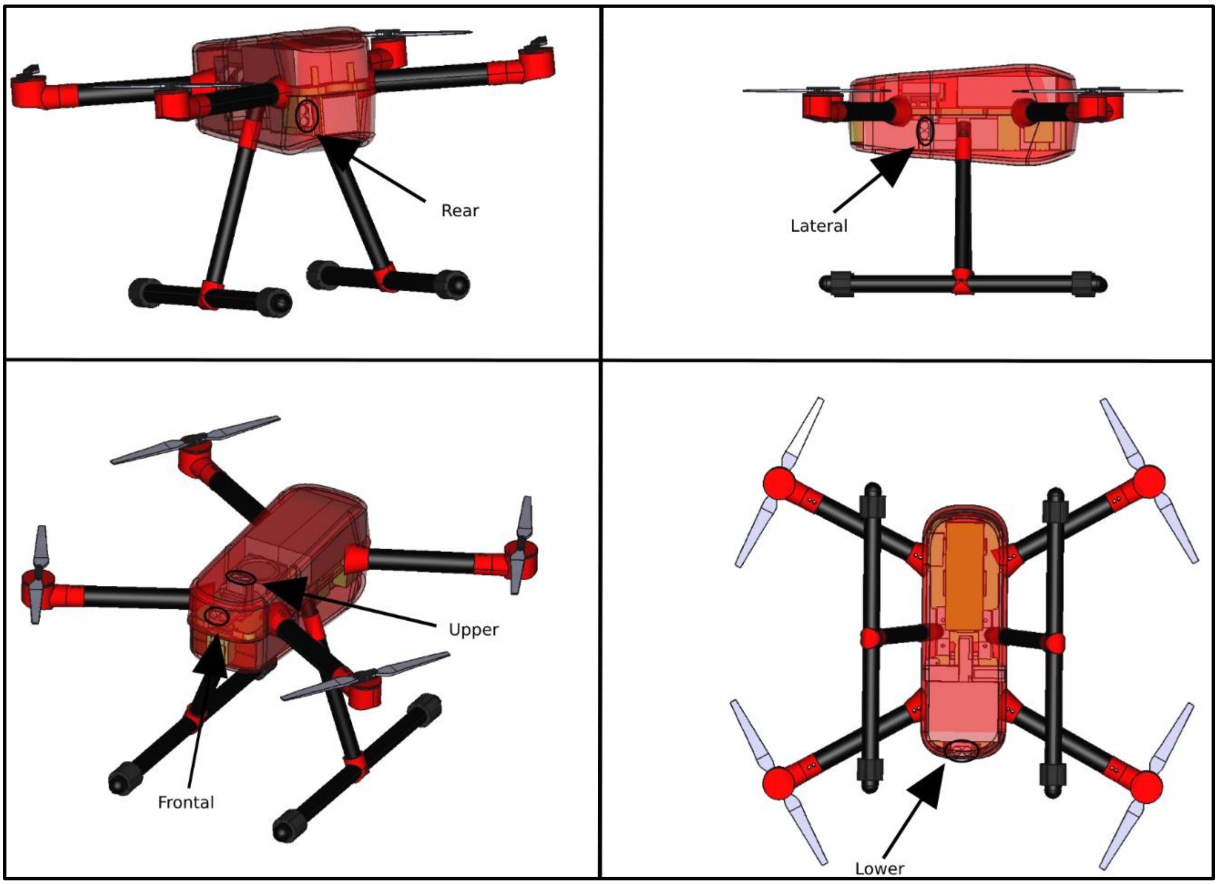

Figure 38. Drone's Lenses Layout

4.5 Drone Final 3D Model

When the drone is finally assembled, the result can be seen below. By this point, the drone should be fully operative, and all tests should have been done. This is the product that the customer will receive at the end of the production chain that will be shown in the VSM (Value Stream Mapping) section of the report.

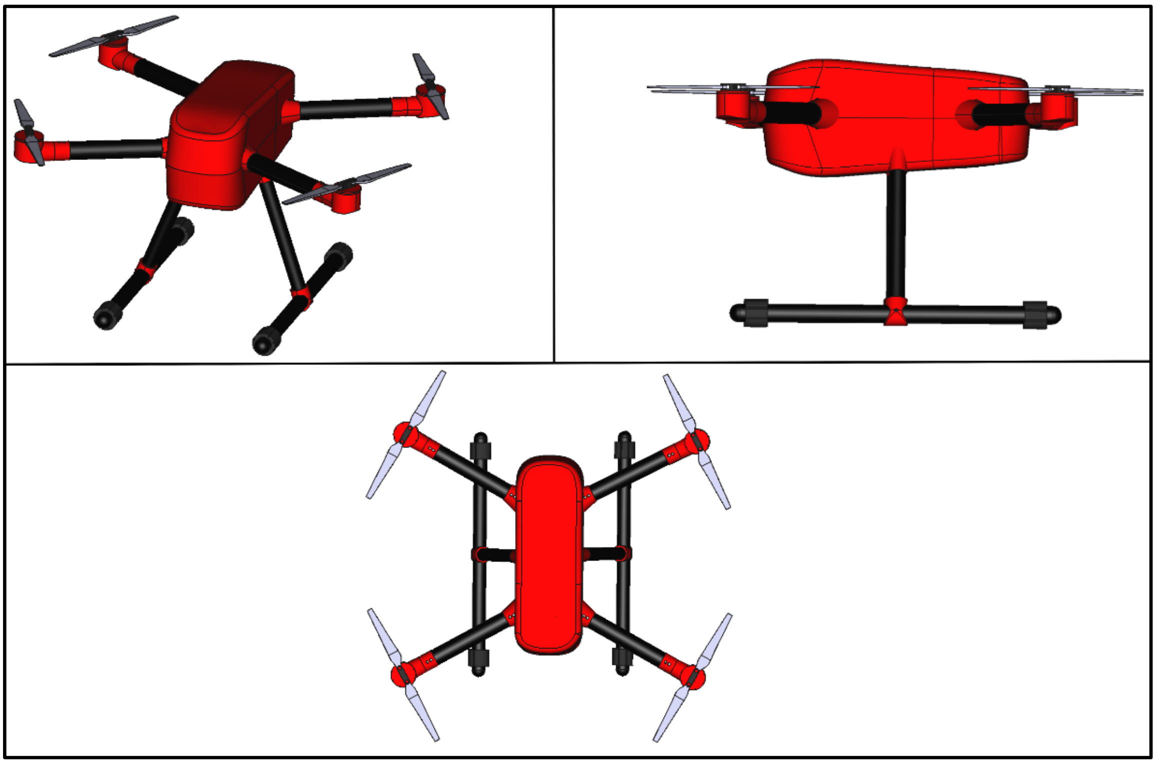

Figure 39. Final 3D Views of the drone

Drone Dimensions	
Length (mm)	708,67
Span (mm)	579,91
Height (mm)	362,7 (*[1])

[1] The height of the drone will vary when the gimbal/camera system is installed.

Chapter 5. Structural Analysis

In order to determine whether the drone would have structural integrity, a structural analysis needs to be done. This structural analysis consists in determining the forces the drone will be subjected to. The first step to determine these numbers is by calculating the total weight of the drone. Then, the lift that the engines should provide to the drone is :

$$Lift = Weight * Safety\ Factor = Weight * 1{,}5$$

The safety factor for drones was thoroughly searched in EASA certification but it was not found. For this reason, a safety factor of 1,5 was used, that is the one applied to CS25 aircrafts [27]. With this measure the drone is assured to have a safe operation.

5.1 Weight Estimation

Using Excel and the 3D program, an estimation of the total weight of the drone could be achieved. The program allows the user to calculate the volume of the components, and this was used to determine the weight of all the structural parts as the density of the material was known.

Components	Material Selection	Material Density (g/cm3)	Material Volume (cm3)	N of units	Individual Weight (g)	Total Weight (g)
Batteries	-	-	-	3	874	2622
Flight Controller	-	-	-	1	186	186
OBC	-	-	-	1	46	46
RC	-	-	-	1	17,6	17,6
MicroLiDAR	-	-	-	6	19	114
Camera	-	-	-	1	828	828
Engines	-	-	-	4	148	592
ESC	-	-	-	4	189	756
Arms	Carbon Fiber	1,75	25,92	4	45,36	181,44
Main Chassis	Carbon Fiber	1,75	413,13	1	722,9775	722,9775
Battery Shell	Carbon Fiber	1,75	16,57	1	28,9975	28,9975
LG Chassis	Carbon Fiber	1,75	7,11	2	12,4425	24,885
Lateral LiDAR Shell	Carbon Fiber	1,75	18,45	1	32,2875	32,2875
Front-Up LiDAR Shell	Carbon Fiber	1,75	7,54	1	13,195	13,195
ESC Shell	Carbon Fiber	1,75	87,97	1	153,9475	153,9475
GPS Structure	Carbon Fiber	1,75	38	1	66,5	66,5
LG Leg	Carbon Fiber	1,75	25,25	2	44,1875	88,375
LG Support Leg	Carbon Fiber	1,75	110	2	192,5	385
Shock Absorbers	Rubber	1,22	18,28	4	22,3016	89,2064
LG Joint	Polypropylene	0,9	6,54	2	5,886	11,772
Engine Shell	PEEK Plastic	1,31	44,6	4	58,426	233,704
Engine Top	PEEK Plastic	1,31	8,08	4	10,5848	42,3392
Propeller Support	Carbon Fiber	1,75	1,79	4	3,1325	12,53
Propeller	Carbon Fiber	1,75	4,88	8	8,54	68,32
Upper Shell	Polypropylene	0,9	523,26	1	470,934	470,934
Lower Shell	Polypropylene	0,9	523,26	1	470,934	470,934
					Weight (g)	8258,9446
					Weight (kg)	**8,2589446**

Table 8. Drone's Weight Estimation

The drone weight was estimated taking into consideration the payload, including the camera selection. Nevertheless, this is an initial estimation and for future studies the weight of the gimbal and the elongation of the landing gear legs should be taken into consideration.
With this weight estimation, the Lift required to operate the drone is :

$$Lift = Weight * Safety\ Factor = 8{,}25 * 9{,}8 * 1{,}5 = \mathbf{121{,}27\ N}$$

It is easier to manage the lift numbers in terms of how many kg can an engine lift. For this reason, the engine lifts :

$$Lift\ (kg) = \frac{Mass * Safety\ Factor}{Number\ of\ engines} = \frac{8{,}25 * 1{,}5}{4} = \mathbf{3,09\ kg}$$

In case the engines could not lift this mass, a re-election of the engine-propellers system should be done.

