YRKESHÖGSKOLAN NOVIA

Centrifugal Method to Clean Waste Cooking Oil

A study of the feasibility of constructing a centrifuge to remove unwanted particles from waste cooking oil using reused materials

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Abstract

The disposal of waste cooking oil (WCO) is a major concern due to its potential impact on the environment. WCO can contaminate water and soil, and its improper disposal can harm aquatic life and the ecosystem. To address this issue, this project aims to fabricate a centrifuge to remove unwanted contaminating particles from WCO, making it clean for appropriate new use (e.g. as feedstock for biodiesel production). The project also aims to demonstrate the feasibility of fabricating a centrifuge without the need for a large initial investment and to contribute to the circular economy by reusing materials.

The centrifuge consists of a 4.1kW three-phase electric motor, a transmission system, a bowl rotating, and an oil circuit. A variable frequency drive regulates the speed of the motor to rotate the bowl at a speed of 3000 rpm. An oil pump with a power of 550 W drives the WCO from a tank to the bowl, and the flow rate is regulated by a manual valve. The total cost of the project was 750.04€, a cheap price due to the reuse of most of the components and materials.

The centrifuge was tested, and a visual test showed significant differences in colour and opacity between the WCO and the cleaned WCO. However, some marginal failures were observed during the operation of the centrifuge, and improvements can be implemented in the future to address these issues.

In conclusion, this project demonstrates the potential of separation technologies to contribute to sustainable engineering and provides a valuable contribution to the field.

Language: English
Key Words: Waste cooking oil, centrifuge, circular economy, biodiesel feedstock.

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Glossary

Acronyms

a_r	Radial acceleration
α	Angular acceleration
CAD	Computer assist design
d	Diameter (small)
D	Diameter (big)
EPDM	Ethylene Propylene Diene Monomer
F_c	Centrifugal force
η	Efficiency
i	Transmission ratio
I	Inertia moment
m	Mass
P	Power
r	Radius
SPWM	Sine Wave Pulse with Modulation
t	Time
T	Torque
v	Lineal velocity
VFD	Variable Frequency Drive
ω	Angular velocity
WCO	Waste Cooking Oil
3D	Three dimensions
Δ	Increment

Units

ºC	Degree Celsius
€	Euros
A	Ampers
Hz	Hertz
kg	Kilogram
m	Meters
mm	Millimetres
min	Minutes
MMT	Million Metric Tones
rad	Radians
rev	Revolutions
rpm	Revolutions per minute
s	Seconds
V	Volts
W	Watts

1 Introduction

The proper disposal of waste oil has become a significant concern due to its potential impact on the environment. Waste oils endanger aquatic life in rivers, lakes and streams due to their high contamination rate: one litre of waste oil can contaminate one million litres of water (European Commission, 2018). In addition, waste oils can severely contaminate the soil if they leak into the ground. Therefore, a revision of the Waste Framework Directive 2008/98/EC was published in (2018), where waste oils were added as an element to be considered. This law shows the real concern of high-level governments about the recycling of waste oil.

Furthermore, when different edible vegetable oils are used to fry meals in homes, hotels, restaurants, and other catering establishments, waste cooking oil (WCO) is produced (Awogbemi, Vandi, Sunday, & Panda, 2021). Global vegetable oil consumption increased from 150 million metric tons (MMT) in 2013/14 to above 200 MMT in 2021/22, shown in Figure 1.

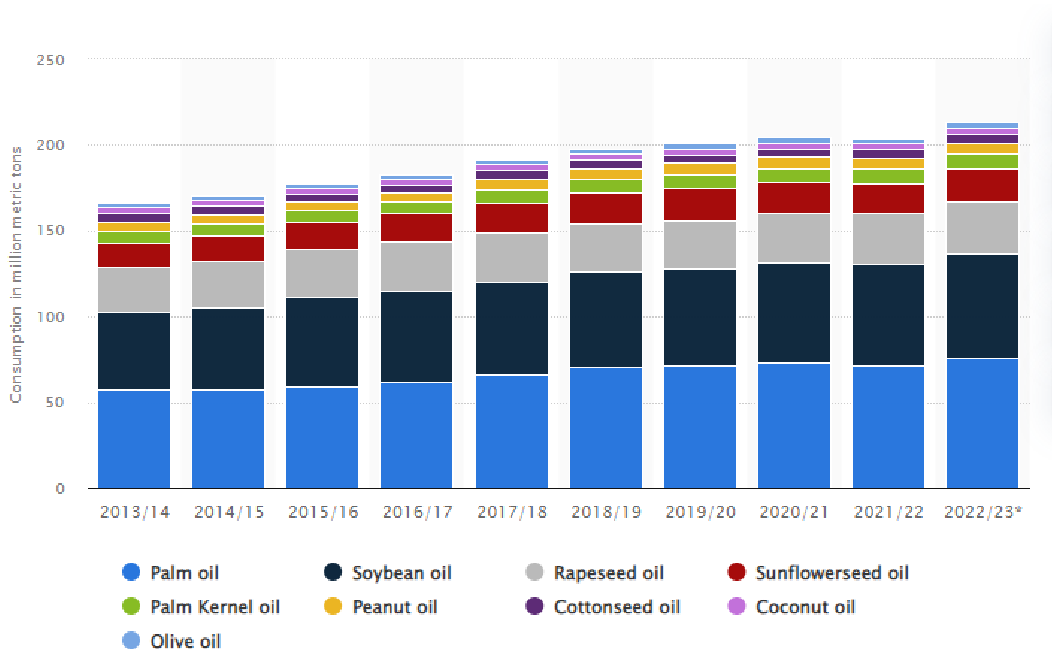

Figure 1. *Vegetable oils global consumption by oil type. Source: www.statista.com*

This statistic, published by M. Shahbandeh (2023), shows world vegetable oil consumption from 2013/14 to 2022/23. In 2022/23, a forecast of sunflower oil consumption was used for the calculation. The graph clearly shows the increase in consumption and consequently the rise in the amount of waste cooking oil generated. Due to its hazardous disposal, this project proposes a solution by utilizing separation technologies to clean it to be reused in further applications.

Many industries, including those in the food, beverage, pharmaceutical, marine, and energy sectors, as well as those that handle water and waste, depend heavily on separation technology (Alfa Laval, 2023). Various processes are used to separate liquids from each other and solids from liquids to split hazardous or beneficial components from the mixture, transforming the contents into cleaner substances, valuable by-products, and less waste to dispose of (The Engineer's Perspective, 2022)

A centrifuge is one of the devices commonly employed in the separation process due to its simple design and inexpensive construction and operation costs (Karagoz, Avci, Surmen, & Sendogan, 2013). Numerous centrifuge examples are available for purchase with a range of costs, however, with this thesis, the viability of fabrication of a centrifuge separation without the need for a large initial capital investment will be demonstrated, as the objective is to use reused material for its construction.

In addition, the reuse of common automotive materials and other metals promotes the contribution to Circular Economy (UNCTAD, 2022), a fact that gives an outstanding value over other projects. Not only reusing old material for a new application, but also allowing the waste to become usable again.

1.1 Aim and objectives

The aim of this study is to fabricate a centrifuge from reused materials to remove unwanted contaminating particles from the waste cooking oil, thus making it clean for appropriate new use.

To meet this aim, the following objectives have been developed:

- Identify the machine’s operating principle and its current applications.

- Fabricate a centrifuge that can be used for waste cooking oil cleaning using reused materials.

- Test and demonstrate the efficiency of the centrifuge constructed.

1.2 Thesis structure

This thesis begins in Section 1 with a general introduction to the subject of the thesis, the aim and the proposed objectives to be achieved.

Then the theoretical part, Section 2 , where it is found a complete review of the physical principles that must be known to talk about the separation processes; the basic principles of operation of the centrifuges; a brief description of the main types of centrifugal separators; the evaluation of the functionality of this method compared to the conventional filters; and to conclude the research part, a brief explanation of the most outstanding applications of this process.

The practical part in Section 3 describes all the components used in the machine construction, the process followed, and how it performs the job for which it was made. This section also contains the different calculations developed during the project.

Section 4 explores the intermediate step between the initial idea and the final appearance. The small modifications applied to the centrifuge are explained.

In Section 5 tests are carried out and the results obtained are displayed, which are discussed in Section 6 . Finally, the conclusions are drawn in Section 7 .

2 Theoretical background

This section explains the fundamental ideas and concepts used in this thesis. In order to design and create a centrifuge that cleans the waste oil by separating the contaminating particles from the oil itself, it is essential to have previous knowledge about the machine, its design, and its advantages and disadvantages.

Section 2.1 focuses on the physics principles which will be essential to know since they are the basis of this work. Subsequently, the operating principle is explained in Section 2.2, and different types of centrifuges are detailed in Section 2.3. Moreover, the evaluation of functionality compared with other filters that are also commonly used is described in Section 2.4. Finally, Section 2.5 presents different applications in which the centrifuge is used.

2.1 Physics principles

In physics, dynamics is a branch of mechanics that studies the causes of changes in motion. This science studies the relationship between the forces acting on objects and the effects they will produce on the motion resulting from their action (Planas, 2022). Whereas kinematics in physics is the study of the motion of a system of bodies without directly considering the forces or potential fields affecting the motion (Hussein, 2007). In other words, kinematics examines how energy and momentum are distributed among interacting bodies. Its analysis involves the determination of the position, displacement, rotation, velocity, and acceleration of a mechanism (Arosemena, 2021).

Most machines, whether working with motors or without, are related to the dynamics and kinematics of physics. As a result, learning the principles of physics is an important aspect of engineering education.

Centrifugal force and sedimentation are the most important principles related to centrifugal filters.

2.1.1 Centrifugal force

The operation of a cyclone separator is based mainly on the principles of centrifugal force. The centrifugal force is an apparent outward force on an object that is moving in a circle

(Biggs & Lucas, 2022). The sensation you get while riding a merry-go-round that makes you want to fly outwards is an example of centrifugal force. Not to be confused with centripetal force, which is a real force that counteracts the centrifugal force and prevents the object from flying out, keeping it moving instead with a uniform speed along a circular path (Nikhilesh, Gauri, & Pooja, 2022). The difference can be seen graphically in Figure 2.

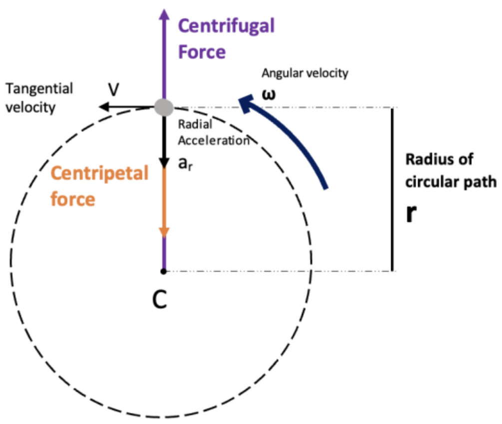

Figure 2. *Diagram of centrifugal and centripetal forces on an object. Source:* www.studysmarter.us

Figure 2 shows an object with a circular path, it is moving with counterclockwise angular velocity. The centripetal force always acts towards the centre of rotation, the force is the result of the directional acceleration acting on the body during circular motion (StudySmarter, 2023). Its result is a vector and is calculated according to the following equation:

$$\vec{F_c} = m \cdot r \cdot \omega^2 \tag{1}$$

Where the force units are newtons, mass is measured in kilograms, radius in meters, and angular velocity in radians per second.

Tangential velocity also appears in Figure 2, which explains the motion of an object along the circle's edge whose direction is always tangential to that circle (Peshin, 2022). As the object is being rotated, this tangential velocity is constantly changing its direction. The centripetal force will always act perpendicular to the tangential velocity (Rice University, 2020). This is how this force is able to continuously alter the direction of the object toward the centre.

Radial acceleration, shown in Figure 2, is dependent on the velocity of an object and direction, it is defined as the acceleration acting along the radius of an object and directed towards the centre of that object (Kare, 2022). It happens because of the centripetal force. So centripetal force is the reason for a radial acceleration (Vedantu, 2023). According to Newton's third law of motion, every action will have an equal and opposite reaction, consequently, the centrifugal force will always act in the opposite direction of the centripetal force, which is away from the centre of rotation.

2.1.2 Sedimentation

The basic principle of sedimentation is that particles of various sizes will settle at various rates in a liquid, with the larger particles settling first. This is because larger particles have more mass and therefore require more energy to move them through a liquid than smaller particles (InfinityLearn, 2022). The fluid's movement or gravity cause the particles to sink to the bottom.

In addition to particle size, density, concentration, and fluid viscosity, other less evident parameters also affect the sedimentation rate. These include convection currents in the surrounding fluid, particle shape and orientation, and chemical preparation of the feed suspension (Wakeman, 2011). For most practical operations, particles with diameters of only a few microns settle too slowly. So, if it is possible, these particles are coagulated or flocculated to increase their effective size and, as a result, speed up their rate of settling (Minnesota Rural Water Association, 2009).

2.2 Operating principle

Mechanical centrifugation is primarily used to separate components with various densities, such as crude oil, water, and solid contaminants in oily sludge (Hui, et al., 2020). This treatment is performed by using centrifugal force, following the physical principles named in the previous section the force is created while a rotor is spinning at high speed. The effect created is substantially stronger than gravity (IOW Group, 2023). Because of the force and regardless of size, anything that is heavier than the fluid will be driven out. With these tools, even little variations in specific gravity are magnified to the point that submicron particles separate very fast (Chastain, 2018).

2.3 Types of centrifuges

According to (Sproston, 2022), centrifuges can be classified depending on their main operating principle. In accordance with these criteria, there are two main types of centrifuges: sedimentation centrifuges and filtration centrifuges.

The sedimentation centrifuge type uses variations in density, also known as specific gravity, as a driving force to separate the constituent parts of the mixture (Torzewski, 2023). In fact, the centrifugal force produced by materials rotating around a fixed axis can be much stronger than gravity and affect the components differently depending on their gravities.

In filtration centrifuges, by contrast, the fluid containment unit has a separator with a perforated wall that is attached to a filter or screen. The fluid passes through the filter and exits the container when centrifugal force is applied, leaving the solids behind (Interfil, 2018). This report focuses on the first centrifuge type in order to develop its examples in more detail. Decanter, conic plate, solid bowl, tubular and multi-chamber are the most common sedimentation centrifuge.

2.3.1 Decanter

A decanter centrifuge works by applying a strong centrifugal force to the mixture of solids and liquids. The heavier sediment that accumulates on the decanter wall is pushed out by a rotating conveyor (Dolphin Centrifuge, 2023). The lighter liquid exits the decanter through the liquid outlet orifice located at the opposite end of the vessel feed. Decanter centrifuges for continuous processes can handle huge volumes of sludge-containing fluids (HuaDa, 2021). Gradual sedimentation is produced by centrifugal force, which also separates the fluid from minute particles. There is a concentric spiral above the rotating bowl which rotates more slowly than the decanter bowl, see Figure 3. Due to this speed difference, the spiral can transport the divided sludge.

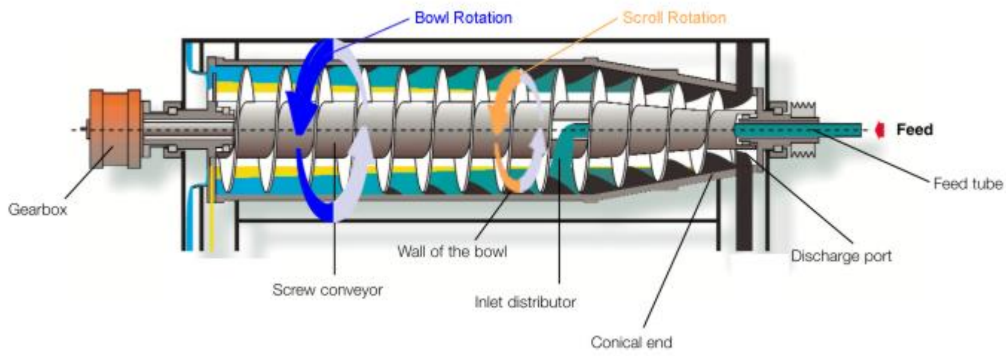

Figure 3. *Diagram of a decanter. Source: https://dolphincentrifuge.com*

As Figure 3 shows, firstly, a conveyor transports the slurry onto the intake pipe of the centrifuge. To create centrifugal forces, the bowl rotates quickly. The solid substance is rapidly separated from the liquid by high-speed spinning (Centrifuge World, 2019). After, the solid material is delivered by the conveyor upward, where it is released by a nozzle. Finally, the liquid is discharged from a different output once the solid stuff has been removed.

