

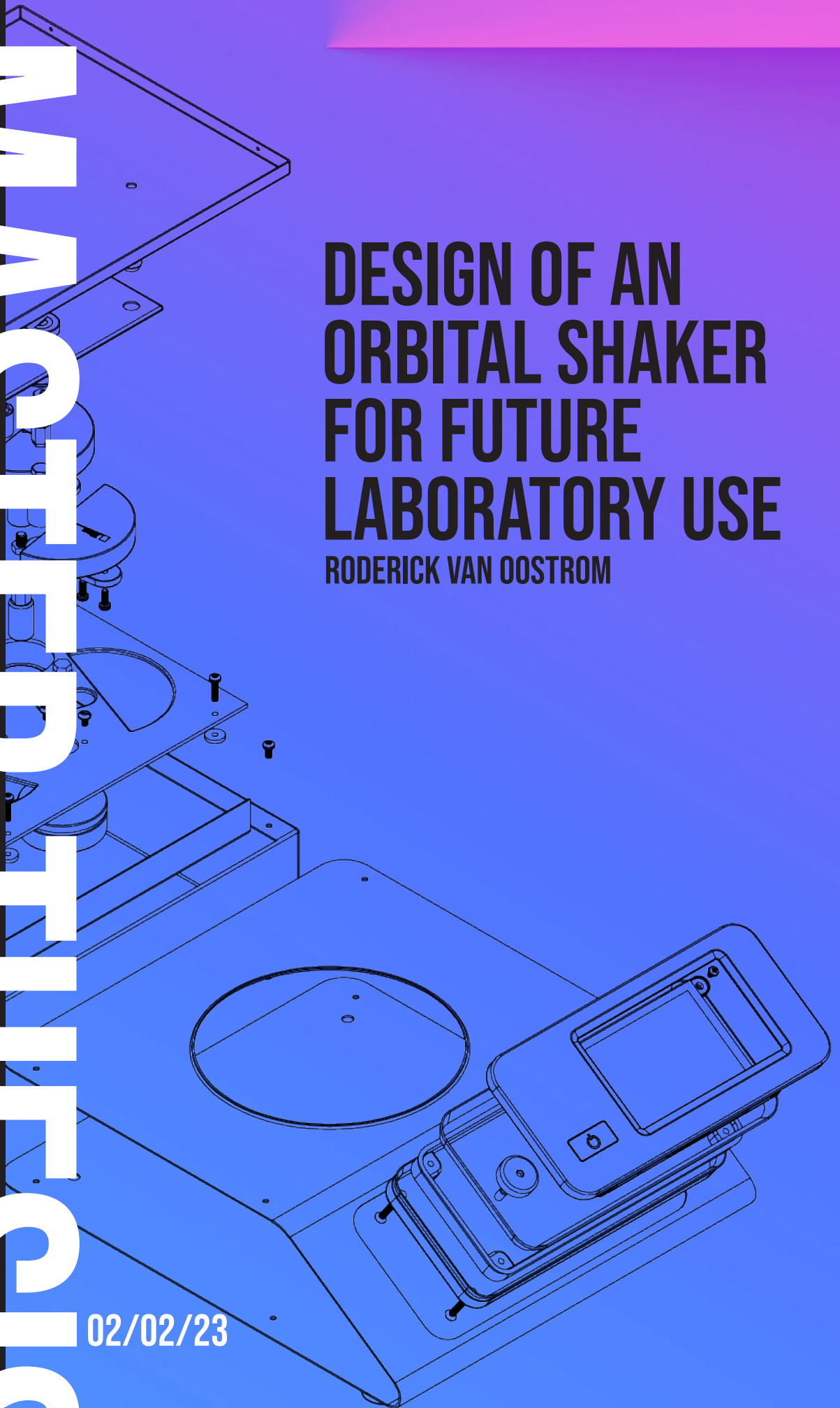
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MASTER THESIS

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DESIGN OF AN ORBITAL SHAKER FOR FUTURE LABORATORY USE

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Summary

With the increasing digitization of laboratory records and practices, as well increasingly stricter cleaning regulations, new laboratory products need to be designed with these changes in mind. Shakers for example, are a basic tool used in a wide variety of laboratories to shake samples, fluids, or simulate a moving environment for cell growth. However, for above mentioned reasons, it is possible to have the shaker fulfill more functions in a laboratory, resulting in the research question “How can an orbital shaker be redesigned to be better adapted to future laboratory usage?”.

The aim of this project is to redesign an orbital shaker to improve its flexibility of use in laboratory environments with increasingly stricter cleaning regulations and open up more future possibilities for integration with digital journals and reporting. One of the end deliverables is a functional, high-fidelity prototype for the company, showcasing the newly designed shakers as well as being a clear milestone from which can be decided to if the development of the product will be continued or not. The research and design will be structured and planned according to the Double Diamond approach (UK Design Council, 2019) which is also evaluated at the end of every section. Before designing, one will do background research in shakers and laboratories by visiting a laboratory on the University of Twente, as well as performing literature research into laboratory work and possibilities in digitization and automation in a laboratory environment. Moreover, one will perform reverse engineering research using the Product Evolution methodology (Otto & Wood, 1998) on three different competitor products to get acquainted with shakers

and their technicalities. The methodology is concluded with qualitative judgements of all competitor products, as well as a morphological diagram used further into the project. Based on the background research, literature research, reverse engineering and in discussion with the company, the requirement specification is set up.