5.2 Arms Structural Analysis

5.2.1 Analytical Approach

The arms of the drone are one of the key structures of the drone. For this instance, it is crucial to determine the deflection in the of the arm to check if it is acceptable.

Using the lift calculation and the weight estimation that was previously done, it can be determined the resultant force that the propulsion system will project to the arm.

$$Force_{Single\ engine} = Lift_{single\ engine} - Weight_{single\ engine} = (3{,}09 * 9{,}8) - (0{,}237 * 9{,}8) = \mathbf{27,95\ N}$$

The behaviour of the arm can be modelled as a cantilever beam problem as it can be seen below. The calculated force (27,95 N pointing upwards) will be applied at the end of the beam, where the engine would be located, and at the beginning of the beam a fixed support will be placed, as it is the connection to the main chassis in which the nuts and screws are placed.

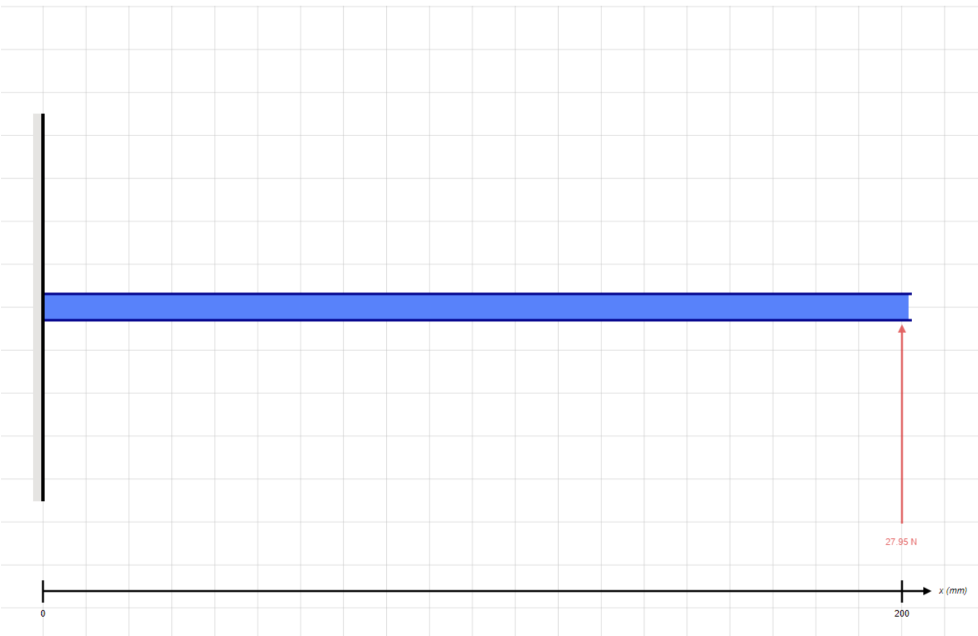

Figure 40. Drone's Arms Forces Implication

The implication of a force applied to a body in static equilibrium implies that for the system to preserve its static condition a reaction and a moment are generated as it can be seen.

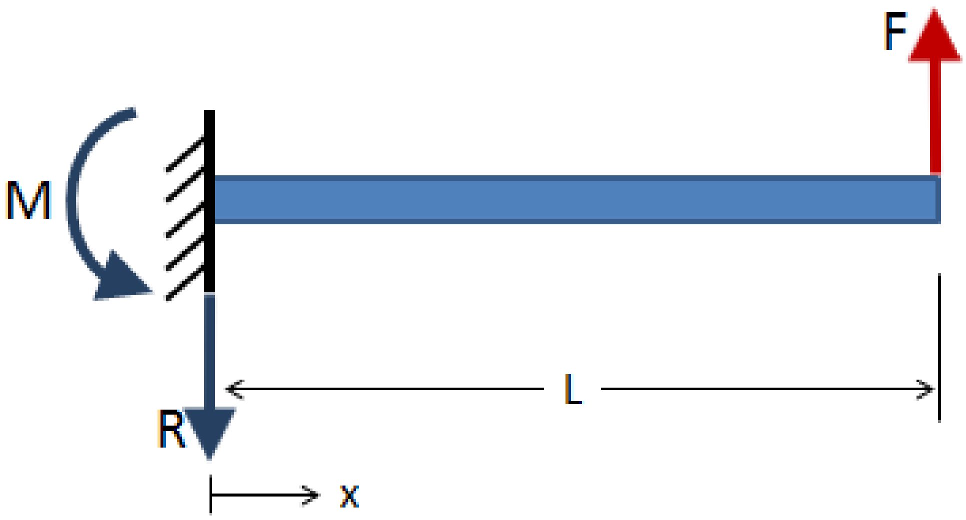

Figure 41. Arms' Free Body Diagram with Reactions

If a summatory of both forces and moments is done then the results will be the following:

1. Summatory of forces in X-Axis :

$$\sum \boldsymbol{F_x} = \mathbf{0}$$

2. Summatory of forces in Y-Axis:

$$\sum \boldsymbol{F_y} = \boldsymbol{F} + \boldsymbol{R} = \mathbf{0}$$

$$\sum F_y = 27{,}95 + R = 0$$

$$\boldsymbol{R} = -\mathbf{27,95}\ \boldsymbol{N}$$

3. Summatory of moments:

$$\sum M = M_F + M_R = 0$$

$$\sum M = (27{,}95 * 0{,}2) + M_R = 0$$

$$\boldsymbol{M_R} = \mathbf{5,59}\,\frac{\boldsymbol{N}}{\boldsymbol{m}}$$

The resulting free-body diagram will be the following:

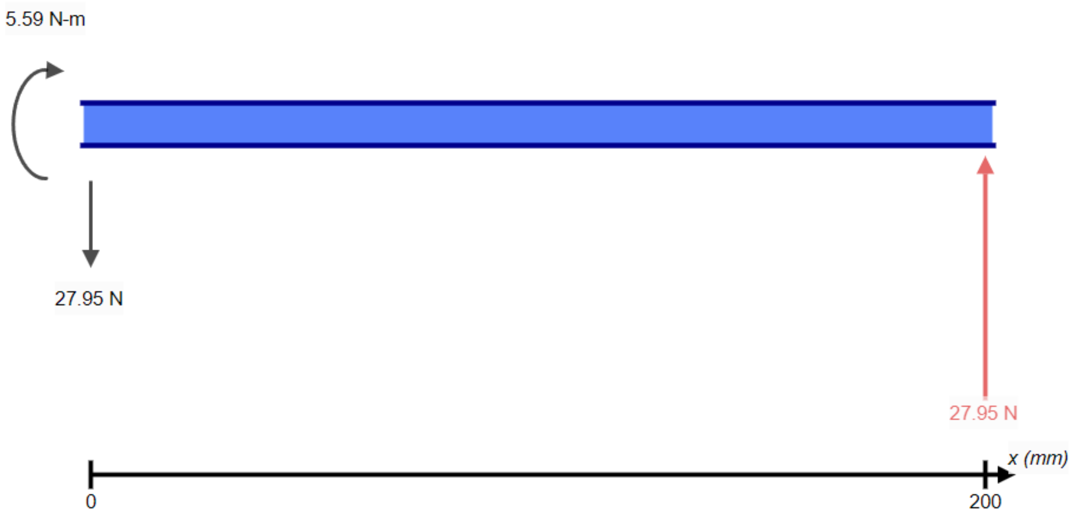

Figure 42. Completed Arms Free-Body Diagram

As the force is considered punctual and constant, the Shear Force Diagram will possess a rectangular shape.