According to IFM (2022), decanter centrifuging generally provides more benefits than drawbacks, however, there are certain restrictions when compared to alternative methods. Some of the advantages such as its versatility allows the selection of different lengths of the tank's cylindrical section and the cone's angle, according to the desired application. In addition, the system can be pre-programmed by automation to predict the type of sludge. This property allows the machine to have several functions, such as thickening or dewatering. Another relevant advantage is the ease of installation and quick start-up and shutdown. In addition, the surface area required for operation is small compared to other competing processes. On the other hand, there are some limitations of the decanter centrifuge, it cannot separate biological solids with very small density differences, such as cells and viruses (Guilian, 2014). Another limitation is the high capital equipment costs, as hard surface and abrasion protection materials are required for the spiral to reduce wear and therefore maintenance of the spiral.

As Records & Sutherland (2001) state in their book, thanks to their versatility, the decanter can treat almost all the liquid/solid concentrations. Also, there are some examples of solid/solid separations if there is a noticeable difference in densities. They also mention that thanks to its great drying capacity, its objective can be the recovery of the solid particles present in the liquid, thus extracting them for reuse.

2.3.2 Disc stack

The conical plate centrifuge, also called disc centrifuge, disc stack separator, or disc separator, is a device that separates solids and liquids quickly by using high-speed centrifugal force (GN Separation, 2023a). This is a type of centrifuge that consists of a series of stacked conical plates, generating centrifuge spaces distributed in parallel between the discs (Huading, 2020), see Figure 4. Disc centrifuges are used in the majority of industrial operations because they can handle a range of raw materials, run constantly, and are highly adjustable (Jagschies, Lindskog, Łącki, & Galliher, 2017). The main difference compared to other centrifuges is the large surface area for fine solids to settle due to the stacked discs (Crown-machinery, 2023).

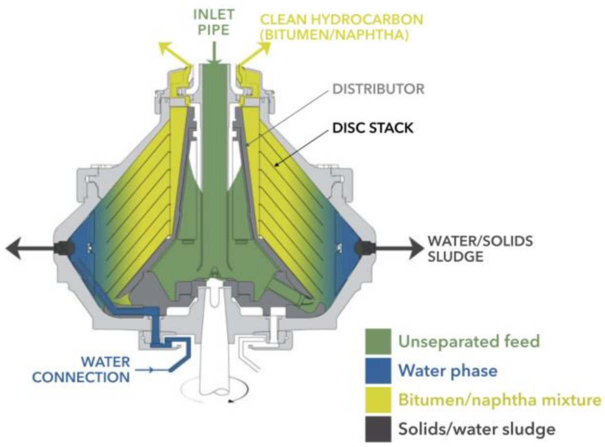

Figure 4. *Diagram of a disc stack centrifuge. Source: https://www.oilsandsmagazine.com*

Following the previous scheme, the feed enters the centrifuge from the top and rotates inside the machine at high speed, according to Oil Sands (2021) these normally exceed 3500 rpm. Water and solids are pushed toward the outer edge of the disc stack by the strong centrifugal forces. The combination of bitumen and naphtha, which is lighter, remains in the centre and is ejected from the upper section of the centrifuge.

The disc-stack centrifuge has several benefits, but as Prabhu (2020) mentioned, it also has some significant drawbacks. For example, there is a predetermined distance between each disc in the stack of conical discs, usually between 500 and 1500 microns. These values determine the particle size that the centrifuge can handle. The gap between discs does not allow larger particles to pass through the discs and become trapped, potentially causing the centrifuge to break. Among other drawbacks, along with other types of centrifuges, the amount of solid material can be a problem, as this type of machine has a maximum capacity.

On the other hand, the production capacity of the separator increases considerably with the insertion of the disc in the drum (ZK Separation, 2023). The purpose of the disc is to increase the settling area of the drum and to reduce the distance the solid particles have to travel to settle. For this reason, materials that cannot be successfully separated by decanter centrifuges or others often require the use of disc centrifuges. However, together with the decanter, the disc stack separator makes up the majority of centrifuges on the market (Sutherland, 2009). As long as cost is not an issue, the use of this machine is important in many processing applications.

2.3.3 Bowl

The bowl centrifuge together with the tubular centrifuge, explained in the following Section 2.3.4, has the simplest design. It could be said that it consists of a disc stack centrifuge without the plates. Because it is the simplest, it is the one that most people make with recycled materials in their homes, and many examples in the networks can be found.

Once the feed sludge is fed into the rotating bowl and the whole unit is accelerated, the solid-walled bowl centrifuge separates the liquid/solid mixture using centrifugal force. This drags the solid particles, mostly contaminants, in the radial direction away from the liquid (Centrifuge World, 2019). Therefore, the liquid in the centre of the bowl and the unwanted solid particles in the inner part of the bowl are accumulated, see Figure 5. When the bowl can no longer hold any more solids, it must be emptied to ensure proper operation. This part of the process can be carried out manually or semi-automatically depending on the design of the machine.

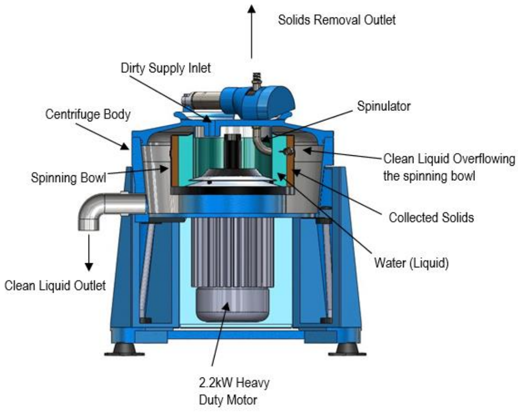

Figure 5. *Diagram of a bowl centrifuge. Source: https://interfil.com.au/*

Analysing Figure 5, the path taken by the mixture can be seen. The motor makes the spinning bowl to rotate at high speeds generating a high centrifugal force. As a consequence, the solid particles remain in the wall, followed by a water/liquid emulsion layer and then the liquid, which is gradually cleaned in the vessel's centre (Chastain, 2018). The cleaned liquid will leak out of the centrifuge and over the top edge of the tank.

One of the most significant benefits is a very high solid-liquid separation efficiency of up to 5 microns (Aquarius, 2018). Also, particle removal is easy and maintenance is quick due to the simple shape-avoiding plates and, in some occasions, the bowl is detachable making even more comfortable (Flottweg, 2023a). The simplicity makes the machine more affordable. However, there are some limitations such as a maximum in the water percentage (Chastain, 2021), above 5% is not recommendable to be processed in this type of centrifuge.

2.3.4 Tubular

With the same working principle as the other centrifugal separators, see Figure 6, the tubular bowl separator, also known as high-speed tubular centrifuge, aims to separate materials with different specific gravity by subjecting them to centrifugal force. This is achieved by spinning at high speed. GN Separations (2023b) defines it as a fine separation apparatus appropriate for liquid-liquid or solid-liquid-solid separation of suspensions with fine concentration, minute particles and small differences in density. These devices are widely used in the chemical industry, in biopharmaceutics for the removal of bacteria from liquids and clarifying, in blood processing, and food and beverage industry (brs biotech, 2022).

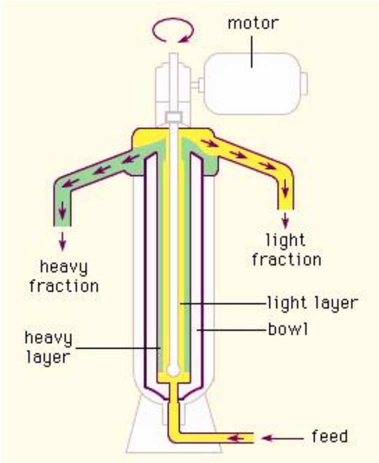

Figure 6. *Diagram of a high-speed tubular centrifuge. Source: www.huading-separator.com*

As Figure 6 shows, a frame, a drive device, a vessel, and a motor are the parts that make up the tubular centrifuge. The process involves the generation of a high centrifugal force which causes the high-density liquid to flow toward the wall of the tube, while the lower-density liquid moves into the centre of the tube (Huading, 2023). The separated liquids are finally discharged at the top of the tube via specific outlets.

The tubular bowl centrifuges are characterised by the fact that they are capable of providing the highest centrifugal forces. Therefore, they are the type of centrifuges that achieve the most manageable throughputs. On the other hand, it can be determined that the operating costs of high-speed centrifuges are higher. However, in particular for the separation of nanoscale materials, the value of the final product usually justifies their use (Egmont, Steiwand, & Nirschl, 2010). For this reason, there is interest in improving the current processes and designs available on the market, as experts consider that there is great potential to improve the current procedures and design tubular centrifuges.

Another disadvantage appears in cases where the machine is used to separate solid particles from a liquid solution (Woon-Fong, 2007). This is because it is periodically necessary to stop the machine in order to remove the particles that remain in the liquid solution with a plunger or a blade, and this makes the process semi-continuous.

2.3.5 Multi chamber

The multi-chamber centrifugation is the combination of a tubular centrifuge arranged in a coaxial form (Haan, 2015), causing the material to be processed in series through each of the chambers one after the other, see Figure 7. The material enters through the smallest tube of the rotor, the central tube, and, as mentioned before, travels in a circuit through the cylinders, which increase in diameter. The denser solids or liquids are trapped on the walls of each chamber (Berk, 2009). The heavier particles will be deposited in the tube with the smallest diameter because the centrifugal force increases as the diameter increases.

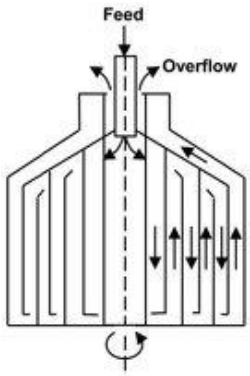

Figure 7. *Diagram of a multi-chamber centrifuge. Source: schoolbag.info*

As the experts have gathered (Lenntech, 2023) and as shown in Figure 7, the material enters the rotor through the upper part of the innermost cylinder. With a marked path, it travels through each of the chambers. Normally, centrifuges consist of more than 6 different bowls connected (Catalano, et al., 2022). The outer wall of each chamber retains the densest particles and the purified liquid spills out of the chamber with the largest diameter.

Some of the advantages of the multi-chamber centrifuge over the tubular vessel are a higher solids capacity (Kiefer, 2022). It is also known that the efficiency of these machines is higher for several reasons, such as the short distance the material has to travel to reach the collecting wall or the longer period the liquid resides in the unit (Najjar & Abu-Shamleh, 2020). On the other hand, there are also drawbacks, for example, the cleaning time, as the greater number of chambers means that the time it takes to remove all the sediment is longer.

According to Chempedia (2019), in addition to the most usual separation application of cutting oils from grinding swarf, multi-chamber centrifuges are primarily employed for the clarity of beers, wines, fruit juices, and varnishes.

A unique feature of this centrifuge is that it separates the collected particles according to their density. This is due to the principle, mentioned above, that the denser particles are trapped on the first wall while the smaller particles are trapped in the larger diameter bowls (Catalano, et al., 2022). For this reason, when cleaning the centrifuge, it is possible to see the collected particles sorted according to their specific gravity.

2.4 Evaluation of functionality compared with other filters

A filter's effectiveness can be assessed by comparing it with other filters that are available for the same purpose. Such comparisons can help identify the advantages and disadvantages of various filters, which are discussed in this section.

2.4.1 Advantages

There are some significant advantages of a centrifugal oil cleaner versus a barrier media filter.

First, a centrifuge's cleaning effectiveness is constant over the course of the service interval (SeparatorEquipment, 2022), i.e. the separated particles collect in a separate sludge space in centrifugal filters without causing any impediment to the fluid flow, whereas the solid particles collecting on the surface of filter media block the passage of fluids over time (Prabhu, 2021b). This accumulation of sediment reduces the flow rate through the filter.

Second, the smallest particle size that can be extracted by a centrifuge is at the point where the centrifugal force that the particle experiences is equal to the viscous drag forces between the fluid and the particle. In a hydraulic fluid power application, this lower limit is much below one micron (Clayton, 2008). Whereas the smallest particles that can be separated by a conventional filter depend on the size of the pores in the filter media (Prabhu, 2021b). That implies that all particles smaller than the pore size of the filter material flow through the filter without being separated.

Another advantage is water and solids removal. A centrifugal filter uses the principle of differential settling to remove both water and solids from the oil. This water separation occurs concurrently with solids removal (Wills & Finch, 2016). On the contrary, the water is not separated by conventional filters, so it passes through the filter and the oil (Filtersafe, 2021).

Low operating cost is another advantage of centrifugal filters, because, in contrast to conventional filters, they separate the liquid from solids by using centrifugal force (IOW Group, 2022). As a result, these filters do not require any filter material or labour replacement, which results in significant cost savings over the course of the filters' operational life.

2.4.2 Disadvantages

Centrifugal filters, like other industrial machinery, have some drawbacks, some of which are given below.

First, industrial centrifuge machines like centrifugal filters require preliminary capital investment (Aw, Gin, Goh, & Te, 2012). Whereas conventional filters do not require an initial investment and are reasonably priced (Prabhu, 2021b).

Subsequently, the periodic changing of the filter media is the only maintenance required for conventional filters. However, a centrifugal filter is a mechanical device that needs routine maintenance (Cannon, 2019), as advised by the manufacturer.

Regarding the maintenance and day-to-day operation of a centrifugal filter, it is necessary a mechanically skilled technician for overseeing the operation (Megadepot, 2020), even though most of centrifugal filters work automatically. On the other hand, operator competence is not required to maintain or service filters. The routine replacement of filter media is a straightforward procedure.

Another drawback is the utilities required. A centrifugal filter typically requires electric power, water, and compressed air (Prabhu, 2021b). In contrast, none of these services are necessary for a typical filter to work.

Although centrifugal filters are capable of filtering smaller particles than conventional filters (D'Antonio, 2017), down to 0.5 microns, as explained in a previous advantage, the actual separation depends on certain operating factors such as flow rate, fluid temperature, particle size, and density (Varzakas, 2014), and can therefore be understood as a disadvantage compared to conventional filters. In these filters, particles larger than the pore size will not pass through the filter (Martínez, 2022), ensuring absolute separation. In short, centrifuges can achieve a higher separation rate, but it is a more delicate and dependent process. In other words, it must be ensured that the process is carried out under the required conditions.

This last disadvantage is not compared to conventional filters or any other filtration method as they cannot achieve this either. For cleaning lubrication oil that has been used in a combustion engine, while the centrifuge will remove all heavier oil particles, it cannot undo changes made to the oil at a molecular level (Dolphin Centrifuge, 2022). For instance, the black colour of used engine oil is not only due to carbon deposits like soot (Baker, 2022), which will be removed, but also to a change in the oil's molecular structure brought on by the combustion of hydrocarbons within it, which results in the production of black liquids like asphaltene (Oilybits, 2020). This coloration cannot be removed by using a centrifuge or any other method of filtration.

2.5 Applications of the centrifuges

Maintenance-conscious managers apply centrifuges to engines, pumps, generator sets and a variety of industrial applications to clean oils and glycols, as well as hydraulic, wash and cutting fluids to improve equipment life and profitability (Clayton, 2008).