Designing the shaker started off with a brainstorm session with two laboratory researchers from different disciplines and ideation for the three main subassemblies of the product, namely mechanism, casing, and controller. Three different concepts were presented to the company with a distinctly different subassembly in all three areas and evaluated both qualitatively as well as quantitatively. From these concepts, a direction was selected and a final design and accompanying CAD model was created. Largely in tandem with the creation of the final design, a prototype was designed and manufactured as well. The prototype was built to reflect the requirements of the final product as close as possible, meaning all components, as well as the controller, are selected and built to fit the constraints of actual laboratory usage, so that the company can decide on future development of this product as informed as possible.

CONTENTS

Introduction	5	Prototyping	68
Background and motivation	5	Planning	69
Orbital shakers	6	Design changes	70
Research question	7	Interface design	70
Methodology	8	Program features	71
Project planning	8	Casing	72
Reverse engineering	10	Assembly	73
Brainstorm	11	Coding	73
		Mechanical assembly	76
Research	12	Summary	78
Planning	13		
Literature research	14	Closing	80
Laboratory work	14	Discussion	81
Digitalization	16	Conclusion	84
Reverse engineering	20	References	86
Execution	22		
Requirement Specification	28	Appendix	90
Summary	30		
Design	32		
Planning	33		
User brainstorm session	34		
Execution	34		
Conclusion	35		
Ideation	36		
Company constraints	37		
Concepts	38		
Concept A	40		
Concept B	42		
Concept C	44		
Selection	46		
Material Selection	50		
Controller concept	51		
Final design	52		
Controller	54		
Casing	58		
Summary	66		

Background and motivation

During my bachelor thesis I worked on a redesign of an animal transfer station for an American manufacturer of laboratory equipment. When working on the project I was intrigued on how much the design was dictated by mechanical engineering and how little the engineers knew about the actual use of the product they were designing. From what I heard from experts in the same market, this disjoined between design and use was common among laboratory products. This lack of innovation was often ruled to be due to regulation and strict standards the products need to adhere to in comparison to a regular consumer market, but I saw more opportunities here. During the project, I found there is still quite some room to improve usability without sacrificing the performance of the products.

With the bachelor thesis focusing on redesigning some parts, I wanted to try and improve a product from scratch, which is where this master thesis came in. It gave me the possibility to tackle a design project for laboratory products in a non-industry standard way, build a high-fidelity prototype to see if my design was well thought through and test the result of my efforts with an end-user.

Orbital shakers

In laboratories, shakers are used for homogeneous mixing of liquids or growing samples in a moving condition. The shaker this project focuses on is the orbital shaker, which is a shaker where the product is placed on a moving platform with a certain distance to the central axis. Orbital shakers usually come in small tabletop sizes, where one shakes at laboratory temperatures. When one needs different temperatures or humidity that one can find in an incubator, one can opt to use the orbital shaker in an incubator like CO₂ shakers or use incubated shakers. These shakers work in a comparable manner, but have the product in a closed, incubated environment while shaking. As well as small tabletop sizes like regular orbital shakers, or in large, stackable sizes, taking over the functions of an incubator as well.

This distance at which a shaker shakes, is called the orbit and can be of different length, depending on the type of research conducted, regulations followed and purpose of the shaking. For example, European academic research usually uses 20mm, while American academic research typically uses 25,4mm. 50mm is also used, although sporadically, for slower, steady mixing of chemicals.

Shakers usually also have a variable time and speed setting, ranging from 50 – 350 rpm. Mechanically, smaller shakers are powered directly by a third party DC motor, but versions also exist with a V snare or original magnetic drive. On top of the basic shaker, many options for different top plates and racks can be bought, depending on the type of vial the product will be mixed in.

University of Twente bioprinting laboratory

The laboratory on the university that I have contacted for assisting in this project is the bioprinting laboratory in the Westhorst. Bioprinting uses networks of PTMC or other materials with biocompatible properties to print scaffolds for arterial tissue engineering. These tissues need vascular networks for nutrients or simulated tissue responses. By controlling the mechanical and chemical properties of a cell's environment, the tissue remodelling can be controlled to create large vessels as well as smaller capillaries for research. The laboratory holds multiple rooms where shakers are used, and this makes it a lot easier to get a better understanding of laboratory work and shaker usage.