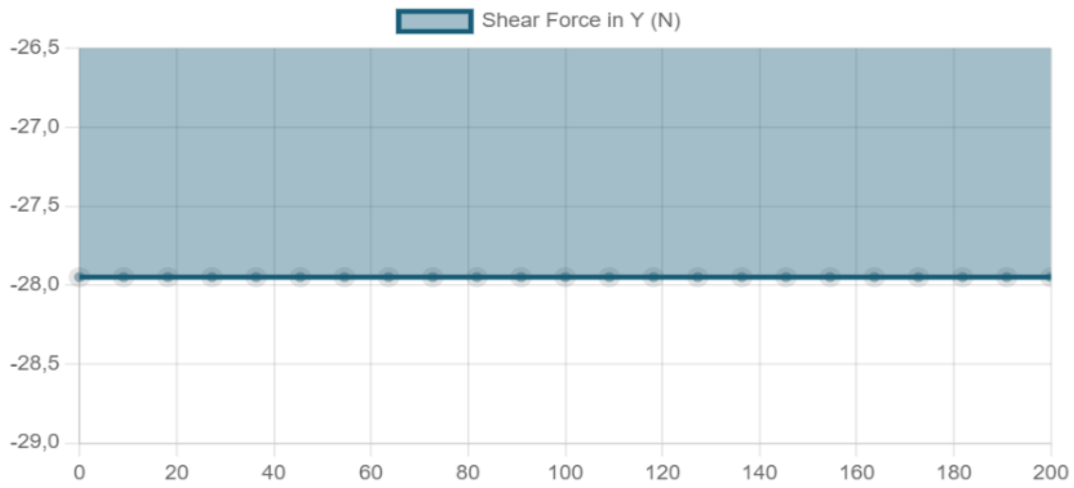

Figure 43. Arms Shear Force Diagram

As for the bending moment, there are only a force and a reaction acting on the system therefore the bending moment will follow the next formulation:

$$M_L = 27{,}95 * x \ \frac{N}{m}$$

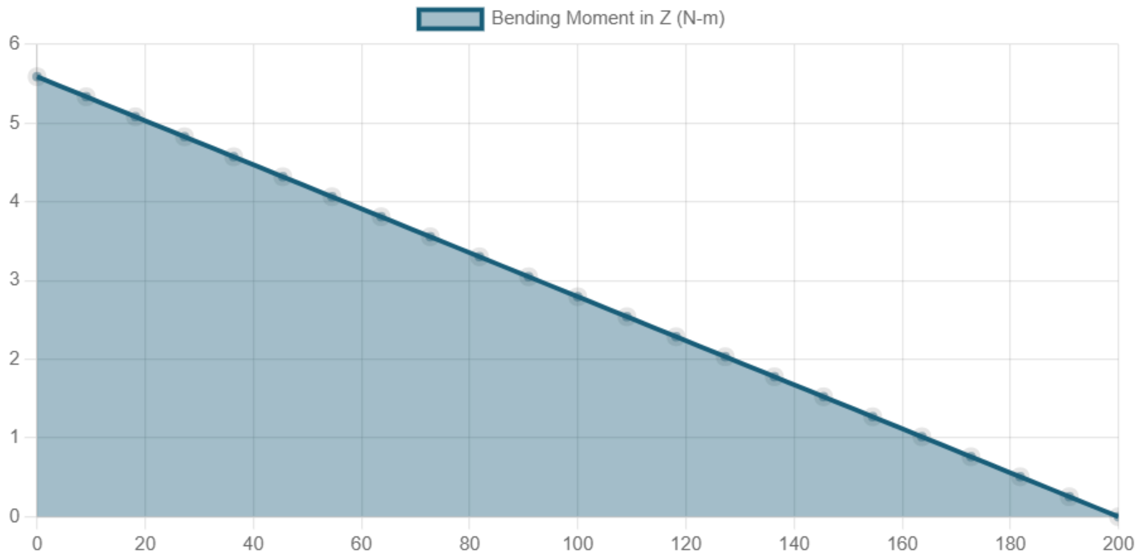

Figure 44. Arms Bending Moment Diagram

In order to calculate the deflection of the beam the Castigliano Theorem will be applied.

$$\delta = \frac{\partial U}{\partial F_i}$$

- $\delta = Displacement$
- $U = Strain\ Energy$
- $F_i = \ Force$

The displacement will occur in the direction of the force.

If this equation above is expanded the resultant formulation is the next:

$$\delta = \frac{\partial U}{\partial F_i} = \frac{\partial}{\partial F_i}\int_0^L \frac{\partial M^2(x)}{2EI}dx = \frac{1}{EI}\int_0^{0,2}(27{,}95 * x) * (x)dx = \frac{1}{EI}\left[27{,}95 * \frac{x^3}{3}\right]_0^{0,2}$$

- $E\ = Carbon\ Fiber\ Young\ Modulus$ = **276 GPa**
- $I = Second\ Moment\ of\ Inertia\ of\ a\ Hollow\ Circle = \frac{\pi}{64} * (D^4 - d^4) = \frac{\pi}{64} * (30^4 - 27^4) = 13673{,}73\ mm^4 = \mathbf{1,367 * 10^{-8}\ m^4}$

$$\delta = \frac{1}{EI} * 27{,}95 * \frac{0{,}2^3}{3} = 1{,}97 * 10^{-5}\ m = \mathbf{0,019\ mm}$$

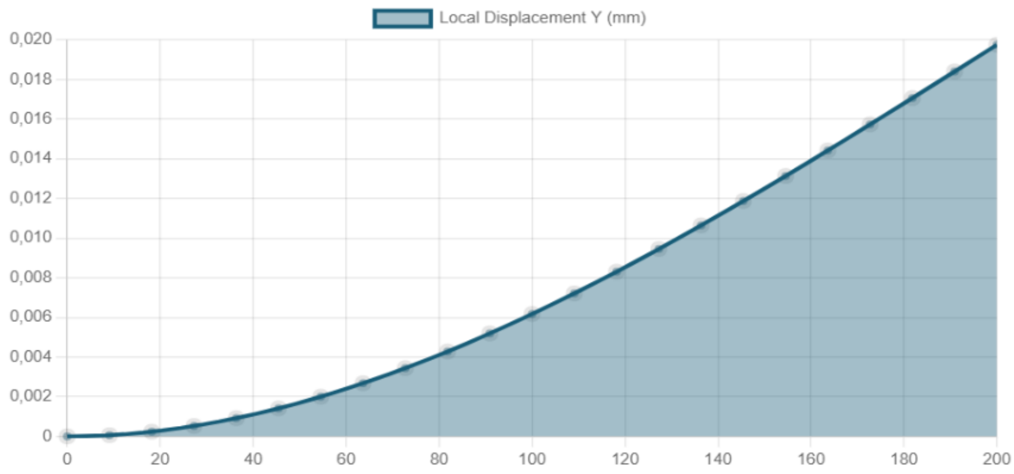

Figure 45. Arms Deformation Diagram

As it can be observed, the maximum deformation that the arms of the drone will suffer is of 0,02 mm which is small enough to be acceptable. This implies that even a further study could be done to reduce the thickness of the arms for weight optimization.

5.2.2 Numerical Approach

After the deformation was obtained, it is of high interest to compare this analytical solution to FEM results in terms of deformation and stress. For this reason, the arm was imported into ANSYS Structural Software for a structural analysis. The results were the following:

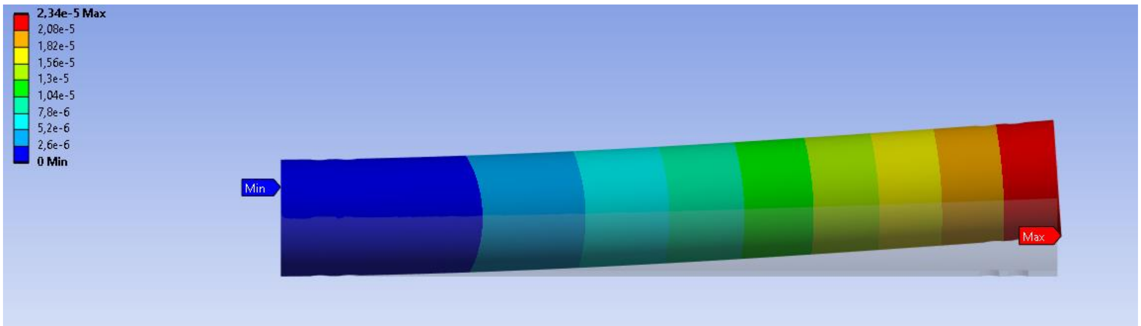

Figure 46. FEM Analysis of the Arms of the Drone

As it can be seen in the figure above, the arm will suffer a deformation at the end of its length where the engine is located due to the lift. Additionally, at the left-hand side of the figure the deformations colour grading can be observed. It shows that at the fixed the deformation is null while at the end of the arm the displacement is maximum and has a deformation of 0,02 mm. Although this deformation is a bit higher than the analytical one the small difference between the results can be explained firstly due to the mesh sizing as it may have had influenced the result and also due to material properties as ANSYS has small variations in terms of carbon fiber material properties. However, the calculations are proved to have coherence between the numerical and analytical approaches due to the small difference in the results.

Additionally, the Von Misses Stress was obtained to observe the possible location of a crack in the structure. The stress concentrates in the connection holes of the engine mount so this is the most possible location were a fracture can happen on the arm.

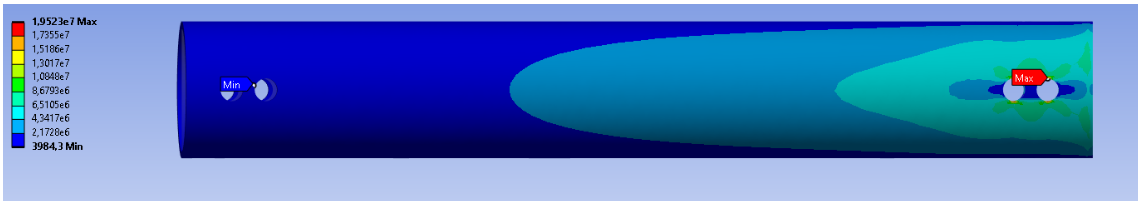

Figure 47. Von Misses Stress FEM Analysis of the Arm of the Drone

5.3 Main Chassis Structural Analysis

This structure is subjected to a remarkable number of forces so it would be interesting to analyse its structural behaviour. However, due to its complex shape the analytical approach will not be done, and the shape of the chassis will be simplified to obtain FEM results as the software presented several limitations calculating the stresses.

The main forces that are desired to analysis in this section of the report is the reaction forces applied by the arms to the chassis as they are key connection points in the drone and structural integrity must be assured in these places as they are the link between the drone body and the propulsion system.