But the centrifugal filter is not only used in mechanical fields, there are also numerous instances in which centrifugal filters are used instead of conventional ones because of the limitations of the former (Prabhu, 2021b). The following are some examples of centrifugal filter applications in different sectors.

2.5.1 Food and beverage industry

There are different cases in the food and beverage industry where the techniques of various types of centrifuges can be applied.

Milk fat is taken out of the milk and then controlled back into the milk as part of the standardizing procedure (Rehman, Farkye, Considine, Schaffner, & Drake, 2003). The principal methods used in the dairy industry to separate milk fat from milk are centrifugal filters in disc-stack separators (Fruitprocessingmachine, 2021).

Fruit pulp and juice are both present in freshly smashed fruit, such as apples, oranges, and the like (Centrimax, 2023). The best way to separate this pulp from the juice is with a decanter or disc centrifugal filter.

Food flavouring, used to flavour commercially baked or prepared foods, is essentially an extract from flood items. The main technique for extracting food taste involves using a solvent to absorb the flavour from the food ingredient (Cravotto, et al., 2022). The best device for extracting this solvent from food biomass is a centrifugal filter as a disc separator (Prabhu, 2021a).

Hops are added throughout the brewing process to provide the beer taste (Beer brewing, 2023). To produce clear beer, centrifugal disc-type filters use nearly centrifugal force to separate minute organic particles (Alfa Laval, 2022a).

To clarify wine from the grape residue, disc stack centrifugal filters are the best option (Trucent, 2022a). A self-cleaning type centrifugal filter produces clear wine continuously.

2.5.2 Maritime industry

Mineral oil filtration has traditionally been done in the maritime industry using oil centrifuge filters (SeparatorEquipment, 2021). Centrifugal oil separators are the most effective method of removing impurities (Alfa Laval, 2022b). The soot particles are collected on a paper insert inside the bowl. The only consumable component is the paper, which is simple to remove after cleaning (IOW Group, 2021). It is more affordable to use a centrifugal filter because it is not necessary to buy pricey new filters.

Huge amounts of lubricating oil are used by seagoing vessels, and the cleanliness of this oil is essential for the proper operation of these reciprocating engines (Wankhede, 2021). Many businesses are examining their lubrication systems to generate maintenance-based savings and lower oil usage (Bannister, 2019) in an era when there is greater demand than ever to be more effective, dependable, productive, environmentally friendly, and resource-conserving. The best way to achieve this is with a centrifugal oil separator.

2.5.3 Pharmaceutical

The main separators used to extract cultivated cell cultures from broth or culture media are centrifugal filters (Doran, 2013), in particular, high separation efficiency disc-type centrifugal filters. Also, are used as the primary method of separation in a wide range of pharmaceutical ingredient production procedures (Prabhu, 2021b).

2.5.4 Oil and gas

In relation to oil and gas, the use of centrifuges is also necessary. The following are real examples where they are used.

In the oil and gas business, the refinery's waste streams pose a serious environmental problem (Palos, et al., 2021). The decanter and disc-type centrifugal separators are the main tools for separation (C&B Equipment, 2021). These separation techniques remove crude oil from other pollutants like water, sludge, and other contaminants (Cambiella, Benito, Pazos, & Prados, 2006).

Crude oil is produced by drilling oil wells with specialized abrasive fluids (Britannica, 2023). Decanter centrifuges are used to recycle these fluids.

Produced water is water that comes out of the well with crude oil during crude oil production (Water Environment Federation, 2018). Also, the centrifugal filter separates traces of oil present in large quantities of produced water.

2.5.5 Environmental

Waste water is an example; sludge is present in municipal or industrial wastewater, and its removal is crucial for water reuse (Wisniowska, Grobelak, Kokot, & Kacprzak, 2019). This function is carried out by centrifugal filters as the main method of wastewater separation for huge amounts of waste (NetSol Water, 2022).

Waste oil can be another example; waste oil or used oil is commonly referred to as oil that has been used and contains pollutants like sludge and water (Petro Industry, 2015). Clean waste oil has commercial value as heating fuel and as feedstock for biofuels (Prabhu, 2021b). Three-phase centrifugal filters (disc stack centrifuges) effectively separate water and fine sediment from used oil in a continuous process to create saleable oil.

2.5.6 Fuels

Diesel, fuel oil, and aviation fuel (kerosene) are examples of fuels with which centrifugal filters are used.

Diesel fuel is the main source of fuel for the transportation and power cogeneration sectors. Its pollution from storage is a frequent issue (Bell Performance, 2022). In order to maintain diesel fuel pure for use in engines, a centrifugal separator splits the water and sludge in storage tanks.

As fuel oil is a considerably less expensive source of energy, it is frequently used in the bulk transport sector (HFO Free Arctic, 2017). Fuel oil becomes contaminated by water and sludge, much like any other liquid fuel that is kept in storage, rendering it useless for engines (Moore, 2021). A centrifugal filter is the only durable and dependable device for continuous fuel oil separation on ships and in power plants.

Aviation fuel, often known as kerosene, is another fuel that is susceptible to contamination (Chevron Products Company, 2007). Again, the main impurities in this fuel are water and sediment (U.S. Department of Commerce, 2019). Centrifugal filters are frequently used to remove these pollutants from water.

2.5.7 Biofuels

Algae harvesting, biodiesel, and ethanol are examples of biofuels with which centrifugal filters are also used.

Algae is the new source of oil for making biodiesel (Demirbas & Fatih Demirbas, 2011). It is also widely used as a food additive (Bogacz-Radomska & Harasym, 2017). In any case, the process starts with the harvesting of algae cells (Wen, Liu, & Chen, 2011), and the best way to collect it continuously is to use the high g-force of a centrifugal filter.

Vegetable oil is divided into biodiesel and glycerine using a chemical process used in the commercial manufacturing of biodiesel (U.S. Department of Energy, 2023). For smaller volumes, gravity separation is effective for recovering biodiesel (Dunford, 2016). But for biodiesel production on a commercial scale, the centrifugal filter is very effective in producing clean biodiesel (Flottweg, 2023b) that complies with ASTM (American Society for Testing and Materials) fuel specifications.

Ethanol made from corn is the required fuel ingredient to create E-85 grade gasoline (Hearst Autos Research, 2020). During the industrial synthesis of ethanol from corn, the corn biomass must be separated from the ethanol by using centrifugal filters (Liu, 2022) such as decanter centrifuges.

3 Fabrication

The initial proposal for the development and design of the waste oil centrifuge from reused components was found on the internet. By analysing and comparing various examples the principal concepts of the project were taken from Figure 8.

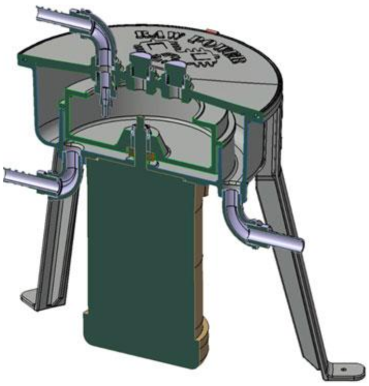

Figure 8. *Schema centrifuge with a vertical section. Source:* www.utahbiodieselsupply.com

The main parts of the centrifuge were taken from the diagram, previous Figure 8: the motor, the tank, the collector, the structure to hold it, and the inlet and outlet pipes. The following section specifies the process followed for the manufacture of the centrifuge. First, the selection and procurement of the components is explained in Section 3.1, subsequently, the assembly process is detailed in Section 3.2, followed by a brief explanation of the coating in Section 3.3, and finally, the start-up is explained in Section 3.4.

See Appendix 1 to learn about welding and lathe processes carried out, which were most commonly used during modifications to components and during assembly.

3.1 Components

Following the inspiration of Figure 8 the authors developed, with a 3D Modelling Software called Creo Parametric (www.ptc.com), a model of the centrifuge. The software enables to create, analyse, visualise, and share designs using 2D CAD, 3D CAD, as well as parametric and direct modelling capabilities. In Figure 9 it can be seen the machine to be built with the most important parts identified.

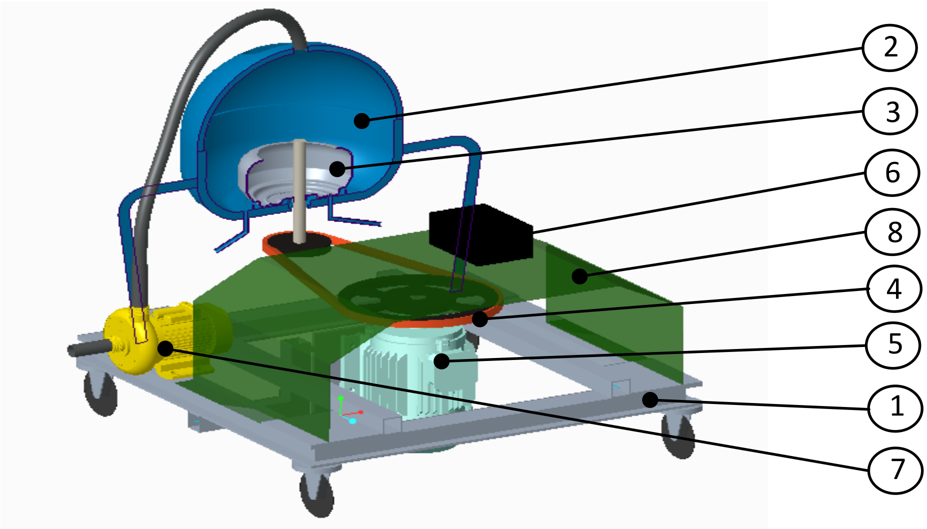

Figure 9. *3D model of the centrifuge with the principals' parts: (1) Structure. (2) Collector. (3) Spinning bowl. (4) Transmission. (5) Motor. (6) Frequency converter. (7) Pump and pipes. (8) Motor cover. Source: author's own.*

The following sub-sections explain how each component seen in previous Figure 9 was obtained and the processes that were carried out in each one to achieve a correct final result.

3.1.1 Structure

The purpose of the structure is to support all the weight of the machine and to house the different elements. For this reason, it must be strong and stable.

A square-shaped structure was made by welding 5 mm thick C-section steel bars. After this first step, 5 mm thick square steel plates were welded at the four corners. Afterwards, two 5 mm thick square section bars were welded transversally to give it more stability. Finally, an L-shaped tube with a square cross-section, where the hinges were welded to support the motor at a later stage, was welded to the structure. All these parts are identified in Figure 10 for a better understanding.

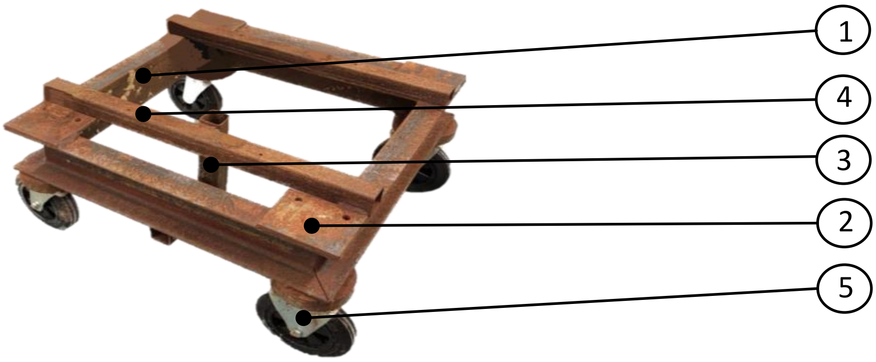

Figure 10. *Structure built. Parts: (1) C-section steel bars. (2) Square steel plates. (3) Transversal square section bars. (4) L-shaped tube. (5) Wheels. Source: author's own.*

In this case, the structure did not have a specific final location, so the idea was to build a mobile machine to be able to move it around freely. This required movement was achieved by adding four wheels underneath the structure, as shown in previous Figure 10.

3.1.2 Collector

The collector part is a recipient that is intended to collect the clean oil that escapes from the centrifuge. An old broken compressor was reused and adapted for this purpose. It is made of metal and had two chambers separated by a small metal wall, see Figure 11. The outer chamber is for oil that is already cleaned, and the inner chamber is for the liquids, either water or oil, that remain in the bowl when the machine stops running. There is an outlet pipe for each chamber through which the liquids mentioned are discharged, these pipes were welded under the collector.

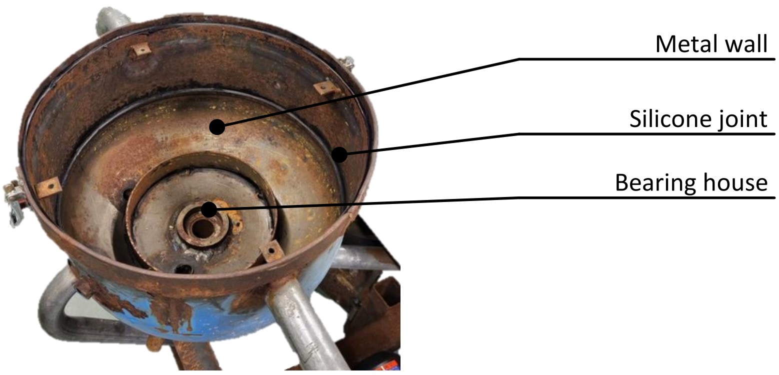

Figure 11. *Inside of the collector. Source: author's own.*

Figure 11 shows the inside of the collector, where can be seen different elements. Firstly, as previously mentioned, the wall that separates the two chambers and the holes through which the liquid exits. Another important part is the welded part in the centre where the shaft will be housed with a bearing that allows it to rotate freely. Finally, the black silicone that was necessary to put on the open joints to prevent leaks and the oil from escaping.

The collector has a cover, see Figure 12, to prevent the oil from leaking out when the centrifuge is running. It was also remodelled from a part of the compressor used for the collector.

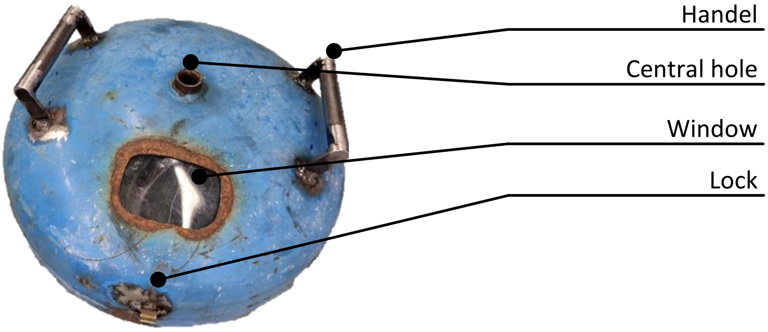

Figure 12. *Outside of the cover. Source: author's own.*

The hole in the middle of the cover, which already existed in the compressor, was used as the oil entry to the bowl, see Figure 12. On the mentioned image, two handles can also be identified, to be able to take it off and put it on freely, and two locks, to give more security while the machine is running. Figure 13 shows one of the locks in more detail. The handles and the locks were welded in the metal workshop using the process MIG, as although it is not as effective on thicker metals as other welding processes, it is better for joining thinner metals with a good finish and less risk of burns (TwiGlobal, 2023).

Figure 13. *Locks of the collector with its cover. Source: author's own.*

In previous Figure 13, it can be seen the welding work carried out to join two elements, the main body of the collector and its cover, by using a lock. In this way, it was ensured that the cover was fixed and immobile during the operation of the centrifuge.

In addition, in the centre of the cover from the inside, a tube that had been previously bent as needed was welded as it is shown in the following Figure 14. Its purpose is to let the oil enters the bowl coming from the pump via the central hole.