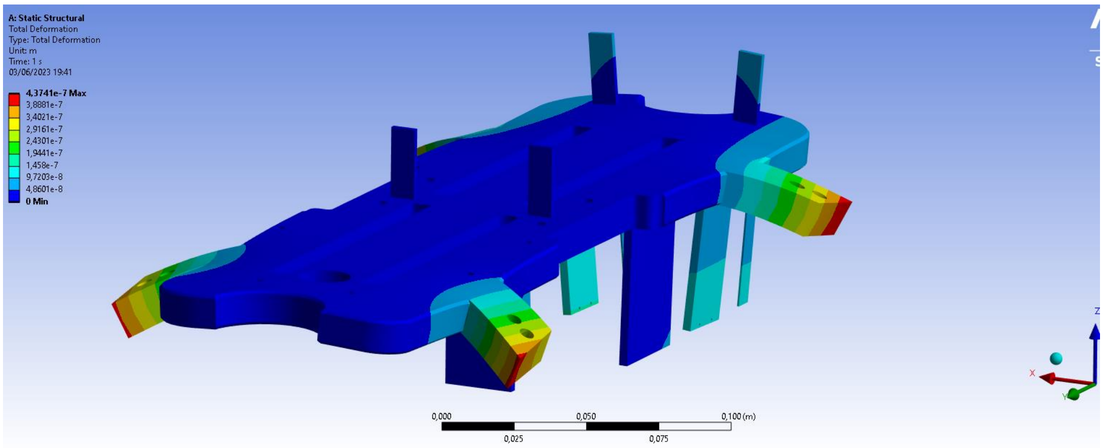

Figure 48. Total Deformation of the Main Chassis

As it can be seen the maximum deformation occurs at the connection points previously mentioned. However, this deformation is 0,0004 mm which is very small and even less than the deformation of the arms. For this reason, no deformation problems are found in this key structure.

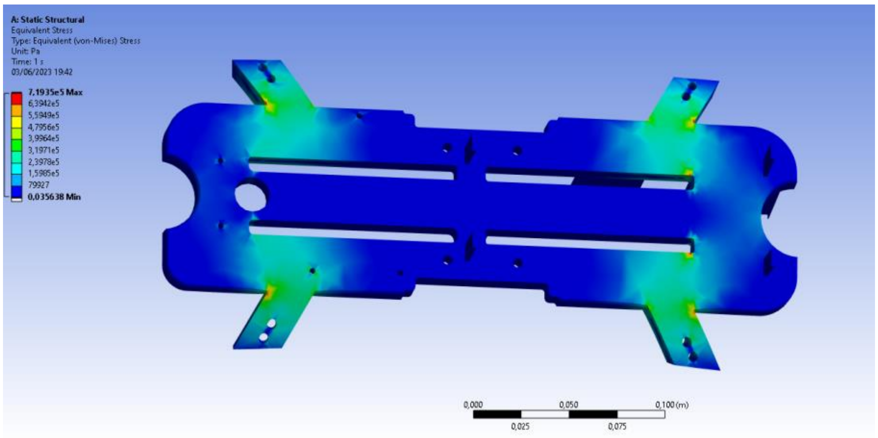

Figure 49. Von Misses Stress of the Main Chassis

The stress in the main chassis is concentrated in the edges of the arms' connection. They are small so there is no structural problem but a future improvement to the chassis could be to round those corners so that the stress will concentrate in a larger area and hence decrease.

Chapter 6. Production System

In this part of the report the production system will be developed. The product structure will be explained with all the different production processes that transform the raw material into the different drone pieces. This product structure include the SOI, Jigs and Tool and machinery of each individual process. It also includes the assembly process.

After the product structure, a quality plan will be designed so that preventive and corrective actions are applied to improve the product structure.

The quality plan will be follow by a Process Failure Mode & Effect Analysis of the braiding process to analyse the possible probles this process would present.

Then a Value Stream Mapping will be done to the whole production system to analyse the efficiency of the system and determine the correct number of stations to avoid overproduction.

Finally, some Lean Methodology strategies will be mentioned that could add value to the production system.

6.1 Product Structure

A product structure is basically a hierarchical decomposition of a product. Every box that appears in the product structure is an operation can includes comments refering to standard operation instructions (SOI), Jigs,Tools and Machinery used in that operation. The whole product structure can be seen below. Although the product structure is quite extense, for easier explanation every repeated production process will be commented once. The product structure will be explained in the detail later in the assembly process and therefore a clearer view will be portrayed.

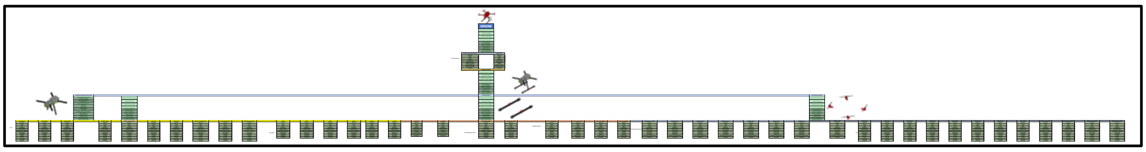

Figure 50. Complete Product Structure

There are 5 main production process in this industrial system to manufacture the different parts:

- **Resin Transfer Moulding (RTM) [Carbon Fiber]**
  - Internal Structure and Internal Preforms
  - Propellers and Propellers Suports
- **Braiding & Injection [Carbon Fiber]**
  - Arms
  - Landing Gear Legs and Landing Gear Support Arms
- **Rubber Production [Synthetic Rubber]**
  - Shock Absorbers
- **Injection Moulding [PEEK Plastic]**
  - Engine Mount Strcuture
- **Vacuum Casting [Polypropylene]**

- External Drone Shells
- Landing Gear Joints

6.1.1 RTM Process

Resin Transfer Moulding is a closed mould process in which a dry fiber preform is placed inside a mould cavity and afterwards a resin (thermoset) is injected until the mould is filled with resin . Later the resin is cured and the part is removed from the mould.

The steps mentioned in the product structure are the following:

QUALITY
PAINT
NDT
TRIMMING
DEMOULDING
INJECTION & CURING
MOULDING
FORMING
LAYING
KITTING
CUTTING
STORAGE

Figure 51. RTM Production Steps

6.1.1.1 Storage

This operation basically consists in storing the resin, the fibres, and the reinforcement binder.

6.1.1.1.1 SOI

The basic SOI of this operation is to do measurements of the storage conditions like temperature readings. This is important as a correct resin storage temperature avoids the polymerization of the thermoset resin. Some manufacturer recommendations state that the storage temperature range vary from 20 to 25 C°[28]. Other variables to measure are humidity and density.

6.1.1.2 Cutting

This operation is usually done by numeric control cutting machines (CNC). The reason of this decision is because a manual cutting does not assure the level of tolerance required for the desired product. Nevertheless, a future study could be done to analyse the cost of using CNC and if the cost is wanted to be reduced manual cutting can be done as for this specific RTM cutting the initial cut will not affect the final part tolerances as there is a trimming process at the end of the cycle.

6.1.1.2.1 SOI

One of the first SOI of the cutting process is to clean the cutting surface

Some other SOI of the cutting process is to check the cutting-edge length to assure a correct cutting. Other parameters that need to be checked are the dimensions of cutting, the cutting speed and the cutting feed.

6.1.1.2.2 Machinery

The machinery used in this step is basically the CNC Machines

6.1.1.3 Kitting

The kitting process consists in the identification of the different pieces and kit creation, as its name states. Another added value of using CNC machines is that these technologies can automatically identify the part by printing a sticker or another similar method. By doing this process manually the operator needs to go one by one identifying each part, which can lead to an increase in cycle team and possible human errors may happen.

6.1.1.3.1 SOI

Some SOI is to confirm the identification number of the part and do an inventory check to assure that all the parts have been kitted.

6.1.1.3.2 Machinery

In case that the CNC machine provides sticker. Otherwise, a sticker deployment tool.

6.1.1.4 Laying

This process is commonly done manually. The reason of this mode of operation is because to avoid undulations and wrinkles that may vary the carbon fiber thickness after the hot forming. For this reason, a common practice done in the industry is to drape the hot forming mould/tool to minimize the possibility of wrinkle formation. There is a possible automated process named fiber lay-up, but it was decided that for the small volume of the first batch a manual laying will be done.

Another recommendation specifically for the RTM process is to avoid non crimp fabric as when heated, due to the thermal expansion, all the fiber with the zero-angle orientation will be thickened and hence will be more prone to undulations formation.

6.1.1.4.1 SOI

Some of the SOI of the Laying process are to check the correct placement of the fibres, check deposition rate, check consolidation force, check temperature and check the shear strength among other operations.

6.1.1.5 Forming

This process is done in almost all the parts that are manufactured. The main reason and objective behind this process is to achieve a plies movement fix during the steps of injection and handling operations.

Binder is used in the fibres as a powder because they are naturally malleable. For manufacturing matters the binder transforms them into manageable materials. One of the forming objectives is to meld this binder with the material.

6.1.1.5.1 SOI

The main SOI of this process are to measure the time and temperature. Assure that the forming tool is clean and do a final check of the part after the forming.

6.1.1.5.2 Jigs and Tools

The main Jigs and Tools used in this process are the vacuum forming box, binder, release film and bladder.

6.1.1.5.3 Machinery

The main machinery that will be used in this process is the oven.

6.1.1.6 Moulding

The moulding process consists in inserting the preform into the injection tool.

6.1.1.6.1 SOI

The main SOI of the moulding process are to install Teflon around racor's thread to ensure tightness, check the vent pipes installation and check the thermocouples assembly to ensure a correct heat and temperature measurement.

6.1.1.7 Injection and Curing

The injection process' main objective is to mix the resin with the preform. This process is determined by two parameters. The injection pressure and the resin front speed. As the preform is assumed to be a porous media the Darcy's Law can be applied. If the resin front speed is kept constant this implies, following the equation below, that the pressure gradient must be kept constant too.

$$q = -\frac{k}{\mu}\frac{\Delta P}{L}$$

Figure 52. Darcy's Law Equation

As the resin flows, this means that the impregnation volume increases which requires an increase in injection pressure if the constant resin front speed condition wants to be fulfilled. This led to several problems like distortion of the fibre network yarns orientation due to the increase of injection pressure. Additionally, the yarns possess two length scales as one is of the order of a fiber diameter while the other of the scale of the fiber tows. This implies that two resin front speeds are required, which cannot be done by this method. Lastly, cleaning problems may appear with this technique as piston injection system needs to be installed.

For all these reasons, it has been stablished that the injection pressure will be constant. This implies, following the Darcy's Law, that pressure gradient will not be constant. As the impregnated volume increases, the resin front speed decreases. This method solves the problem of the distortion of the yarns' orientation and due the fact that the resin front speed varies, it adapts better to the preform.

The main steps of this process are to first set a steady vacuum with the objective of removing the air from the carbon fiber layers. Then another steady vacuum is done to let the resin flow and mix with the preform and fill the totality of the mould until the mould frontier.

6.1.1.7.1 SOI

The main SOI of the injection and curing process are to measure thickness deviations, check positioning of the element, check resin temperature, adjust tolerance level, check sealing regime, preheat for one shot injection curing, check Injection pressure and measure the viscosity.

6.1.1.7.2 Jigs and Tools

The main jigs and tools used in this process are feeder mesh, peel ply, release film, vacuum bag, mastic sealant, steel injection mould and aluminium inserts. The moulds will be made from steel due to its durability and stiffness.

6.1.1.7.3 Machinery

The process will take place in a press as it allows one shot injection.

6.1.1.8 Demoulding

This process consists in demoulding the cured piece from the injection mould.

6.1.1.8.1 Jigs & Tools

The main Jigs and Tools that will be used in this process are cryogenic non-abrasive cleaning system and demoulding agent.

6.1.1.9 Trimming

This process consists in trimming the excess of material from the final piece. This process should be as automated as possible.

6.1.1.9.1 Machinery

The machinery used here is the CNC machine.

6.1.1.10 NDT

The Non-Destructive Tests process is a step in which every part of the industrial cycle inspected for undesired deviations. Ultrasonic and visual inspections are the most common types of NDT. The most recurrent causes of deviations in the product are a bad design, bad material, or an incorrect manufacturing process. One of the most common yet important deviation is delaminations which can directly affect to the final part properties.

6.1.1.10.1 Jigs and Tools

Standard Jigs and Tools for NTD are ultrasonic flaw detector, ultrasonic thickness gauge and non-destructive stress analyser among others.

6.1.1.11 Paint

It is the process of painting the final part.

6.1.1.11.1 SOI

The standard operations regarding painting are to wash the aircraft and displace it into a clean environment, remove flight control or components that have risk of damaging during pain operation, apply the chemical strip, apply epoxy chromate and polyurethane basecoat, lay the pain arrangement, and apply the colours desired among others.

6.1.1.11.2 Jigs, Tools, and Machinery

Standard jigs and tools of painting are spray guns, air compressors, coating containers, system air filters, electronic thickness gauges to measure paint thickness, viscosity measuring cup and mechanical paint stirrer to mix among others.

6.1.1.12 Quality (Final Assembly Quality)

This is the last step in the production of the part in which the final quality inspections are done. This quality process is extrapolated to the final assembly too. This means that although individual part inspection is done, the quality process is done in depth at the final assembly. The quality checks are done after each part is manufactured but this quality process is highly important in the final assembly part.

6.1.1.12.1 SOI

As the drone has a lot of wiring, this one needs to be checked. This implies that all cables are connected and have a correct functioning. Additionally, some SOI were found from the FAA regulation[29]. These ones include shells distortion inspection, external bracing and attachment fitting inspection as some imperfection, cracks of distortion may have happened. In the case of the drone specially, check that the wiring has a proper routing and there is no chafing. Another operation shall be to check the battery and all internal components so that they have correct operation. Also, the engines and rotors should be tested among other operations.

6.1.1.12.2 Jigs and Tools

This section includes fiber optic scopes, headlamps, inspection kits, leak crack detection, magnifiers , mirrors, pitot static systems and video scopes among others.

6.1.2 Braiding & Injection Process

This process is relevant as all the tubular shaped parts of the drone, which imply the legs and the arms, will be manufactured with this method. This method just varies from the RTM in the fiber laying as the injection and the following steps are done in a similar way.

QUALITY
PAINT
NDT
TRIMMING
DEMOULDING
INJECTION & CURING
MOULDING
FORMING
BRAIDING
STORAGE

Table 9. Braiding and Injection Production Steps

As mentioned above, all the steps are the same instead of the fiber laying which braiding subtitues the cutting, kittin and laying steps in a single one.

Braiding Process

Composite braiding is an upcoming technology which allows carbon fiber yarns lay up in a faster,more reliable and cheaper way than conventional AFP, ATP o Fiber Lay-Up. This method consists in a circular platform that is in charge of holding the spools of carbon fiber yarns. The spools are proportioanl to the desired thickness of the piece. As the yarns need to be interlaced, the warp carriers rotate in a clowise direction where as the weft carries rotate in a counter clockwise direction. In this specific production system the mandrel has been decided to be placed in the center of the brading platform as it will ease the fiber laying. Additionally, this mandrel needs to be normal to the braiding platform plane as it can be seen below.

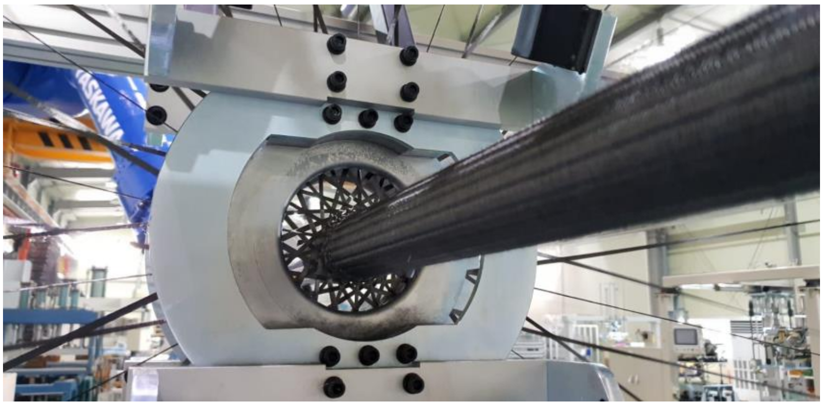

Figure 53. Carbon Fiber Braiding Machine

The braid can be created on the entire mandrel surface thanks to the mandrel's translational movement. The mandrel's yarns are rolled up by the carriers' circular motion around the braiding axis, while their sinusoidal motion causes the yarns to interlace. This can be seen in the picture below.

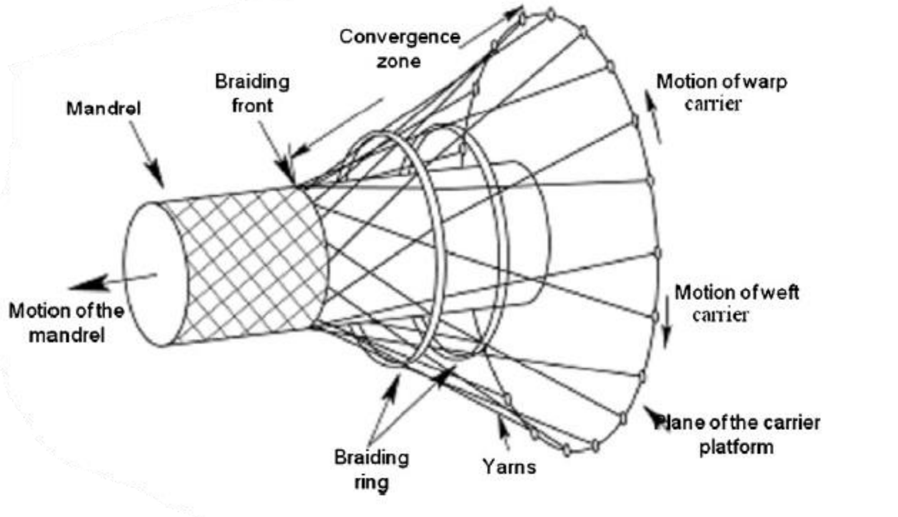

Figure 54. Braiding Machine Working Principle

Progressive interlacing of the yarns as they exit the spools creates a convergence zone between the yarns exit carriers’ plane and the braiding front located at the point of contact with the mandrel.

This process has a few disadvantages that need to be considered in the SOI. The first one is that the yarns experience friction in the convergence zone during interlacing after leaving the carriers. The friction between the yarns reduces the rotational speed of the yarns around the braiding axis, which in turn affects the braid's final properties (such as the braiding angle). The second one is that the location of the braiding front is altered by a change in the process parameters (such as the platform's rotational speed) introducing a temporary stage before the steady-state run is established. The relative movement of the yarns on the mandrel caused by variations in the location of the braiding front may change the braiding angle and thus affecting the properties of the piece. Lastly, stretching the yarns causes a tensile force that makes the yarns to slide on the mandrel. This will vary the yarns' orientation.

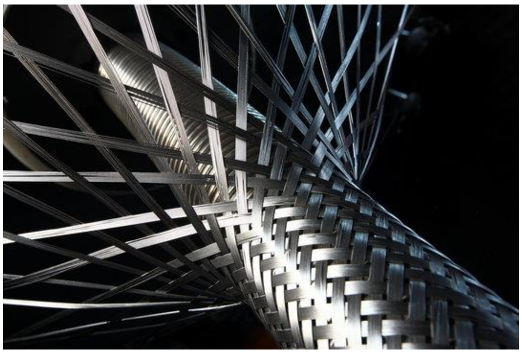

Figure 55. Fiber Braiding Front Ilustration

6.1.2.1 SOI

Some SOI of this process are to check the braiding angle, the crimp, and the coverage factor. Another one is to set the rotational speed and check that the braiding front is located as expected. Several SOI will be added in this process by the quality plan.