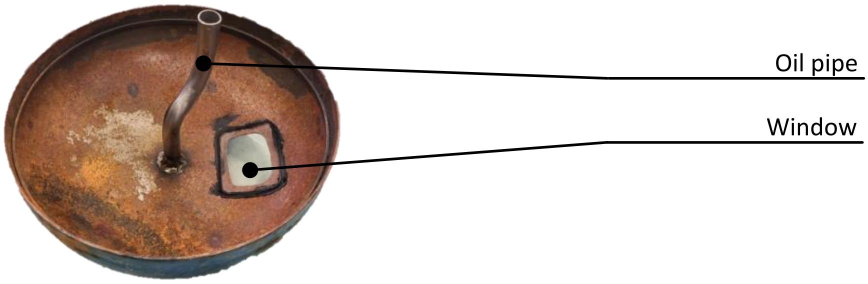

Figure 14. *Inside of the cover. Source: author's own.*

The shape of the pipe was made as in Figure 14 to guide the oil into the bowl avoiding the contact of it with the shaft. The no contact between the oil pipe and the shaft supports was considered, see Figure 33 in Section 3.2. The cover had a part without material in which a piece of hard, transparent plastic, was placed with silicone as if it were a window, see Figure 14, in order to be able to see through it the bowl in operation.

3.1.3 Spinning bowl

The spinning bowl is the piece where the centrifugal force is used to separate the contaminating particles from the waste oil (Trucent, 2022b). The high bowl speed accelerates the mixed liquid, creating increased g-forces.

A turbine from a car's automatic gearbox, which causes the transmission to spin, was reused to produce this item. The desired form was obtained by cutting the upper part with a radial saw, see Figure 15.

(a) (b)

Figure 15. *Spinning bowl. (a) Where the waste oil enters. (b) Turned upside down. Source: author's own.*

Figure 15 shows the cut made at the top of the turbine and the welding done to achieve the rounded shape. This shape of the bowl is essential to achieve the correct rotation.

The principal dimensions of the bowl are its diameter of 290 millimetres, its height of 150 millimetres and its weight of 4.62 kilograms. Initially, the bowl had a weight of almost 6 kilograms, but to make it more suitable for the requirements of the centrifuge, a lathing operation was carried out on it, as shown in the following Figure 16.

Figure 16. *Bowl after applying the lathe operation. Source: author's own.*

This operation reduced almost 1.5 kilograms the bowl weight and therefore its inertia, consequently, the force that the motor had to generate to achieve high rotational speeds was also decreased. In this case, the reduction of the material was not a disadvantage, as the final thickness was sufficient to perform its function.

To fix the bowl to the shaft, four holes were drilled in the bowl to be bolted to the piece in the middle of the shaft. In addition, another four holes were also drilled in the bottom of the bowl to drain the water or oil that remains in the bowl when the engine stops running.

3.1.4 Transmission

The transmission of the torque produced by the electric motor to the shaft which rotates simultaneously with the spinning bowl was carried out by two belt pulleys and a V-belt. These components were purchased new for this particular use.

A belt is used in centrifuge transmission due to its flexibility in transmitting power between shafts over relatively long distances (Abasolo, Navalpotro, Iriondo, & Corral, 2023). The belt drive establishes a transmission ratio between the two connected shafts (Sild, 2022). The belts are mounted on pulleys of diameter d (smaller diameter) and D (larger diameter), whose rotational speeds are respectively ω_d and ω_D. Assuming that the power is transmitted integrally from one shaft to the other, the transmission ratio (i) is calculated as follows:

$$P_d = P_D \rightarrow T_d \cdot \omega_d = T_D \cdot \omega_D \rightarrow \; i = \frac{\omega_d}{\omega_D} = \frac{T_D}{T_d} \tag{2}$$

Where T_d and T_D are the torques on the shafts with the smaller and larger pulleys, respectively. Where v is the linear (forward) belt speed, the transmission ratio can also be defined as:

$$v = \omega_d \cdot \frac{d}{2} = \omega_D \cdot \frac{D}{2} \rightarrow i = \frac{\omega_d}{\omega_D} = \frac{D}{d} \tag{3}$$

- **Pulley fixed to the motor:**

The pulley attached to the motor's shaft is the pulley with the largest diameter. The torque produced by the motor and the angular velocity at which it rotates are the same as those of the pulley. It is shown in Figure 17.

Figure 17. *Pulley to be fixed to the motor. Source: author's own.*

The nomenclature of the pulley fixed to the motor shown in Figure 17 is SPA 280/1 TB 2012, the most important value is the nominal diameter of 280 millimetres. For more characteristics and information see Appendix 2.

- **Pulley fixed to the output shaft**

The pulley fixed to the output shaft (driven shaft) is the smaller diameter pulley. Therefore, there is a multiplier system, since the transmission ratio is greater than 1, i.e. a higher angular velocity is obtained on the output shaft than on the motor shaft. This pulley is shown in the following Figure 18.

Figure 18. *Pulley to be fixed to the output shaft. Source: author's own.*

The nomenclature of the pulley fixed to the output shaft shown in Figure 18 is SPA 67/1 TB 1108. Its diameter is 67 millimetres and, as mentioned before, is the main value to consider. More information about this pulley can be found in Appendix 3.

The ratio transmission compares the two pulleys' diameters, in order to make this element visual in Figure 19 the two pulleys were placed side by side to see the difference in real size.

Figure 19. *Difference in sizes (diameters) of the pulleys. Source: author's own.*

The difference in the diameters of the pulleys is clearly shown in previous Figure 19. And considering the big diameter (D) equal to 280 mm and the small one (d) equal to 67 mm and following Equation (3), the ratio transmission can be calculated numerically.

$$i = \frac{D}{d} = \frac{280\ mm}{67\ mm} = 4.18$$

The ratio transmission value obtained was 4.18, meaning that the bowl spins four times faster than the motor speed.

- **V-belt:**

V-belts allow higher torques compared to other belt types and a higher linear belt speed, which can reach up to 30 m/s without any problems. V-belts work optimally at linear speeds in the range of 20-22 m/s. These belts should not operate at speeds above 30 m/s, as the high centrifugal force generated would eventually pull the belt out of the pulley groove. On the other hand, if they were to operate at lower speeds, they would also require a static balancing process to achieve optimum performance.

To ensure that the linear speed limit of the belt is not exceeded, the revolutions at which the motor will rotate at the moment when this speed is reached shall be calculated. The motor and the large pulley roll simultaneously and together with them the belt, so it can be calculated the rotational speed as the linear speed divided by the pulley radius (Hall, 2021). Therefore, the equation is as follows. Knowing that the angular velocity unit is radians per second and its symbol ω, the linear speed unit is meters per second and it is identified by a v, and the radius of rotation (r) in meters:

$$v = \omega \cdot r \tag{4}$$

The angular velocity at which the engine can operate due to the belt tracking in safety speed is calculated as follows. Considering the radius equal to 0.14 meters, half the diameter of the big pulley (D), and the limit linear speed of 30 meters per second the operation is:

$$\omega = \frac{v}{r} = \frac{30}{0.14} = 228{,}57\ s^{-1}$$

By applying the conversion factor $2\pi/60$ radials per second is equal to 1 revolution per minute:

$$\frac{228{,}57\ rad}{1\ s} \cdot \frac{60\ s}{1\ min} \cdot \frac{1\ rev}{2\pi\ rad} = 2045.28\ rpm$$

The maximum speed of the engine had to be below 2046.28 revolutions per minute.

In this case, the belt has the designation AVX13X1325, i.e. a timing V-belt of section A, shown in Figure 20. These belts work on the basis of the contact established between the sidewalls of the belt and the pulley channel walls. See Appendix 4 for further explanation of V-belts and their cross-sections.

Figure 20. *Timing V-belt used. Source: author's own.*

Timing V-belts have notches on the underside, as Figure 20 shows, allowing them to have a smaller bending radius.

The material of this belt is EPDM (ethylene propylene diene monomer rubber). This material is extremely durable and flexible (Chauhan, 2019). In simple terms, pure rubber becomes brittle with temperature variable, wherein synthetic rubber (EPDM) remain flexible and withstand temperature variations for decades.

- **Bearings:**

Three bearings were purchased, shown in Figure 21, which are used to hold the shaft in a vertical position with the collector and to avoid friction between the metal parts and the shaft when rotating. To ensure the stability of the shaft two bearings would be enough, however, the third one gives an extra support to make it steadier and smoother.

Figure 21. *Bearing. Source: www.witmermotorservice.com*

Figure 21 shows one of the bearings used. The three bearings used are identical and have the same dimensions.

- **Output shaft:**

A plunger of a hydraulic cylinder was bought to perform as the vertical shaft, see Figure 21. It aims to transfer the angular velocity from the small wheel to the bowl. In order to achieve the correct operation, some modifications were made to this component.

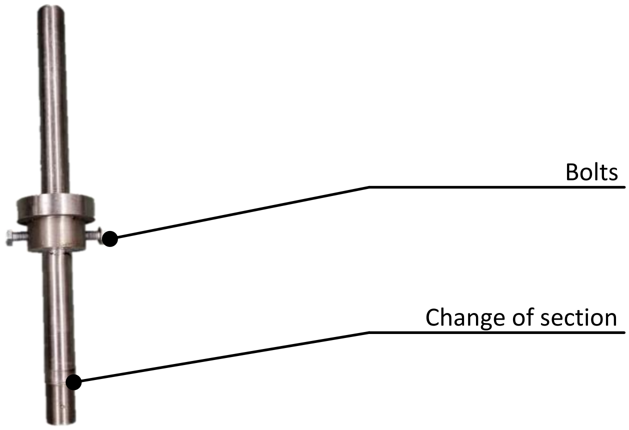

Figure 22. *Output shaft. Source: author's own.*

Firstly, the steel piece in the middle was placed with two bolts on each side to fix it, as shown in Figure 22. The bowl is bolted to this piece and rotates simultaneously with the shaft. A change of section can be distinguished on the lower part of the shaft, which is intended to hold the bearing in position. Moreover, a groove was made there to fit the key which ensures the synchronisation of the shaft with the small pulley. The length of the shaft also had to be shortened as it was too long and could appear interferences with other elements.

Finally, an idea had to be implemented to prevent the third bearing added at the top of the shaft from shifting downwards due to its weight, and also to ensure that it was always placed in exactly the right position. The solution is shown in the following Figure 23.

Figure 23. *Ring placed on the shaft. Source: author's own.*

A groove was made with the lathe in order to place an open ring, see Figure 23, and use it as a bottom support. This is solving the problem presented with the third bearing.

To summarize the transmission process, the largest pulley is attached to the motor and, through the V-belt, transfers the angular velocity multiplied by 4.18 to the small pulley, which is attached to the output shaft, to which the bowl is fixed with bolts.

3.1.5 Motor

The electric motor is a device that converts electrical energy to mechanical energy, usually by employing electromagnetic phenomena, which shows that a force is applied when an electric current is present in a magnetic field (Slemon, 2023). This force produces a torque on a loop of wire in the magnetic field, which causes the motor to rotate and perform useful work (Energy Education, 2018).

In this case, the torque gives the force necessary (Dodge, 2020) to rotate the spinning bowl at the angular velocity required to achieve the project goal. The electric motor used in this project was reused from previous applications. It was manufactured by the company Stromberg belonging to the ABB group. It is a 4.1 kW KMER 100 Lx4 model, see Figure 24.

Figure 24. *Motor. Source: author's own.*

Since it is an old electric motor and the specifications plate is damaged, not all the characteristics could be completely ensured, for further information about it see Appendix 5. However, some calculations were done to ensure the required power to make the bowl rotation.

In engineering, power plays a very important role, and in rotational motion, as with linear motion, if the force or momentum applied is constant, it can be easily calculated

(BCcampus, 2016). The torque (T) multiplier of the angular velocity (ω) is what determines how much power (P) is used in a system rotating around a fixed shaft.

$$P = T \cdot \omega \tag{5}$$

Only one torque shall be considered in this machine, the one that the bowl generates as resistance to the rotational movement. And although the moment of inertia is not constant, due to the oil flow, it will be considered as such. This assumption is made on the basis that the mass of the oil that varies compared to the mass of the bowl in motion represents a small part of the total. The torque needed to rotate a solid or a group of elements with respect to a fixed shaft can be calculated by developing Newton's second law (Roberto, 2022), the force is equal to the mass times the acceleration.

$$\mathrm{T} = I \cdot \alpha \tag{6}$$

Where the α represents the angular acceleration, which was supposed to achieve 6000 rpm in 10 seconds. And the I represents the inertia moment with respect to the rotation axis. To obtain this value the 3D solid model of the bowl was extracted from the initial sketch done with Creo Parametric. The program is capable to calculate the moment of inertia in the origin, determined by the user, or the centre of mass (PTC Help Center, 2023).

Bearing in mind that this is an indicative calculation as some data of the bowl, such as density and its exact geometry, could not be obtained. The value obtained in the software for the inertia in the gravity centre was around 6e+04 square millimetre kilogram.

The angular acceleration calculation is a differential value that can be simplified by taking an average result (Requena, 2014). The formula says that the angular acceleration is equal to the variation of the velocity in radians per second, between the start and the end, divided by the time elapsed:

$$\alpha = \frac{\Delta\omega}{t} \tag{7}$$

A positive sign means that the object is accelerating, while a negative sign means that the object is slowing down. The calculation assumed a time of 10 seconds to reach 6000 rpm.

$$\frac{6000\,rev}{min} \cdot \frac{1min}{60\,s} \cdot \frac{2\pi\,rad}{1\,rev} = 628.32\,s^{-1}$$

$$\alpha = \frac{628.32}{10} = 62.83\,s^{-2}$$

By following Equations (5) and (6), the power requirement of the bowl in watts can be obtained. The units of inertia must be square metres multiplied by kilogram and the rotational speed of the bowl is 6000 rpm in radians divided per second.

$$I = 6 \times 10^4\,mm^2kg = 0.06\,m^2kg$$

$$P = \mathrm{T} \cdot \omega = I \cdot \alpha \cdot \omega = 0.06 \cdot 62.83 \cdot 628.32 = 2368.64\,W$$

Assuming an ideal situation, the power produced by the motor (P_{in}) is equal to the one consumed (P_{out}) (Energy Education, 2019). However, in the centrifuge case there are some energy losses, for this reason an efficiency (η) of 94 percent was considered for the belt drive (García, 2022).

$$\eta = \frac{P_{out}}{P_{in}} \tag{8}$$

$$P_{in} = \frac{P_{out}}{\eta} = \frac{2368.64}{0.94} = 2518.9\,W$$

As the required power value of the motor, 2.5 kilowatts, is smaller than specified in its characteristics, the working capacity could be achieved. On the other side, it was necessary to control the excess power, therefore a variable frequency drive was used to regulate the rotational speed of the motor.

3.1.6 Variable frequency drive

A variable frequency drive (VFD) is an industrial controller that sits between the electrical power supply and the electric motor. The power from the grid passes through the drive, which is responsible for regulating this energy before it reaches the motor. Then, the frequency and voltage are adjusted according to the requirements of the process (Innova, 2021). This is important because the speed of a motor should exactly match the speed demanded by the process in question, and use only as much power as is needed. Therefore, this ensures that the electricity supplied to the motor is adjusted to the actual demand of the application, reducing the motor's energy consumption by 20-70% (Dosupply, 2022).

Figure 25. *Variable frequency drive. Source: eur.vevor.com*

The VFD used, Figure 25, is from VEVOR Company, a brand that specializes in equipment and tools (VEVOR, 2023). This is three phase VFD with 3-phase 380 V input and 3-phase 380 V output, and with a power of 4 kW. This VFD can be utilized for both constant torque loads (such as hard starting: Air compressors and HVAC units) and variable torque loads (such as pumps and fans). It functions as both a phase converter and a motor speed control. While using this VFD, the different speeds can be adjusted as desired. This item uses sine wave pulse width modulation (SPWM) for the control system and performance excellently. More specifications of the variable frequency drive used are detailed in Appendix 6.