6.1.2.2 Jigs and Tools

Some Jigs and Tools used in this process are the mandrel, warp carrier, weft carrier and braiding rings among others.

6.1.2.3 Machinery

The main machine that will be used to braid the arms and legs of the drone is a 2D braiding machine.

6.1.3 Rubber Production Process

In this section of the report the production of the shock absorbers will be explained. As they are made from rubber this industrial process will be explained.

QUALITY
PAINT
NDT
TRIMMING
DEMOULDING
CURING
SHAPING
MIXING
MASTICATION
STORAGE

Figure 56. Rubber Production Steps

As the previous mafucaturing process, the braiding process, this step has some steps that are done in the same way as the others and for the sake of the report coherence they will not be commented again.

6.1.3.1 Mastication Process

In this process the elastomer is trimmed and cropped, and the resulting molecules are broken down in order to provide the mixing an easier flow.

6.1.3.1.1 SOI

Some of the basic SOI of this process are to check cylinder’s rotational speed, check cylinder’s direction, check roll mill’s status, insert rubber raw material and check rubber softness among others.

6.1.3.1.2 Machinery

The machine that will be used for this process is a rubber mil. More specifically a Banbury Mixer.

6.1.3.2 Mixing

This process is done inmediately after the mastication step when the additives are added.

6.1.3.2.1 SOI

Some basic SOI of the mixing process are to apply protective chemicals, sheet out the compound, release the soap coating and storage the steel pallets.

6.1.3.2.2 Jigs and Tools

The usual Jigs and Tools for this process are release soap and fillers.

6.1.3.2.3 Machinery

This process is done inside the mastication process machine, the rubber mill.

6.1.3.3 Shaping

This process is done in different ways in the industry. However, the chosen method will be rubber extrusion that is the process that produces the tire treads. The basic principle of this step is to produce a profile that will be cut in length. Doing this allows the system to produce a single long shock absorber that can be cut and put into the injection tool. This makes the production system faster. The main machinery used in this step is the extruder.

6.1.3.4 Curing

In this case a curing press will be used as in the RTM process. This curing is usually done in stell plates that are pressurized. Some temperature estimation round about the 150 °C to 160 °C. As the shock absorber that are going to be produced are relatively thick this will affect the curing cycle time as heat slowly penetrates rubber. Additionally, due to the thickness of the shock absorbers, the curing cycle not only will be slower but a temperature close to 150 °C will be done. Moreover, a pressure of 1 MPa will be applied to maintain the desired shape of the shock absorber.

6.1.4 Injection Moulding

This process will manufacture all the engine shell with PEEK plastic as it needs to support the heat of the brushless motor. Injection moulding is very common process in plastic manufacturing, and it aims to obtain moulded products by injecting plastic materials that are molten by heat into the mould cavity, then cooling and afterwards solidifying them.

QUALITY
PAINT
NDT
TRIMMING
DEMOULDING
COOLING
MOULDING
INJECTION
MATERIAL PREPARATION
STORAGE

Table 10. Injection Moulding Production Steps

6.1.4.1 Material Preparation

This step consist in preparing the material and feeding it into the injection tool. Some SOI in this process may regard the batch checking, meaning that there are no defects in the material batch. Also, the material accommodation to the injection tool may be manual and so an operator may need to be present. In this step the clamping unit is set to moulding mode and it is fixed. This type of clamping will be of toggle type.

6.1.4.2 Injection

The main objectives of this process are to melt the plastic material and inject this molten material into the mould. The screw, that can be seen in the figure below, is rotated to melt the material that is being fed in the hopper. This process takes some time until enough material is gatherer at the point of the screw and then injection starts.

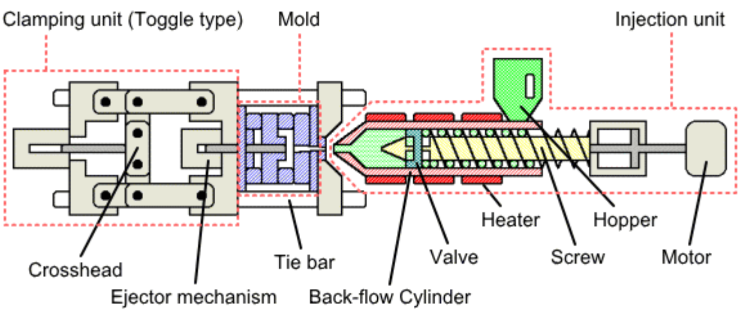

Figure 57. Injection Moulding Process

The injection speed is determined by precision machine that dictates the speed of the crew. Additionally, this injection speed also controls the dwell presser after the cavities of the mould are filled.

6.1.4.3 Moulding

This process consists in the molten plastic filling the mould cavities through a sprue by means of gates and runners. The mould will be made out of steel as the one in the RTM process.

6.1.4.4 Cooling

This process consists in letting the piece cool to solidify. Special care must be taken in this step as shrinkage may happen. This deviation can cause tolerance mismatch which will affect the propulsion assembly. Some manufacturers apply water cooling to PEEK cooling step and mention that the cooling process should not be extremely fast as voids may form. The method that will be applied in this industrial system will be air cooling follow by a water immersion. The temperature of the water is recommended to be in the range from 20°C to 50°C [30] . Some tools that may be used in this process are thermocouples to monitor cooling rate.

6.1.5 Vacuum Casting

This process is much simple compared to the other processes previously explained. A simplification of the process can be seen in the following illustration.

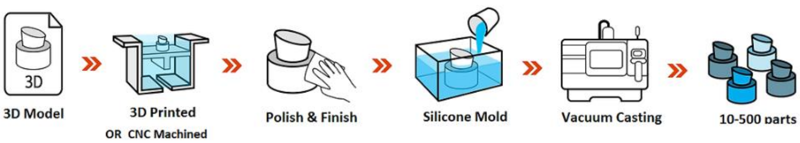

Figure 58. Vacuum Casting Steps

The first steps of the process involve the mould creation. This step is very important as the precision of the mould will directly affect the shape of the final piece that in this case are the upper and lower shells. Imperfections in the mould will be reflected in the final part and this is not desired. For this reason, 3D printing technology is usually applied to create the master pattern for the mould shape.

After the mould is done the polyurethane resins are mixed and heated at temperatures that round the forty degrees. After the resins are ready a vacuum is applied to the mould to remove the air from it and resin pouring starts. After the cavities are filled the resins are heated up to curing temperatures in a curing room until its solidification. Finally, a demould operation shall be done, and a surface cleaning would be applied. Then the rest of the steps are repeated like the other processes. This implies trimming, NDT, paint, and quality operations.

6.2 Assembly

In this section of the report the assembly process will be explained in detail.

There are two main assembly process in this industrial system. The ones that are permanent assemblies and therefore they will not detach without some complex operation, and the ones that are “temporary”, meaning that they can be easily detached by some tools.

The main steps of a permanent assembly are the following:

REMOVE ELEMENT FROM JIG
FILLET SEALANT
OVERHEAD SEALANT
RIVETS INSTALLATION WITH WET SEALANT
ELEMENTS MOULDING
INERLAY SEALANT
INTERFACE CLEANING
ELEMENTS DEMOULDING
REMOVE TFD
REMOVE DRILLING CLAMP
D DRILLING
REMOVE TFD
TFD INSTALLATION
D DRILLING
DRILLING TEMPLATE INSTALATION
TFD INSTALLATION
ELEMENT MOULDING
CLEAN EXCESS OF SHIM & RELEASE FILM
ELEMENT DEMOULDING
SHIM CURING
TFD INSTALLATION
ELEMENTS MOULDING
RELEASE FILM & GROSS FILMING
ELEMENTS DEMOULDING
GAPS MEASUREMENT
TFD INSTALLATION
D2 HOLES DRILLING
MANUAL CLAMP
ELEMENT MOULDING
ELEMENTS POSITIONING

Figure 59. Permanent Assembly Process Steps

The main steps of a temporary assembly are the following:

REMOVE ELEMENT FROM JIG
INTERFACE CLEANING
ELEMENTS DEMOULDING
REMOVE DRILLING CLAMP
NUT INSTALLATION
SCREW INSTALLATION
WASHER INSTALLATION
HOLES DRILLING
MANUAL CLAMP
ELEMENT MOULDING
ELEMENTS POSITIONING

Figure 60. Temporary Assembly Process Steps

In the following figure the assembly of the drone can be seen.

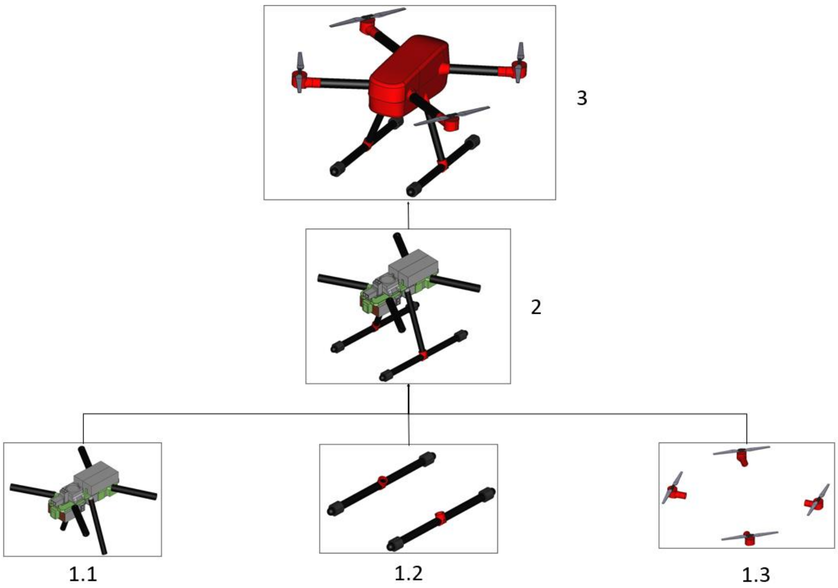

Figure 61. Complete Assembly Steps

If the assembly process is observed different comments can be done. There is an initial assembly of three differentiated groups, the internal structure, the landing gear, and the propulsion system. The internal structure follows a permanent assembly excluding the GPS and the MC internal structures as they are installed with a temporary assembly. The reason of this decision is because by installing a temporary assembly these structures can be uninstalled and easier access to the OBC and the ESC is achieved. The landing gear is temporary assembled, and the shock absorbers are installed by applying pressure. The propulsion system is temporary assembled as it is necessary to access the engines in case of malfunction. Then the second level assembly will be done. One thing to mention is that landing gear chassis is assembly inside the shells and the reason for this is to prevent assembly errors. This will be later explained in the Poka Yoke section. Also, to install the landing gear the lower shell needs to be introduced first as if the support leg is installed the lower shell will not fit.