3.1.7 Pump and hoses

Fuel transfer pumps are used to transport fuel from the fuel tank to a vehicle or from one location to another (Hytek, 2019). Various liquids and fuels, such as diesel, oils, AdBlue, water, and gasoline, can be used with fuel transfer pumps.

In this case, the oil to be cleaned had to be transported from a tank to the rotating bowl. For this purpose, it was decided to purchase this type of pump to carry out this process, shown in Figure 26. This pump sucks the waste oil from the tank in which it is stored and pumps it into the bowl. Hoses with the necessary dimensions, a manual flow valve and a quick coupler were also purchased for its correct performance.

Figure 26. Oil pump. Source: www.fruugo.fi

The description and characteristics of the pump used, shown in Figure 26, are detailed in Appendix 7.

3.1.8 Motor cover

For the purpose of protecting the centrifuge user from the engine and transmission, a protection was designed to cover this part of the machine.

The sheet metal part's geometry is changed by applying force during the sheet metal bending process (Lee, 2022). This force stresses the sheet metal beyond its yield strength, resulting in physical deformation without failure or breakage. Although the process is quite common, it is more complex than it seems.

The first step was to make a good design, it was developed with the help of Creo Parametric, the 3D software previously mentioned. This program contains a specific section where it is easy to create metal sheets (PTC Help Center, 2019), see Figure 27.

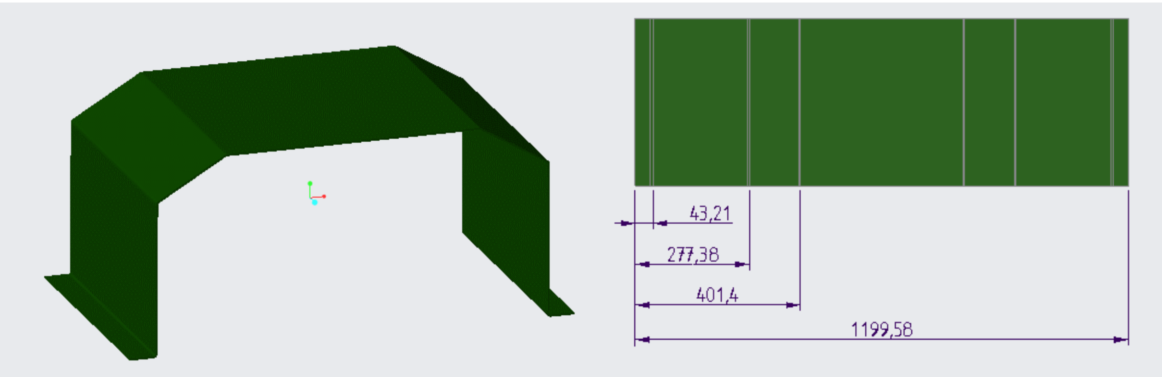

Figure 27. *A 3D model of the motor cover on the left side, and its unfolded pattern with the exact measurements on the right. Source: author’s own.*

The program's basic method consists of a first step where a 3D model was developed of the metal sheet desired with its corresponding measurements, as can be seen on the left side of Figure 27. Then, the programme generates a presentation of the unfolded pattern with the exact edges, as shown on the right side of the previous Figure 27. This allows an easy measure of the distances between planes and to get the exact marks on the design for its correct blending.

Secondly, the bending sequence of the sheet metal had to be carefully studied in order to avoid subsequent interference between the sheet metal and the bending machine. This problem would lead to the failure of the sequence and consequently to the failure of the process (Lin & Chen, 2014), so it can be said that this is the most critical step. The authors were directly in charge of this, as they had previous knowledge in the field, see Appendix 8.

Once the cutting and folding work was finished and analysing the structure it could be seen a collision with the square plates welded in the structure corners. Consequently, some of the bottom part of the cover was then cut off with a radial saw and bound to achieve a rounded finish. Also, some drills were done in the base of the sheet to the posterior assembly with the structure.

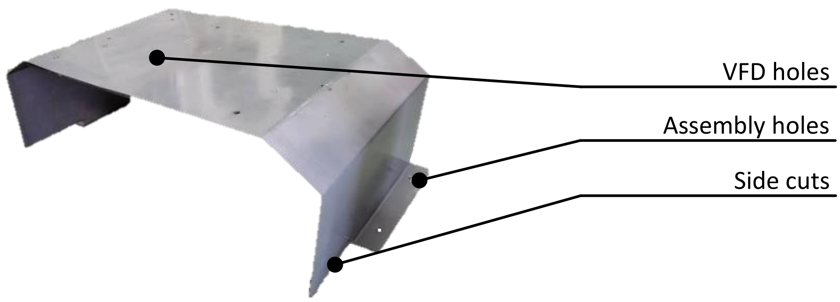

Figure 28. *Motor cover sheet. Source: author's own.*

Figure 28 shows the result of the blending process. It can be seen the side cuts in the front of the image. Also, the holes used to allocate the VFD on the top, and the holes to assemble the cover to the structure on the side.

3.2 Assembly

Subsequently, the process followed for the assembly of all the components previously presented is explained. Furthermore, a sequence of pictures of the component-by-component assembly process can be found in Appendix 9.

Firstly, to fix the collector on top of the structure, five circular steel bars were welded together. Two of the bars were welded to two square steel plates, two others were welded to the transversal square section bars, and the remaining one was welded to a C-section steel bar, see Figure 29.

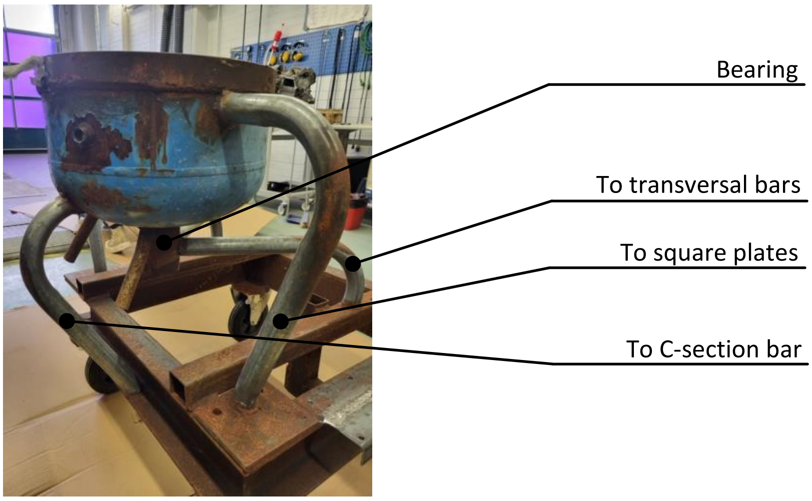

Figure 29. *Collector welded to the structure. Source: author's own.*

Once the collector was in place and fixed, as shown in Figure 29, the two bearings housed in the collector were fitted, and then the output shaft without the aforementioned ring was placed.

A plate was bolted under the motor as a support with hinges on the side. These hinges had to engage with the hinges of the structure. This provided a point of rotation on this axis, which allowed the motor to be rotated slightly so that the V-belt could then be fitted easily.

Figure 30. *Motor fitted to the hinges. Source: author's own.*

After the motor was placed, the two pulleys were fitted. The large pulley on the motor shaft and the small pulley on the output shaft. To position them, keys were added to the shafts, as shown in Figure 31, to ensure that pulleys were securely fastened and could rotate simultaneously without displacement.

Figure 31. *Pulley attached with a key. Source: author's own.*

The next and last component of the transmission was the V-belt, which, as previously mentioned, was easily fitted into the pulley grooves because the motor could oscillate slightly.

A simple mechanism was designed to tension the V-belt using the rotation point obtained from the motor. This was a long bolt from the structure to the motor base plate with a nut at each end. By tightening the nut shown in Figure 32, the position of the motor was moved slightly and the belt was tensioned.

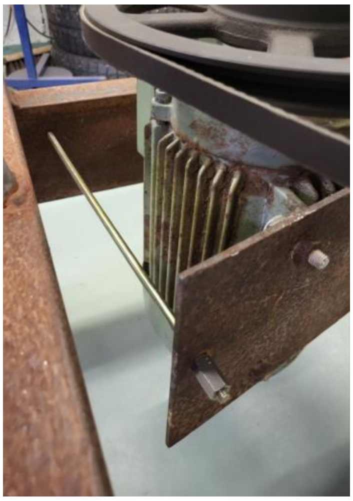

__Figure 32.__ Bolt tensioning the drive belt. Source: author's own.

This simple mechanism shown in previous Figure 32 is very important because the V-belt must be properly tensioned to achieve the correct transmission of power and angular velocity.

After this, the bowl was bolted to the output shaft, thus achieving simultaneous rotation of both. Once the bowl was in place, it was possible to fix the ring in the groove that was made in the shaft, as mentioned in Section 3.1.4 in the shaft part. Now it was time to fit the third and final bearing. This bearing, shown in Figure 33, was positioned at the top of the shaft, resting on the ring, and fixed with bolts to four flat iron rods which in turn were fixed to the collector.

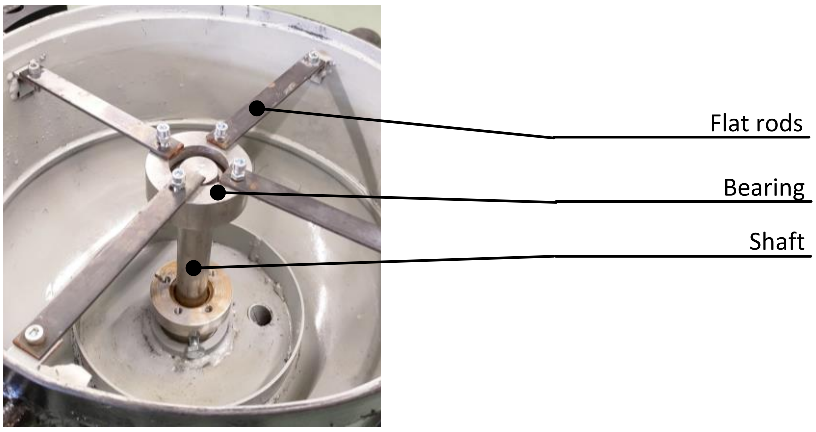

__Figure 33.__ Bearing fixed to the collector to give an extra support. Source: author's own.

Note that the bowl was not positioned in Figure 33, it is made this way so that the output shaft is clearly visible.

With all the components inside the collector in place, the cover could now be fitted and closed with the locks.

The next step was to place the pump on the side of the structure, for which a 5 mm plate had to be welded to the side, see Figure 34, with the corresponding dimensions so that it had enough surface to rest on.

Figure 34. *Welded plate to support the pump. Source: author's own.*

Once the sheet metal was welded, four holes of the corresponding metric (M8) were drilled, as shown in previous Figure 34. And after these steps, the pump could be put in place correctly. It was placed using rubber plugs instead of directly on the iron surface of the structure, in order to avoid propagating the vibrations produced by the pump.

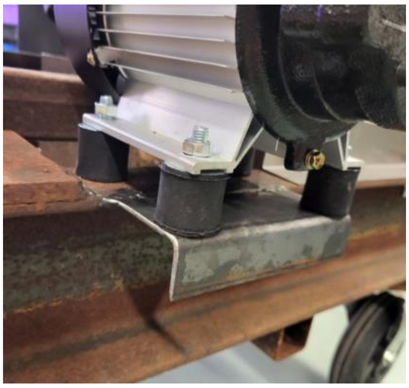

Figure 35. *Pump in place with rubber plugs. Source: author's own.*

Then, four holes were drilled in the structure to put the motor cover into position. The variable frequency drive was placed on top of the motor cover using also rubber plugs to avoid the propagation of vibrations.

Finally, the oil circuit was installed. The suction hose, which has a larger diameter, takes the oil from the tank, where it is stored, to the pump. Following this, the impeller hose takes it into the collector, through the flow valve. Also, the hoses in both outlet pipes from the collector were connected. A yellow adhesive tape was added to the hose of the cleaned oil outlet pipe and a blue adhesive tape to the hose of the uncleaned oil outlet pipe, to quickly differentiate them.

All joints and connections of hoses to other components were carefully made in such a way that they were tight and with no possibility of future leakage.

Figure 36. *Hose attached to the adaptor with a clamp, and Teflon on the adaptor. Source: author's own.*

Clamps were used to press the hose to the adapters, as well as Teflon on the threads of the connectors and adapters, see Figure 36.

3.3 Coating

The surface of any object is its weakest part, as it is exposed to the environment (Evans, 2016). This can lead to rust, cracks, rot, scratches, and dents. Coatings are an effective solution to prolong the life of an object by protecting it against such damage. Some coatings are designed for specific objects or conditions, while others can be used on a wide range of surfaces. They also have a decorative function, adding colour and gloss to an object (Ayold, 2017). In short, coatings perform the dual function of protecting and enhancing the appearance of an object.

Proper surface preparation is essential to guarantee the durability and effectiveness of metal coatings (Parker, 2015). Advanced metal coating technologies are bound to fail without adequate preparation of the surface. Before painting, metal surfaces require a preparation process.

On one hand, the structure and the outside part of the collector were treated with a rust sealer, see Figure 37, as they contained a lot of rust.

Figure 37. *Coating used to prepare the metal. Source: www.motonet.fi*

This black-coloured coating, bought in a local shop, protected the metal from rusting and gave its final aspect. The supplier specifications can be found in Appendix 10.

On the other hand, the inside part of the collector and the motor cover were painted with a light grey spray. The colour was chosen to bring light into the interior of the collector and to make it easier to see through the window on the cover.

During the painting process, all parts that did not have to be painted were covered with adhesive tape.

3.4 Start-up

With the whole centrifuge assembled and painted, the next step was to put it into operation. First, the start-up consisted of connecting the cables necessary to operate both the motor and the pump. The second part consisted of the configuration of the variable frequency drive. And the last one was the installation of the complete oil circuit, i.e. the suction pipe was introduced into the tank and the necessary vessels were placed to collect the output oil.

3.4.1 Motor connections

The connections consisted of the conduction of the electricity from the grid to the electric motor. A three-phase cable connection was needed to make the motor work. The first part of the cables entered the VFD and the second part of the cables went from that device to the motor directly, see Figure 38. An electrical schematic diagram can be found in Appendix 11.

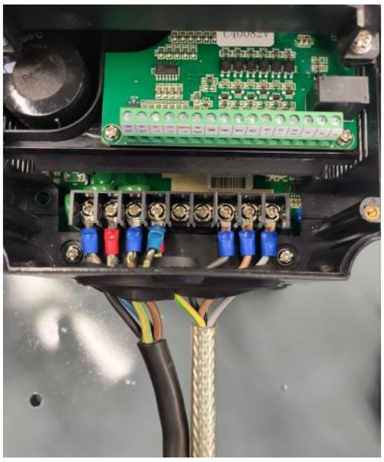

Figure 38. *Variable frequency drive connections. Source: author's own.*

In Figure 38, the black wire on the left connects the VFD to a 400 V grid. The cable used in the second sector, the one on the right in Figure 38, has a special metal coating to protect the other devices from magnetic fields and disturbances.

Following the motor specifications, the triangle form was the correct way to connect the motor with the supply, in this case through the VFD, see Figure 39.

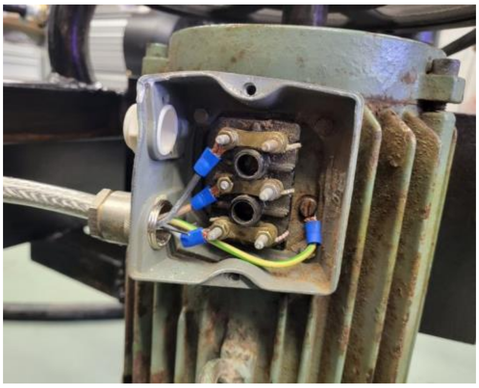

Figure 39. *Motor connections. Source: author's own.*

The special recovery cable coming from the VFD and how the poles of the motor are connected in a triangle connection can be seen in Figure 39. It can also be seen that the green and yellow ground wire is connected in position.

All the connection was supervised by an electrical engineer who signed the responsibility of the machine performing in that area.

3.4.2 Variable frequency drive configuration

In its first run, the VFD had to be configured to ensure a good connection with the specific motor. The configured parameters are described in chapter 7 of the instruction manual attached in Appendix 6. With the help of an electrical engineer, the important parameters were configured and the engine was put into operation.

3.4.3 Oil circuit

Once the engine was verified to be spinning, it was time to feed the bowl with the oil. For this reason, the oil circuit from the tank to the bowl had to be finished.

Firstly, the suction pipe, attached with the quick coupler to the suction hose, was introduced in the WCO tank. In the second place, the pump was launched to prove its functioning. Afterwards, the flow valve was adjusted by different empiric tests to allow the exact amount of oil to enter the bowl. And finally, the proper vessels were located down the outlet pipes, one to recollect the clean oil and the other to recollect the remaining liquids in the bowl when the machine stops rotating.

4 Developing

After the commissioning of the machine, some operations were made to improve its performance. To avoid irreversible damage, the engine revolutions were progressively increased. Some problems were found and had to be modified. Vibrations problems are explained in Section 4.1. Subsequently, issues in bowl balancing are discussed in Section 4.2. Finally, a bearing upgrade is detailed in Section 4.3.

4.1 Vibrations

Vibrations were the main problem identified, as the engine generates movement at high speeds.

The most critical part was the motor cover due to its thin profile. The first solution was to add some reused rubber pieces between the metal parts that were bolted together, see Figure 40.

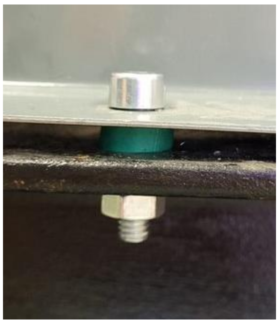

__Figure 40.__ Rubber joint to separate the metal. Source: author's own.

In Figure 40 it can be seen the assembly of the motor cover with the structure and the green rubber piece between them. The elastic property of the rubber ensures the absorption of most of the vibrations avoiding the transmission of it from one metal to another.

Also, some steel flat bars were welded on the underside of the motor cover to make it more resistant to vibrations.

The second critical component was the VFD, in addition, its initial position was upper the motor cover, which is the part that caused more problems. This combination was completely counterproductive as it made the vibrations even worse. To ensure the life durability of the VFD it was decided to change its position. A new position with low vibration and sufficient space for ventilation was searched, see Figure 41.

__Figure 41.__ VFD's new position. Source: author's own.

Finally, a plate on the front of the structure, next to the motor, was welded to place the VFD, as Figure 41 shows. For the assembly, the bolts with the rubber plug were used to attach the device to the new plate.

4.2 Bowl balancing

On the centrifuge, one of the most influential parts of the final result is the bowl, therefore it was one of the most analysed parts. The vibrations that may occur in this component have a direct impact on the performance of the machine. For this reason, different checks were carried out to ensure the minimum vibrations produced by itself. The most likely ways for this element to produce vibrations were either a bad connection with the shaft or a mass imbalance in its geometry. The first possibility was controlled by adjusting in the correct form the bolts and the second with a specific balance test.

The balance test checked if the mass of the object was equally distributed along all the geometry. The imbalances produce an increase and decrease of the centrifugal force as can be confirmed with Equation (1). A remarkable alteration of the mass in a specific point of the bowl produces a cyclic balancing, and running at high speed it can be identified as vibration.

The test was done with an Impaq Elite Portable Dynamic Signal Analyzer, shown in Figure 42, which is a 4-channels data collector and compact vibration analyser. It runs on Microsoft Windows CE and the latest digital signal processing technology (Benstone Instruments, 2023).

Figure 42. *Photo of an Impaq Elite Portable Dynamic Signal Analyzer device. Source:* *www.benstone.com*

In the upper part of the device, it is possible to see the channel inputs where two 3-dimension sensors were connected to calculate the vibrations, one on the upper bearing, see Figure 43, and the second one on the lowest bearing.

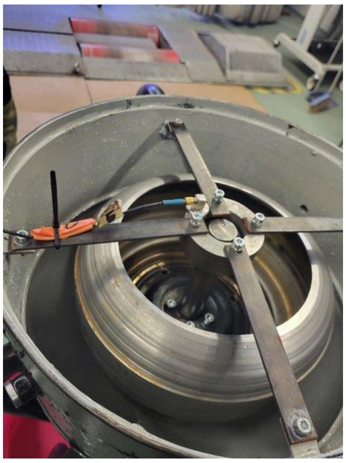

Figure 43. *The bowl with the vibration sensor attached to the upper bearing. Source: author's own.*

The two sensors were needed to apply a balanced technique developed by a special balancing software in the device. This test captured vibration data from two planes and determined where to add the additional weights to balance the bowl.

In order to obtain a more accurate result the test was performed multiple times using small test weights and looking for the most optimal solution. Finally, two 25-gram pieces of steel were welded in the determined position, see Figure 44.

Figure 44. *The steel pieces welded to balance the bowl rotation. Source: author's own.*

As Figure 44 shows, the two pieces were welded, one at the top of the bowl and the other at the bottom. Each piece corresponds to a measurement plane.

4.3 Bearing

The upper bearing of the shaft was finally removed, the reason for this decision was that the friction between the shaft and the bearing caused an important elevation of temperature in the area with the bowl spinning at high speed. Some tests were carried out without the bearing and the operation of the machine was satisfactory and good enough.

5 Tests and results

This section explains the tests conducted to analyse the performance of the machine and the by-product generated and evaluates the thesis' results obtained. First, it is explained the different centrifuge performance tests done in Section 5.1. Secondly, in Section 5.2, it is shown the oil tests carried out, and how the WCO is affected by the separation technology. Finally, in Section 5.3 there is a summary of the project's global cost.

5.1 Centrifuge performance tests

By starting up the machine and carrying out some more specific checks, the following operating results were obtained. These are displayed in the order in which the components were assembled and end with an overall view of the machine.

5.1.1 Structure and collector

The first result came with the robust and stable design of the structure, as it was one of the main pieces and was a very important step for the later success of the project. It was able to support all the components that were assembled on it, including the motor of around 30 kg with hinges. The implementation of wheels was very useful for its transportation due to the heavy structure weight.

Secondly, the collector's contribution to the operation of the machine was satisfactory. But it could be improved with a hermetic cover, as some oil leaks were observed. This was due to the reuse of the materials as they could be slightly deteriorated. In addition, the operation of the window was unsatisfactory, as it was impossible to see what was going on inside the collector. Although the interior was painted light grey to make it bright, there was not enough light coming in.

Also in the collector, the correct draining of the liquids was checked. Firstly, whether the oil came out of the correct tube when the bowl was not rotating. Next, it was verified that, only when the bowl was rotated at a high enough speed, the oil was coming out of the centrifuged-oil hose with a cleaner appearance. The results of these checks were positive, as the unit fulfilled its function.

5.1.2 Motor and variable frequency drive

The next result to discuss was the study and the selection of the motor. Taking into account all the working conditions and the needs of the project, the following step was to study the type of motor to be used, as well as its characteristics in order to achieve the proposed objective. To this end, relevant calculations were carried out and the results obtained gave an initial idea of which motor was the most suitable, these calculations indicated that the required power was 2.52 kW. Observing these results, it was determined the possibility of reusing a 4.1 kW electric motor available in the laboratory, as the characteristics were similar and it achieved the required power. This fed back into the objective of realising the project with reused components and materials in order to make its fabrication more economical and contribute to the circular economy.

But even though the characteristics were similar, the laboratory's electric motor was more powerful than what was actually required, so an alternative had to be thought of to adjust this excess power. The initial idea was to buy a new motor that would perfectly meet the requirements, but it was too expensive at around 300-400 euros. The alternative was to look for a variable frequency drive, explained in Section 3.1.6, which would limit the input of electrical power from the grid to the motor, transmitting only that required by the motor to avoid losses and reduce the motor's electrical consumption. The variable frequency drive sought was suitable for the needs and requirements and was also reasonably priced, at 165.99€. This second alternative was the definitive one, which was cheaper and also allowed to save energy and consumption.

A test to determine a safe operating speed range was executed. First of all, it was tested whether the motor could rotate at 1500 revolutions per minute. The result was the appearance of a lot of unwanted vibrations when this speed was achieved. Therefore, for the safety of the components, it was determined that the operating motor speed would be 700 revolutions per minute meaning almost 3000 revolutions per minute in the bowl. This speed was high enough to obtain a clear difference between the WCO and clean oil, as can be seen in Section 5.2.

5.1.3 Bowl

To check the speed achieved by the bowl, two results were compared. The first value was displayed by a speedometer and the other value was calculated by applying the transmission ratio to the speed indicated by the VFD, which corresponds to the speed of the motor. Both results coincided meaning that the transmission ratio was well calculated and that the VFD was displaying the correct speed.

5.1.4 Pump and circuit

The next part to analyse the results obtained involved the selection of the pump. As was done in the previous steps, the same process was carried out, trying to make it as economical as possible. In this case, no pump was found to be reused so it had to be purchased. Finding a pump to suit the requirements of the project at a low cost was a slow but successful process. The cost of the pump was 119.04€, a very competitive cost compared to other pumps with similar characteristics and specifications.

The correct functioning of the pump was tested, and it was left to run continuously for several minutes to see if any pressure or temperature increases were observed. The pump's functionality with our product (waste cooking oil) was satisfactory. However, it was important to note that the pump was continuously pumping almost the same quantity of oil. This quantity was higher than the desired flow rate inside the bowl, which was regulated by the flow valve. Therefore, this led to an increase in pressure and temperature in the impeller hose and an overheating of the pump. In the long run, this could cause problems, so one solution was proposed in Section 6.4 of suggestions for project improvements.

Having the pump and knowing its dimensions, it was also necessary to purchase the appropriate hoses and other circuit components for its use, which was a simpler process, and obviously cheaper.

5.1.5 Centrifuge operation as a unit

The following result referred to the operation of the centrifuge as a unit, i.e. with all components assembled together. Analysing the operation of the machine without yet taking into account the analysis of the final product, a satisfactory result was obtained. The operation principles were verified by powering the machine and verifying that the variable frequency drive switched on accordingly. Subsequently, by pressing the RUN button, the motor started spinning at the revolutions indicated on the VFD. Consequently, the V-belt transmitted the movement from the motor pulley to the other pulley and simultaneously to the shaft. After that, the shaft made the bowl rotate at the theoretical revolutions. This result was checked with a speedometer that measured the revolutions of the bowl and was compared with the velocity indicated by the VFD.

Next, the result obtained by starting the pump and the motor at the same time, but without taking into account the flow of oil pumped or paying attention to the quality of the oil, was also satisfactory. It could be seen that the machine worked perfectly, i.e. the pump correctly performed its function of sucking the used oil from the tank and impelling it into the bowl; the motor and the variable frequency drive performed correctly their function of making the bowl rotate; and the bowl and the collector also performed their function of taking out the clean oil through one outlet pipe, and the uncleaned oil through the other when the bowl stopped rotating.

The last verification was made by stopping the rotation of the engine when the STOP button of the VFD was pressed. The VFD was switched off when it was disconnected from the electric grid.

In conclusion, the overall performance of the machine was satisfactory, and its construction was completely finished, see Figure 45.

Figure 45. *Final state of the centrifuge. Source: author's own.*

Figure 45 shows clean oil coming out of its pipe during the centrifuge performance and how the construction of the centrifuge looked in the end.

5.2 Oil tests

For the oil testing, two oil samples were collected. The first one, always identified with the blue colour, is the untreated waste cooking oil. To collect it, oil was pumped from the tank with the centrifuge off. This oil was collected in the inner chamber of the collector and deposited in a previously cleaned container.

Secondly, the cleaned oil, always marked with a yellow colour, is the result of the separation treatment. This was collected from the outer chamber of the collector which contains the oil that escapes from the bowl when it was running at around 3000 revolutions per minute. In this case, it was also deposited in a previously cleaned container.

All samples taken for testing were extracted from these containers, thus ensuring the accuracy of their results.

5.2.1 Visual aspect

Two oil samples of the containers were placed in a transparent vessel for visual comparison, see Figure 46. On one hand, the first one was extracted from the waste cooking oil container, marked with a blue colour. On the other hand, the second sample was collected from the cleaned oil container, marked with yellow.

Figure 46. *Two vessels, the left one with waste cooking oil and the right one with cleaned oil after centrifuge. Source: author's own.*

The difference between the two samples could be clearly seen with the human eye. The WCO sample, with a blue mark, had an opaquer colour as opposed to the cleaned oil, with a yellow mark, which is much more transparent.

This visual test was a very simple but very informative test that clearly showed the difference between the two samples. For this reason, it was considered to be the most relevant test and showed at least a minimum performance of the machine. The results obtained were very satisfactory, as the great difference in viscosity and colour between one oil and the other could be observed at a glance.

5.2.2 Paper filter

A second test was carried out to check the impurities or denser particles contained in each of the two samples. In this test, 0.2 litres of each container were poured through a paper filter and then they were checked to see any sediment on it, see results in Figure 47.

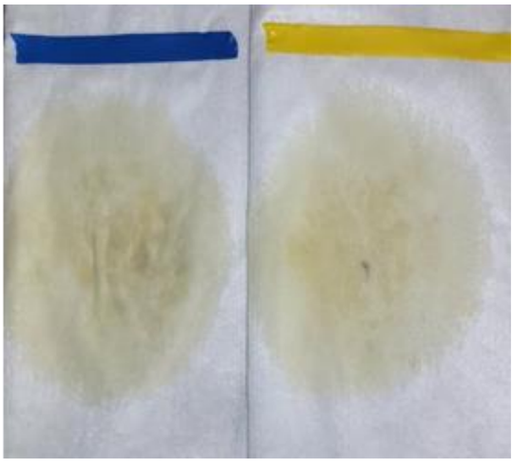

Figure 47. *Paper filters used to catch sediments, on the left from waste cooking oil and on the right from centrifuged oil. Source: author's own.*

Some oil stains could be seen on the paper filter in Figure 47. These represent some sediments that were trapped, depending on the colour difference it could be identified if these sediments were relevant. The difference between the two filters was practically non-existent, as both papers had a similar appearance. However, during the test, it was noticed that the WCO filtered more slowly, probably due to its higher viscosity because of unwanted particles.

This result could be read as unsatisfactory, thinking that the paper filter test may not be suitable in this situation, or on the contrary, as very satisfactory. If this test is analysed together with the previous one, it can be deduced that the particles that were retained by the centrifuge were smaller than those that could be collected by the paper filter.

Therefore, in the visual test, the difference between the two samples could be seen, but not in this one. Resulting that the filtration of the smallest particles, consequently the most difficult to extract, can be carried out with the centrifuge, which would be very satisfactory.

5.3 Cost

Finally, the total budget for the project was drawn up, see Table 1, taking into account the costs of all the components and materials purchased for its realisation.

Table 1. *Budget list of components.*

CONCEPT	COST
Oil pump	119.04 €
Variable frequency drive	165.99 €
Pulleys	95.00 €
Components in stock	60.00 €
Paint, locks, belt	130.00 €
Bearings, pipes, adaptors, connectors	180.00 €
TOTAL	**750.03 €**

Source: author's own.

As seen in Table 1, the result of the total amount of the budget is 750.03 €. A larger amount of money was avoided due to the reuse of an electric motor and other reused materials throughout the project. And comparing the final price with examples available on the market, it can be confirmed that this is more economical than the others. In concrete terms, a centrifuge with a 4.1 kW motor, a bowl of this capacity and similar characteristics can cost around 3,000€ or 4,000€.