The last step and third level of assembly is the shells installation.

6.3 Quality Plan

A quality plan has been designed to apply both preventive and reactive actions to the industrial system. The ideal case would be to apply the quality plan to every single process, but a simplification will be done, and it will be applied to some processes just to demonstrate how the full quality plan would look like.

6.3.1 Preventive Actions

The preventive actions of the Quality plan can be seen below:

Process	Preventive Action
All processes	Routine equipment maintenance
All processes	Machine cleaning after every operation to avoid dust and dirt
Trimming/ Cutting	Lubrication of rotating systems like trimming machines to avoid early wear
All processes	Operators' training
All processes	Operators testing to determine proficiency level
Storage/kitting	Check material batches on a daily basis
All processes	Check variables before first daily use
Trimming/ Cutting	Clean out chips from trimming machines
Trimming/ Cutting	Check, clean or replace the filters on the coolant tank
Injection and curing	Inspect injection moulds
Injection and curing	Inspect injection gates
All processes	Energy consumption check
All processes	Check tool wear
All processes	Machine calibration
Storage/kitting	Check ventilation parameters

FQC	Inspect voltage and amperage of motors
FQC	Wire inspection
Storage	Examine fire detection systems
FQC	Leakage inspection
All processes	Check operators' methodology
NDT	Thickness measurement of fibres
NDT	Strength test of random batches
Paint	Check paint finish
Trimming/ Cutting	Assembly tool correct placement
NDT	NDT material inspection
All processes	Operators' workplace inspection
Braiding	Random checks of the yarn in braiding to avoid the sliding of the yarn
NDT	Check the preform hardness using a Durometer
Moulding	Check mould uniformity
Injection and curing	Check closing time of the press

Table 11. Preventive Actions of the Quality Plan

6.3.2 Corrective Actions

Some corrective actions of the Quality Plan can be seen below.

Process	Corrective Actions
Cutting/Trimming	If cutting tool suffers acceptable tool wear , provide a maintenance checklist to ensure its correct functioning
Cutting/Trimming	If cutting tool suffers medium wear the tool must proceed a reparation process
Cutting/Trimming	If cutting tool suffers unacceptable wear tool must be disposed off
Cutting/Trimming	If cutting tool suffers unacceptable wear earlier than expected, the MRB should review the life cycle of that cutting tool and generate additional SOI to prevent this even from happening
Cutting/Trimming	If material thickness is higher than expected additional trimming operations should be required

Moulding	If mould is deteriorated it should be replaced
Braiding	If the rotational speed of the yarns is decreased, adjust its value to the desired one
Braiding	If braiding angle is displaced reposition the braiding front
Braiding	Mandrel reposition if the resulting preform is not the desired one
Braiding	If braiding front speed is not as expected check braiding machine mechanisms
Injection & Curing	If the RTM process produces excessive flash decrease charge weight
Injection & Curing	If in the RTM flow lines appear increase transfer pressure

Table 12. Corrective Actions of the Quality Plan

6.4 PFMEA

A PFME is a Process Failure Mode and Effects Analysis. It is a quantitative method that stablishes the most possible causes of failure of a process. This list is usually done by experts and tries to reflect all the possible way in which the process can fail, its effects and solution. The PFMEA of the Braiding process can be seen below.

Process Failure Mode And Effects Analysis (PFMEA)

Process	Function	Requirement	Failure Mode	Effects	Severity	Cause	Occurrence	Detection Control	Detection	RPN	Recommended Action: Action
Braiding	Manufacture the drone's legs and arms	Provide structural strenght to the drone body and withstand the stress it is subjected to	Misaligned yarns during braiding procedure	Loss of Inertia	7	Friction during the interlacing at the convergance zone	8	Mandrel Sensors	3	168	Study the properties of the resultant deviated part
				Mechanical properties deterioration	8	Uncalibrated reference system	3	Braiding machine charts	2	48	Machine Parameters calibration
				Braiding machine wear	4	Uncalibrated rotational speed	5	Tachometer	1	20	Stop the braiding machine and adjust the rotational speed
				Thickness deviation	4	Batch defect	2	Visual Inspection	5	40	Identify the deviated batch and inform the supplier
				Inaccurate assembly	3	Weft plane displaced	2	Braiding machine charts	2	12	Machine Parameters calibration
				Resin injection problems	3	Slower braiding front speed	2	Mandrel Sensors	2	12	Stop the braiding machine and adjust the yarns

Figure 62. Braiding Cycle PFMEA

Although the PFMEA is self-explicatory some explanation will be given. Firstly, it has been assumed that the failure mode of the braiding cycle is the distortion of yarns' orientation. This can lead to the effects that are shown in the illustration above.

The RPN that is calculated above is the combination of the severity, occurrence, and detection level of the failure mode. As it can be seen, friction between the yarns and the convergence zone is inevitable which implies that is its occurrence is high. Additionally, this distortion of the orientation of the yarns can lead to a loss of inertia and mechanical properties deterioration that can compromise the drone's structural integrity. For this reason, it is important to dictate an action if this event happens. For this reason, if the legs or arms possess misalignment of the yarns an analysis will be done of this deviated part and its new modulus and properties will be studied to determine if that part is under the operation modulus range and can be installed without additional actions.

6.5 Lean Strategies

As a modern industrial production system, it is essential that the processes are optimized. For this reason, Lean Methodology will be applied. Essentially Lean Methodology is a way of managing processes in which the main objective is to reduce the time, effort, and investment.

The way this methodology works is by identifying and eliminating waste. Waste is grouped into 7 categories as seen below.

Figure 63. 7 Wastes of Lean

All these 7 wastes, inventory, waiting, defects, overproduction, motion, transportation and overprocessing are going to be optimized in the VSM section.

6.5.1 Poka Yoke

Poka Yoke is a Lean tool which prevents defects. Its application method implies in designing systems with simplicity, security, automation, and interconnection.

As mentioned earlier in the report, there was a design decision regarding the landing gear. The leg of the drone is temporarily assembled to the landing gear chassis inside the shell volumes and before installing the landing gear this process needs to be done. This was intentionally done to prevent a possible operator mistake in the assembly process. If the operator tries to assemble the drone in another order than the one shown in the product structure it will not be possible. Designing the landing gear with this system applies a Poka Yoke methodology to the assembly process and avoids possible defects of the product.

Figure 64. 3D Model of the Landing Gear

If the support leg is assembled previously to the landing gear leg it will be very complex to assembly it to the landing gear chassis.

6.5.2 VSM

The main reason to design a VSM for this production system is to optimize the different production processes so that there is neither delay nor overproduction of the components. Having several production process implies different VSM and so this will be reflected in this section of the report.

Before proceeding to show the different mappings it is important to determine the takt time of the industrial time. This time means the estimated time that requires to produce a drone to avoid overproduction and delays.

In the market analysis section of the report the production rate and desired launch date were determined. This were a production rate of 42 drones per year and the initial batch would be delivered by 2025-2026. If a two shifts per day configuration is chosen this implies 16 working hours per day. The average working days per year are 260 days. Although there are 2 years ahead it has been decided that the production will start in 2024. If the production were to begin in 2023 there will be considerable losses in terms of storage costs.

$$Time_{TAKT} = \frac{Shift\ hours * Working\ days * Years}{Production\ Rate} = \frac{16 * 260 * 1}{42} = 99\ h = 4{,}13\ days\ \approx 4\ days$$

This calculation estimates that the Takt Time of the production system is 4 days. This means that a drone should be produce every 4 days.

With this requirement the VSM can be designed. The different time intervals that appear in the VSM are not random. For the injection and curing several curing cycles has been researched and for the quality inspection it was estimated after observing some media content regarding depth and thickness measurement using IR NDT.

6.5.2.1 RTM Process VSM

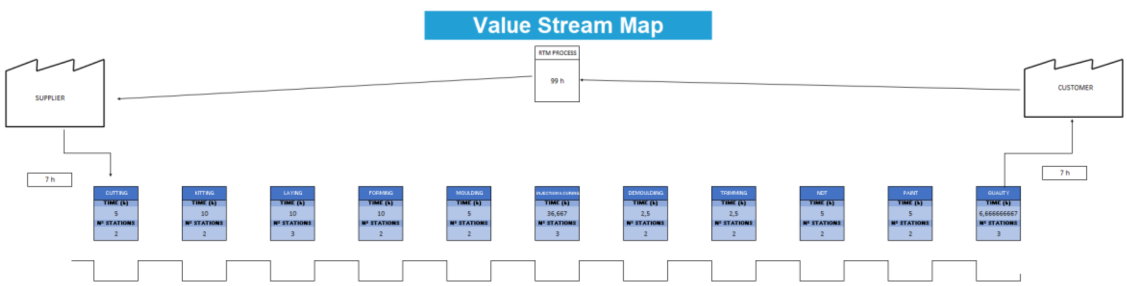

Figure 65. RTM Process VSM

It has been decided that in order to deliver a Lead Time of 99 hours the RTM process should require more stations in the process that take most time which are injection and curing and laying. Besides, the other stations have been increased up to 2 to have some spare time in case a deviation occurs.