6 Discussion

The discussion section evaluates and reflects on the results presented concerning the initial aims and objectives in Section 6.1, the limitations of the work in Section 6.2, the consistencies and inconsistencies in Section 6.3, and suggestions for project improvements in Section 6.4.

6.1 Initial aims and objectives

To meet the aim of the project three objectives were established. The first objective was to identify the working principle of the machine and its current applications. This was completed by a detailed and extensive background study on centrifuges and their most common applications. This previous work helped in the development of the next objective with more confidence.

The second objective was to fabricate a centrifuge that can be used for cleaning waste cooking oil using reused materials. This objective was achieved satisfactorily and can be proven by the performance tests carried out. However, with more time and knowledge of the subject, some components could have been improved. It is also worth mentioning that some of the components had to be bought, which means that the machine was not made entirely from reused materials.

The third objective of the work, which was to test and demonstrate the efficiency of the machine, could not be fully achieved and developed. The visual test provided a lot of information about the operation of the machine, but the efficiency could not be determined in any way. No scientific evidence assures the cleaning improvements obtained with the operation of the centrifuge. The initial idea for testing the oil results was to carry out several tests with a spectra device that determines the number of insoluble substances, the amount of water in the oil, the viscosity, and the total base number. This test could not be finally implemented due to a lack of the equipment in the laboratory and proper planning.

6.2 Limitations of the work

Numerous limitations were materialised during the development of the thesis. To start with the fabrication part, all the metallic work developed in Technobothnia's laboratory, such as welding, blending sheet, use of radial saw, drilling and others, had to be done with the teacher supervising. By using a specific workshop, it was necessary to have a responsible person controlling and allowing the entrance to the room each time. For this reason, access to these resources was dependent on a third person.

Another limitation of the centrifugal optimal performance discovered was a poor-quality flow valve. The manual flow valve did not allow good control of the amount of liquid entering the bowl, and this value is very significant to achieve optimal performance.

Last but not least, one of the most important limitation of this project was the time and material to carry out relevant quantitative tests. This would provide numerical results on the actual efficiency achieved, as well as the quality of the oil or its exact flow.

6.3 Consistencies and inconsistencies

During the development of the project and finally taking an objective and global view, different consistencies achieved can be named. The fabrication of the structure together with all modifications such as welded parts was safe and firm, so it was a great success. The selection of the motor and variable frequency drive was consistent and did not give any problems. Next, although, as discussed in Section 5.1.2, the initial proposed target of reaching 6000 rpm on the bowl was not achieved, the transmission as a unit is another consistency. This can be assured because the speed is correctly transmitted by the V-belt and the failure to achieve the objective of turning the bowl at 6000 rpm is not due to these components.

On the other hand, inconsistencies also appeared during the development of the project. The failure to reach the proposed 6000 rpm was due to excessive vibrations that could lead to unwanted breakages and affect the safety of the components. Therefore, it was decided to decrease the revolutions per minute of the bowl to 3000 as this was still sufficient to meet the target.

Another inconsistency is that although the oil pump correctly performed its function of taking the WCO into the bowl, it is important to note that its selection could have been more closely matched to the requirements. The pump purchased had a higher flow capacity than the demand required for the optimal functioning of the centrifuge. This meant that the manual regulator had to be closed very tightly, which created a higher pressure in the outlet hose than in the inlet hose and consequently increased the oil temperature and the pump tended to overheat. Oil vapour could even be seen coming out from inside the collector.

Following, reusing a component to make the bowl was prioritized over ensuring the optimal functioning of the centrifuge. Therefore, the geometry and material of the bowl make its selection an inconsistency.

6.4 Suggestions for project improvements

This project can be considered as the first step of a bigger project in the laboratory. One idea that has emerged was the generation of biodiesel from the waste cooking oil as some trials have been developed in the laboratory. In order to achieve this aim, the idea is to clean the oil and then add methanol and a base acid. Letting this mixture react the biodiesel is obtained.

If the objective is to improve the performance of the centrifuge, the bowl might be substituted. Scientific studies show that the most important factor in the performance of a centrifuge is not the speed, this is the correct balance of the oil flow and a proper bowl geometry. For this reason, it is proposed to design a new aluminium bowl by studying its geometry for better performance.

Another component that should be replaced to improve the performance of the centrifuge is the flow regulator. With an electronic device or a pointer valve, a higher continuity and accuracy of the operation can be ensured.

A potential improvement to eliminate the overheating of the pump would be to create a loop between the outlet and the inlet. This would avoid pressure build-up in the impeller hose, as the flow that does not go into the bowl returns to the pump inlet.

Finally, another way to improve the consistency of this project would be to get quantitative results in oil tests. The suggestion is to perform the tests that initially were proposed in the discussion of the third thesis objective.

7 Conclusion

Separation technologies play a critical role in a variety of industries. They refer to the various methods and techniques used to separate and purify different components of a mixture or solution. This project consists of the fabrication of a centrifuge to clean waste cooking oil. In addition, the project aims to be developed with reused materials to contribute to the circular economy and demonstrates the feasibility of cleaning waste cooking oil without the need for a large initial investment.

The fabricated centrifuge had a robust, stable and mobile structure made of reused materials that supported all the components. A 4.1 kW three-phase electric motor available in the laboratory was reused to power the machine. As the power required to run the centrifuge was lower (2.52 kW), a variable frequency drive was purchased to regulate the speed of the motor. With a transmission ratio of 4.18, the drive system rotates the bowl at an optimum speed of 3000 rpm, consisting of two pulleys, a V-belt and an output shaft. Meanwhile, an oil pump with a power of 550 W drives the waste cooking oil from a tank to the bowl; the flow rate is regulated by a manual valve. All the components of the oil circuit, some components of the transmission and, as mentioned before, the variable frequency drive, were the only materials purchased with a final cost of 750.03€.

Despite the challenges faced during the project, the results demonstrate a generally good performance of the centrifuge. It can be verified by a visual test developed, where two samples, one of used cooking oil and one after centrifugation, show significant differences in colour and opacity. Even so, the quantitative tests that could reinforce the positive evaluation of the machine could not be carried out due to a limitation of equipment.

However, improvements can still be implemented in the future, as some marginal failures were observed during the operation of the centrifuge. Instances include overheating of the pump due to excess flow capacity, oil leakage through the collector cover due to lack of sealing, or imperfect design of the sight window.

A very interesting further study would be to generate biodiesel from waste cooking oil. The centrifuge could be used to remove unwanted impurities for the subsequent chemical reaction.

In conclusion, the completed centrifuge is a testament to the hard work and dedication of the team. Furthermore, this thesis serves as a valuable contribution to the field of sustainable engineering, providing insight into the potential of the centrifuge for cleaning waste cooking oil and inspiring further research and development.

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Appendix 1. Welding and lathe processes

- **Welding**

Welding is a fabrication process in which two or more parts are fused together by heat, pressure, or both, forming a joint when the parts cool. The completed welded joint may be referred to as a weldment (TwiGlobal, 2023). The most frequently welded materials are metals such as aluminium, mild steel and stainless steel. In addition, plastics can also be welded (Kemppi, 2023). In plastic welding, the heat source is either hot air or electrical resistance.

During the welding process, you are exposed to some situations such as the risk of burns, ultraviolet B and ultraviolet C radiation, and continuous exposure to infrared radiation (Academia Gasex, 2021). Therefore, it is necessary to be equipped with the appropriate protection, which are welding mask, leather gloves and apron, gaiters, safety shoes, cap and respiratory masks.

There are a variety of different welding process types with their techniques and applications for industry, which are MIG welding, stick or arc welding, TIG welding, plasma arc welding, electron beam and laser welding, and gas welding (The Manufacturer, 2021). In this case, MIG welding was the process used, as although it is not as effective on thicker metals as other welding processes, it is better for joining thinner metals with a good finish and less risk of burns (TwiGlobal, 2023). The machine used was the one available in the Technobothnia metal workshop, see the following figure.

(Source: author's own.)

The welding machine in the previous figure was used to join 4-millimetre-thick rectangular steel bars to the protective cover, in order to give it more stability against vibrations and more resistance in case elements have to be placed on top of it.

The rectangular bars were welded to the outside of the upper surface. Thirteen spot welds were made to ensure proper joining.

- **Lathe**

A lathe is a machine tool used in manufacturing and machining processes to remove material from a workpiece to create a desired shape or size with a variety of possibilities (Virasak, 2017). The workpiece is mounted on a spindle that rotates against a cutting tool, which removes material from the workpiece as it rotates. Lathes are commonly used in metalworking, woodworking, and other manufacturing industries (John, 2022). They come in many sizes and types, from small table-top models to large industrial machines, and can be operated with computer numerical control (CNC) technology or manually, as the one used in this project shown in the following figure.

(Source: author's own.)

In this project, the lathe shown in the previous figure was used to smooth the bowl surfaces. By fixing the bowl it was ensured that both the inside and the outside of the bowl reduced the number of burrs. In this case, the part was machined by removing material as the final thickness of the material was sufficient for the bowl to function.

As Wilson (2021) suggests, the first step in the turning process is to ensure safety, and the second stage is to choose the right cutting tool. Afterwards, the working tool must be positioned correctly, and the ruler must be adjusted to the starting position. A test cut is also recommended to check its correct functioning before the final cut is made.

Appendix 2. Pulley fixed to the motor (large diameter)

The following table shows the characteristics of the SPA 280/1 TB 2012 pulley.

Profile	SPA
No. of grooves/teeth	1
Bore	TB 2012
Weight	4.79 kg
Pitch diameter	280.0 mm
Material	Gray Cast Iron

(Source: adapted from www.wychbearings.co.uk)

This is a V-belt pulley for Taper Lock bushes. Its design is based on the ISO 4183 (DIN 2211) standard (Tyma, 2023). These pulleys are attached to the shafts using Taper Lock cone bushes (TB 2012), which allow for both axial locking against displacement as well as shaft fixation with a keyway.

The SPA V-belt pulleys for Taper bush are used in all branches of mechanical engineering, from fine mechanics to heavy engineering, and they fulfil the strictest standards of modern drive technology (Industry lots, 2023).

Appendix 3. Pulley fixed to the output shaft (small diameter)

The nomenclature of the pulley fixed to the output shaft shown is SPA 67/1 TB 1108. The following table shows its characteristics.

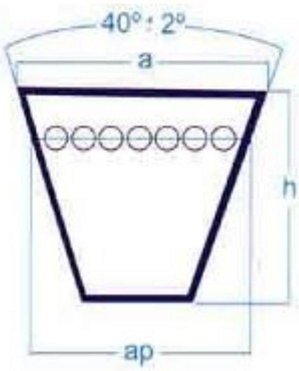
Profile	SPA
No. of grooves/teeth	1
Bore	TB 1108
Weight	0.29 kg
Pitch diameter	67 mm
Material	Gray Cast Iron

(Source: adapted from www.tyma.eu)

This is also a V-belt pulley for Taper Lock bushes, and its design is also based on the ISO 4183 (DIN 2211) standard, as is the pulley fixed to the motor (Tyma, 2023). These pulleys are attached to the shafts using Taper Lock cone bushes (TB 1108), and as with the other pulley, this allows both shafts to be fixed with a keyway and axial locking against displacement.

Appendix 4. Standard profiles for V-belts

According to ISO standards, V-belts are divided into two main groups: belts with classic Z, A, B, C, D, and E cross-sections, and narrow belts with SPZ, SPA, SPB, and SPC cross-sections. The following figure shows a schematic representation of a V-belt cross-section.



(Source: www.ingemecanica.com)

Where (concerning Figure), a: the width of the top face of the belt; h: the height or thickness of the belt; ap: the so-called primitive width of the belt.

The following table shows the values of the above parameters according to the belt profile:

Cross-section	a (mm)	h (mm)	ap (mm)
Z	10	6	8,5
A	13	8	11
B	17	11	14
C	22	14	19
D	32	19	27
E	38	25	32

(Source: adapted from www.ingemecanica.com)

Timing belts can have standard cross-sectional dimensions, narrow, wedge, band, and fractional power V-belts. Except for wedge belts, the common designation for timing belts has an X after the V-belt section number. The designations for wedge timing belts are XPA and XPB.

The following table shows the specific characteristics of the timing V-belt used, designated as AVX13X1325:

Category	Timing V-belt
Cross-section	AVX13 (13mm X 8mm)
Weight	0,148 kg
Internal development	1325 mm
External length	1375 mm
Belt height	8 mm
Belt width	13 mm
Primitive length	1355 mm

(Source: adapted from www.123rodamiento.es)

Appendix 5. Motor

The motor was manufactured by the company Stromberg which belongs to the ABB group.

The table shows the characteristics of the motor, extracted from the plate.

Brand	ABB
Model	KMER 100 L X 4
Type	3-Phase Electric Motor
Rated Power	4.1 kW
Rated Speed	1430 rpm
Nominal frequency	50 Hz
Motor Voltage (Δ / Y)	380 / 660 V
Rated Current	6.8 / 3.9 A
Power Factor	0.8

(Source: author's own.)

Appendix 6. Variable frequency drive

Frequency variators work in the following way: The first step in the process is to convert alternating current from the mains into direct current. This is carried out by an essential part of the inverter, called the rectifier (Solerpalau, 2020). The next stage is taken care of by the inverter's capacitors. These are charged with the DC transformed by the rectifier and smooth the waveform of the resulting electric current. Finally, the last stage is the inverter, which converts the direct current back into alternating current (Abb, 2023). This is how the motor actually receives the supply adjusted to the appropriate frequency and voltage requirements.

Specifications of the variable frequency drive used are detailed in the following table.

Power	4 kW
Output Voltage	380 V ± 15%
Output Frequency	0 – 400 Hz
Output phase	3 phase
Working Temperature	-10 – 40 ºC
Input Voltage	380 V ± 15%
Input Frequency	48 – 63 Hz
Input phase	3 phase
Control Mode	SPWM
Humidity	0 – 95% Relative Humidity (without dew)

(Source: adapted from eur.vevor.com)

On security protection, it provides security concerning overloads, fuses, over-voltage (DC voltage > 800 V) or under-voltage (DC voltage < 400 V), restart, short-circuits, stalls, and over-heats. Moreover, it adopts a large area of cooling vents and a forced air-cooled fan, offering powerful cooling capacity.

In this project a VEVOR variable frequency drive of 4.0 kW and 380 purchase is the one in the following figure.

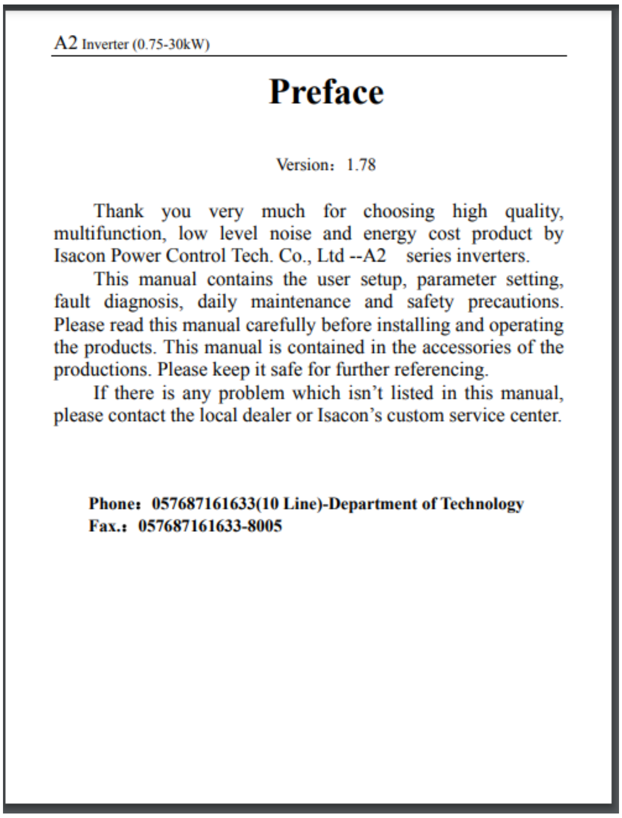
VEVOR 4.0KW 380V VFD Variable Frequency Drive Inverter for Spindle Motor Speed Control (4.0KW 380V)

And here is the manual provided by the company:

Link: http://qiniu.vevor.net/2020031918014038.pdf

Pages: 24

Data: 238 KB



A2 Inverter (0.75-30kW)

Preface

Version: 1.78

Thank you very much for choosing high quality, multifunction, low level noise and energy cost product by Isacon Power Control Tech. Co., Ltd --A2 series inverters.

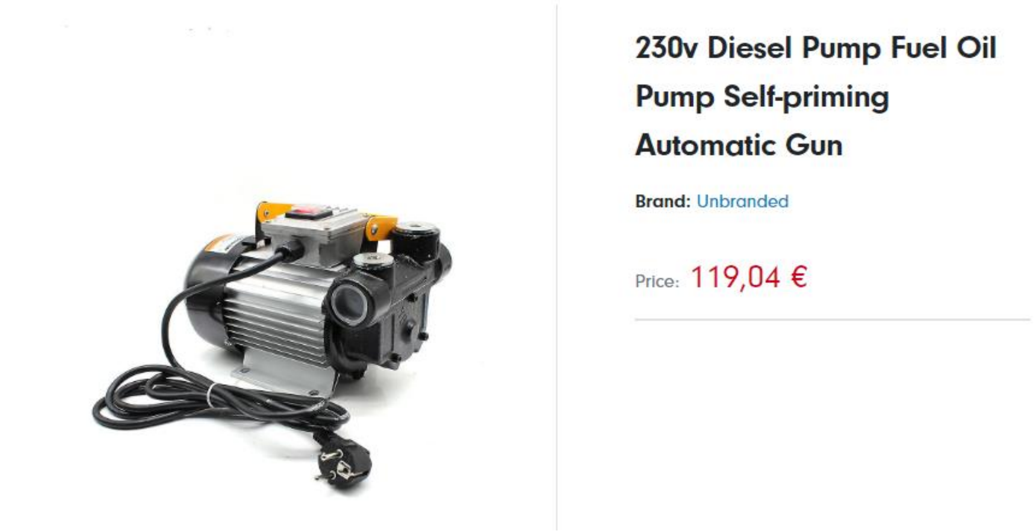
This manual contains the user setup, parameter setting, fault diagnosis, daily maintenance and safety precautions. Please read this manual carefully before installing and operating the products. This manual is contained in the accessories of the productions. Please keep it safe for further referencing.

If there is any problem which isn't listed in this manual, please contact the local dealer or Isacon's custom service center.

Phone: 057687161633(10 Line)-Department of Technology
Fax.: 057687161633-8005

Appendix 7. Pump

The following link leads to the website where the pump was purchased, where all the specifications and details are explained: www.fruugo.fi



- **Manufacturer's description:**

This fuel oil pump uses an entire copper motor, enabling automatic self-priming, high power, and high efficiency, so it is not necessary to worry about refuelling. This self-priming oil pump can be used for a variety of tasks, including automotive repair shops, automotive recycling or agricultural purposes, refuelling of machines, tractors or other vehicles, and cargo ships.

- **Key Features:**

High Flow Rate: The pump has a 550-watt motor and a maximum flow rate of 3600 litres per hour at 2800 rpm.

Self-priming Function: By automatically sucking oil, this oil pump can save time and effort.

Brass Motor: This oil pump uses a brass motor with high-quality copper wire, supporting high-speed and strong suction, which can effectively increase work efficiency.

Coarse Filter: The product has a coarse filter to prevent contaminants from entering the diesel or kerosene.

Brushless Motor: This product has a fan-cooled, brushless capacitor motor that effectively increases the machine's lifespan.

Durable Material: The housing and base of this oil pump are made of durable cast aluminium.

- **Details:**

Intensified Heat Sink Holes: The oil pump does not grow hot when used continuously because of the very effective heat dissipation holes, which also increase the useful life of the device.

Portable Handheld Design: The humanized hand-carrying design makes it comfortable to hand and easy to carry.

Safety Switch: This diesel/oil pump has a transparent cover on the switch, making it waterproof, dustproof, and leak-proof.

- **Application:**

The pump is specially designed for diesel, kerosene, white oil, and other light oils. This self-priming diesel/oil pump is perfect for vehicle workshops, car recycling, and agricultural use to refuel machines, cargo vessels, tractors, and other vehicles.

Rated Voltage	220 V
Flow Rate	20 – 60 L/min
Speed Range	2800 rpm
Rated Power	550 W
Frequency	50 / 60 Hz
Absorbing Distance	5 m / 16.40 ft
Size	28.5*21.5*23.5 cm / 11.22*8.46*9.25 in
Gross Weight	9 kg / 19.84 lbs

(Source: adapted from www.fruugo.fi)

Other notes on prevention, risks, and warnings can also be found in the link provided at the beginning of the appendix.

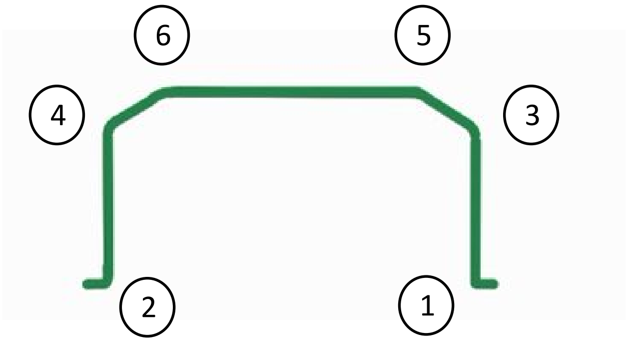
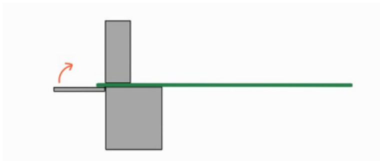
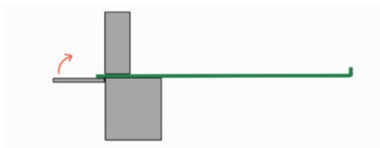
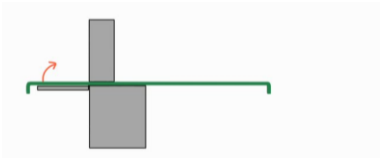
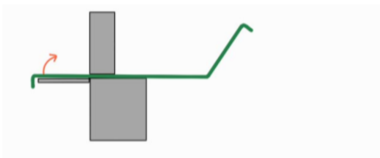
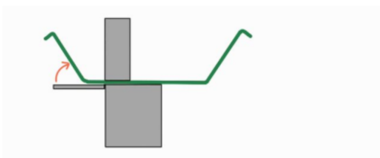
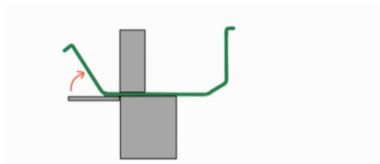
Appendix 8. Blending sequence

Once the final design of the part is completed, the next step is determining the bending sequence. In order to achieve a satisfactory finish, the possible collisions between the part and the bending machine must be considered.

In this project a Cidan bending machine available in the laboratory was used, see the following Figure. The working principle of the machine consists of a hinged surface that bends the sheet up to a maximum of 90 degrees. The sheet is fixed between the base surface and a press that applies force.

(Source: author's own.)

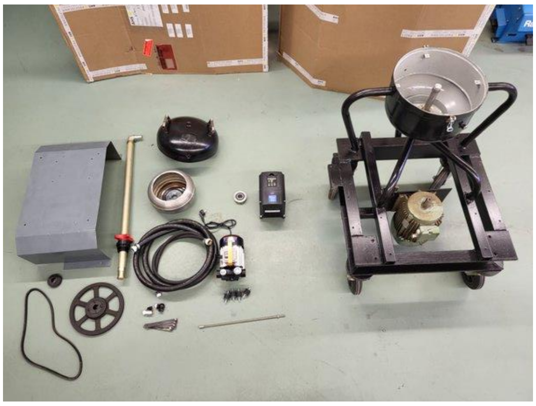
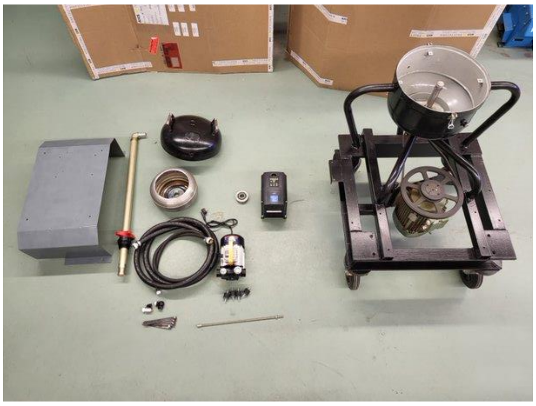
After the geometric study, the following instructions for the folding process were designed.

RESUME:		
PROCES:	**OPERATION:**	**RESULT:**
1. 90º		
2. 90º		
3. 60º		
4. 60º		
5. 30º		
6. 30º		

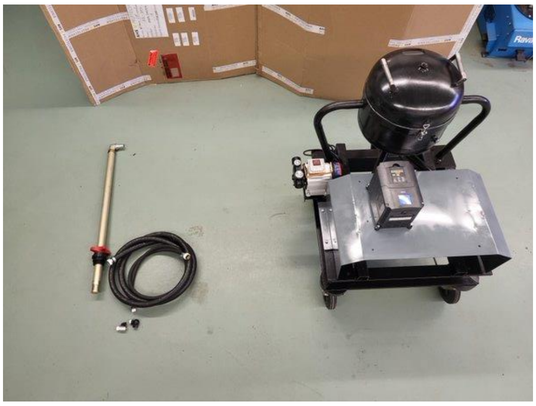
(Source: author's own.)

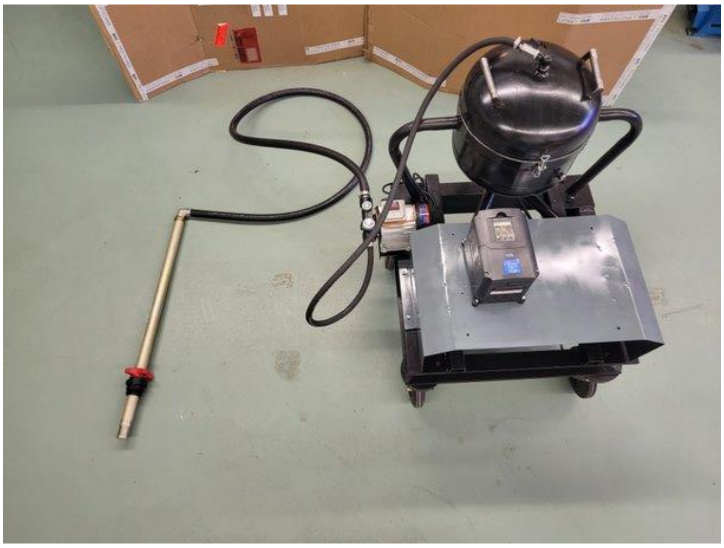
Appendix 9. Assembly sequence

The following table shows all components and their order of assembly.

	
1. Components + Structure	2. Motor
	
3. Shaft	4. Pulleys
	
5. V- belt	6. Tensioning mecanisme

	
7. bowl	8. Bearing*
	
9. Bearing fixation*	10. Collector cover
	
11. Oil pump	12. Motor cover

	
13. Variable Frequency Drive*	14. Pump-collector hose.



15. Tank-pump hose. FINAL RESULT

(Source: author's own.)

* Note that this assembly was performed before the development studies discussed in Section 4 . Therefore, steps 8 and 9 were finally not carried out due to the reasons explained in Section 4.3, and should be deleted. Moreover, the location of the VFD (step 13) changed position as explained in Section 4.1.

Appendix 10. Coating

Supplier specification www.motonet.fi:

CRC Rust Seal Rust stopper 750 ml
60-2120

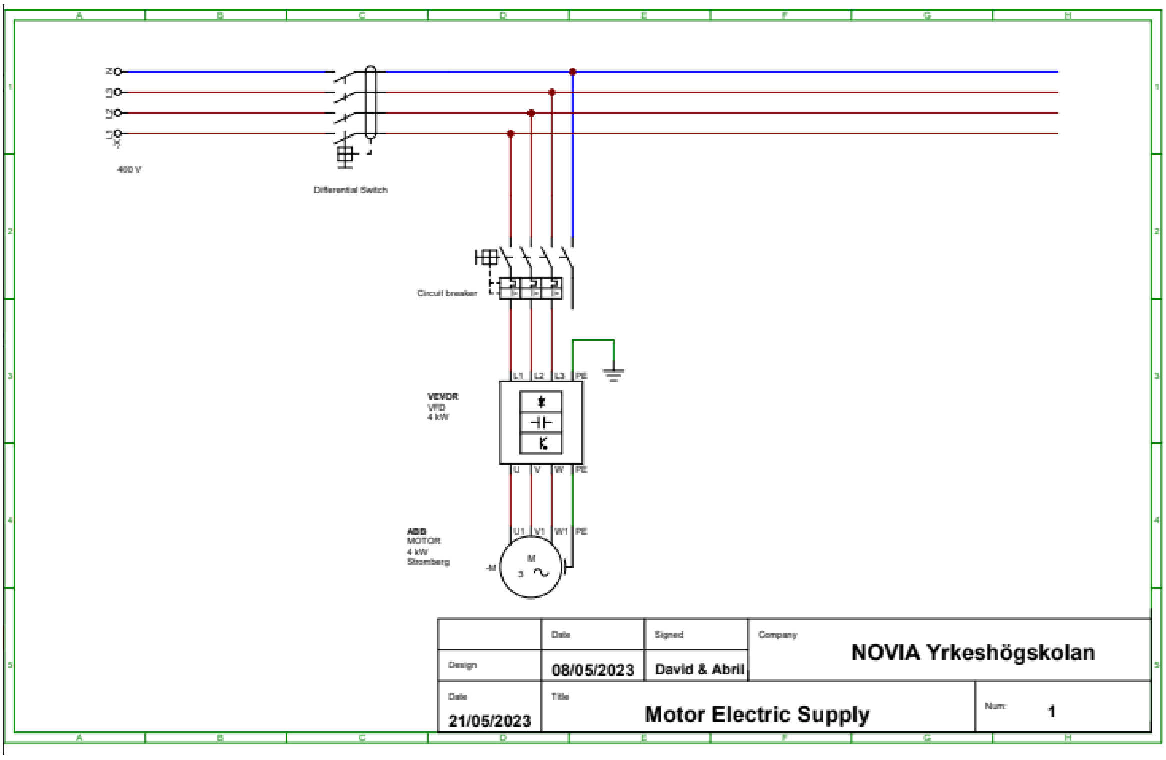
CRC Rust Seal is an ideal pre-treatment agent before painting a rusted metal surface.
It stops the rusting process by forming a black protective layer that isolates the rust from moisture. In this way, it transforms rusted metal into an easily paintable surface without time-consuming sandblasting.

Properties:
- Protects the paint surface from rusting
- Fast drying: can be painted after two hours
- Water-based: safe to use and environmentally friendly
- Time-saving: only a little surface preparation (no need for sandblasting)
- The paint adheres well to the surface
- Also works without a paint surface

Applications:
All rusted materials, such as :
- pipes
- fasteners
- fences
- containers

Appendix 11. Electrical connections

The following figure shows the electrical connections, including the differential switch, the circuit breaker, the VFD and the electrical motor, by using the software CADe_SIMU (cade-simu.com).



(Source: author's own)