6.5.2.2 Braiding & Injection Process VSM

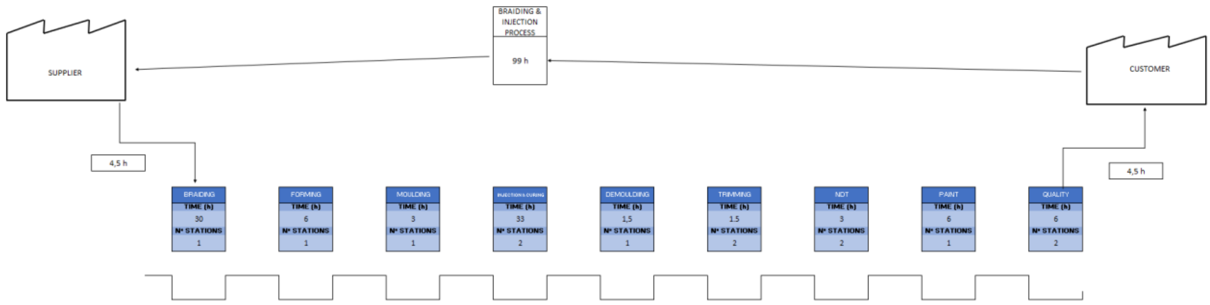

Figure 66. Braiding & Injection Process VSM

This process was faster as less pieces are doing by braiding and this method is faster than the RTM laying. The braiding station was decided to be one as for an initial batch the investment of several braiding machines would not be optimal as the learning curve of the operators in charge of the braiding process will not be efficient. This can be seen in the picture below.

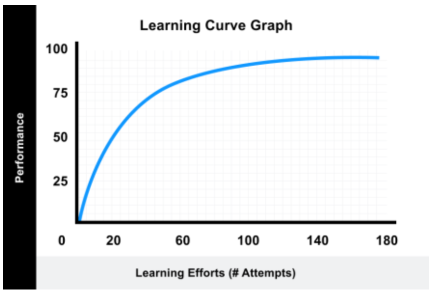

Figure 67. Operator Learning Curve

The operators need time to adjust to the machinery and the process to be proficient at their tasks. As a new production system is being designed it has been assumed that not all operators have experience and hence that is the reason for the number of braiding stations.

However, this number of stations is related to the initial batch and objective of 42 drones per year. If the business model becomes successful then the number of stations can be increased.

6.5.2.3 Rubber Production Process VSM

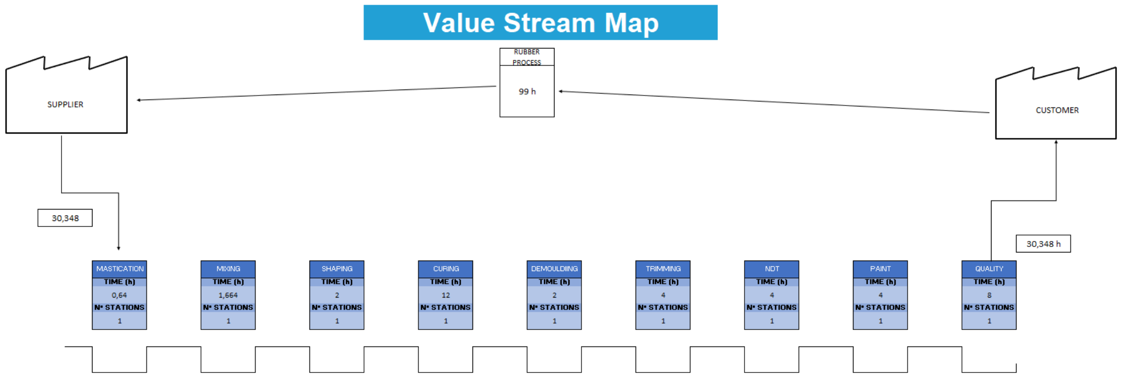

Figure 68. Rubber Production Process VSM

As this process is much faster than the one previously mentioned there is no need to increase the number of stations. In fact, the supplier and the customer delivery times needed to be increased otherwise there was going to be overproduction of pieces or unnecessary storage.

6.5.2.4 Injection Moulding Process VSM

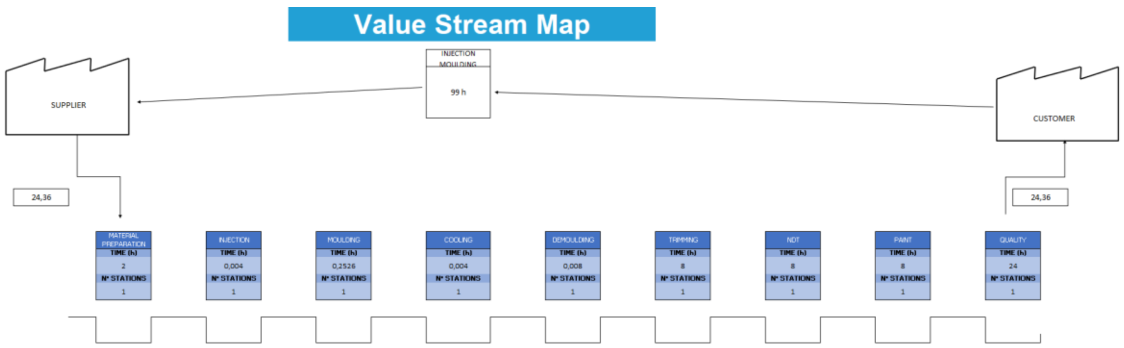

Figure 69. Injection Moulding Process VSM

In this case a similar thing happens like in the rubber production process. As this process is faster than the carbon fiber production, they need to be slowed to avoid overproduction.

6.5.2.5 *Vacuum Casting Process VSM*

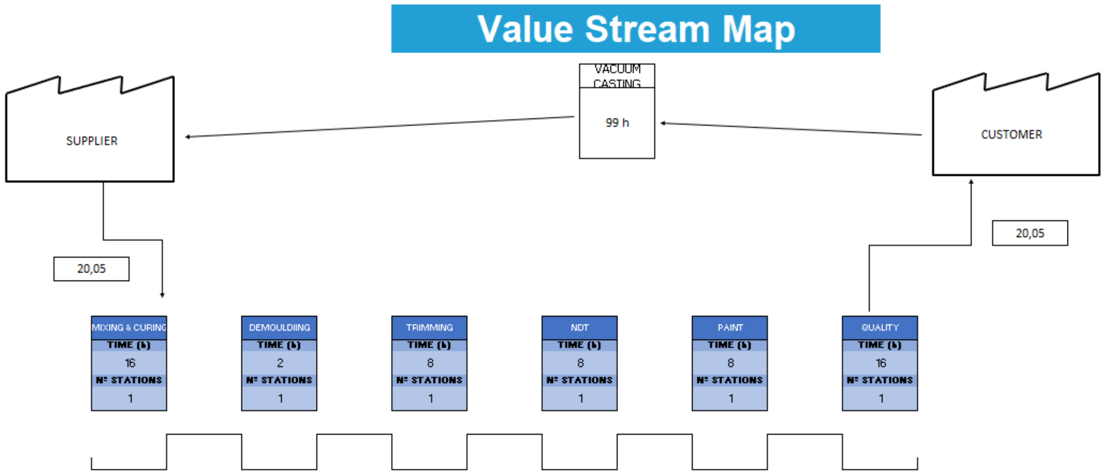

Figure 70. Vacuum Casting Process VSM

As mentioned before this process needs to be slowed to avoid overproduction hence the single station per process.

Chapter 7. Conclusions and Future Works

The production rate and delivery date of the initial batch of drones provides a great approximation of a realistic business proposal. Additionally, the requirements for a middle of the market Oil & Gas inspection drone offer a solid base for different drone designs. Thanks to the components selection all the essential components of the drone were selected. A fully operational drone with realistic dimension was designed with a 360-proximity sensors system. The design of a quadcopter with a chassis support system provides adaptability for the internal components layout and facilitates the assembly build sequence. The design of the internal assembly of the landing gear offers a Poka Yoke principle to the drone which prevents human mistakes. Thanks to the weight estimation the drone was weighted and succeeded with respect the initial requirements . Due to the comparison of the FEM and the analytical solutions the results were validated, and the deformations and stresses were analysed, concluding that the drone presented structural integrity. As the product structure was designed, all the different actions required for the production of the drone were defined. The assembly process of the drone was defined, classifying every part by its type of assembly. The creation of a Quality Plan proved that additional actions were required. Thanks to the PFMEA the braiding process was optimized. Thanks to the VSM all the different manufacturing processes were optimized in accordance to the calculated Takt time and overproduction, and delays were assured to be prevented.

As future improvement of the work done, the first step will be study with more depth the laminate dimensioning and produce an initial prototype to test tolerances and fabrication. In terms of design it would be necessary to implement the lenses into the 3D model, design a gimbal for the chosen camera and implement its assembly into the assembly process. A more detailed 3D model would be favourable as well as a stability analysis and center of mass calculation. In terms of the production system, a curing cycle design would be optimal as well as a study of the braiding yarns orientation properties. Additional operations to the Quality Plan should be added to cover the whole production system as well as an individual PFMEA should be done to all the steps of the product structure. An economic study of the cost of the production of the drone and a possible market prize for the drone would be interesting and a study of the ATEX regulation would be great for implementing design decision to achieve an ATEX certification sticker for the drone to operate in Zone 0 and Zone 1.

Chapter 8. REFERENCES

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