Research question

The assignment goal is to design a new orbital shaker specifically designed to fit safer laboratory working protocols, as well providing a basis for integrating the orbital shaker in an increasingly digital laboratory environment. This results in the research question:

**HOW CAN AN ORBITAL
SHAKER BE REDESIGNED
TO BE BETTER ADAPTED
TO FUTURE LABORATORY
USAGE?”.**

METHODOLOGY

Project planning

To get familiar with orbital shakers and laboratory work in general, research was carried out in several aspects that could be encountered in this design project. To structure and plan this project, an adapted version of the double diamond model was used (UK Design Council, 2019). The original method has, as the name suggests, two diamonds visualizing two diverging and converging thought processes throughout the project. For this project, a third, smaller one, was added to include prototyping and user testing. When building the prototype, some problems require on the spot solutions that were not thought of beforehand in designing. These solutions are then put to the literal test during testing, where new problems associated with these solutions would arise, thus diverging again into finding new solutions. An example of these 3 diamonds can be found on the left in figure 1, with the planned contents of this project.

For every major chapter, a diamond is filled with smaller subjects of work, which roughly match the expected planning of the whole project and its parts. Every chapter in the report contains one diamond and its content. The planned diamond and its content are discussed at the start of each chapter, while at the end of each chapter, a revised diamond is discussed which shows how the project part actually went.

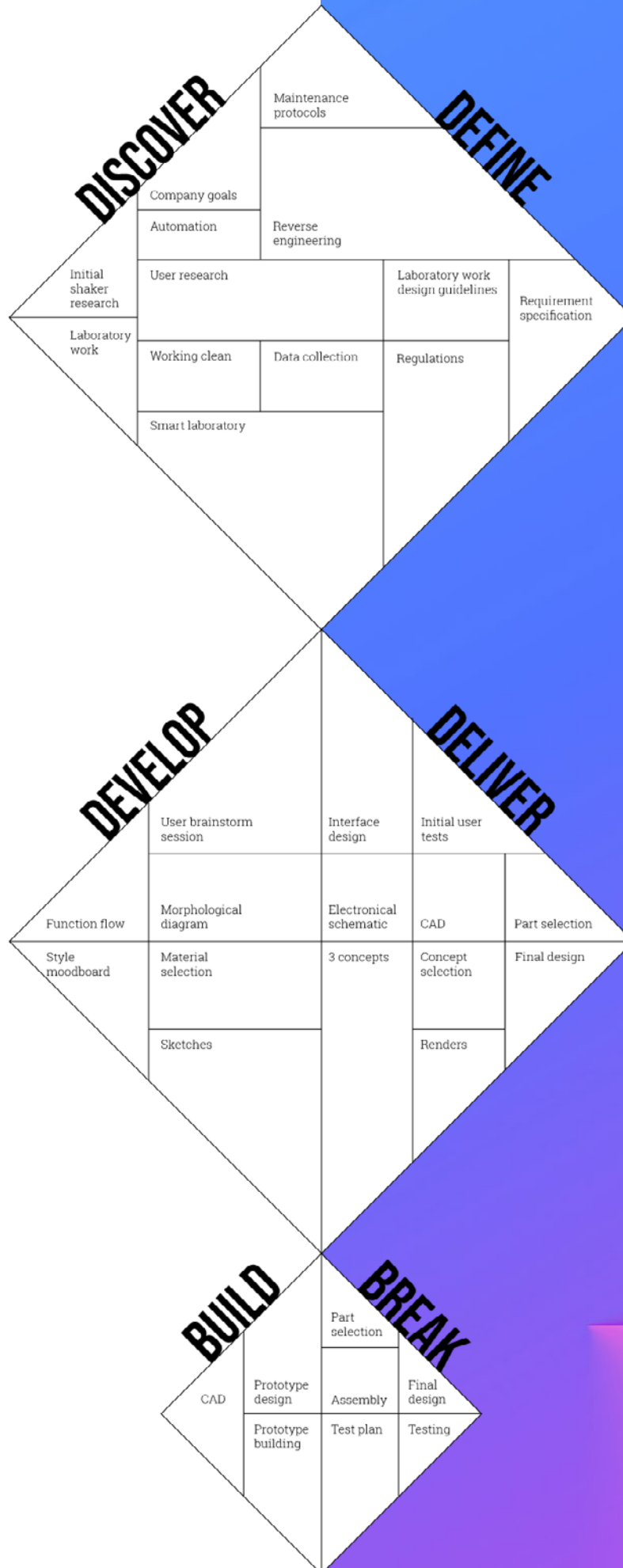


Figure 1: Double (triple) diamond diagram for the project planning

Reverse engineering

Since the to-be designed shaker is not a completely new product, rather a specific adaption of a general use shaker, it was decided to reverse engineer some competitive products with characteristics that are relevant for the new design to adapt. Three different competitor products were reverse engineered with distinctive characteristics, which are explained in detail further in the report on page 23. The methodology however, is explained here.

Product evolution

The method used is the Product Evolution reverse engineering and redesign methodology (Otto & Wood, 1998). This methodology is at its core a redesign methodology, meaning that a current product is used as basis of a redesign for that same product. It has 3 distinct phases: reverse engineering, modeling and analysis, and redesign. The first phase, reverse engineering, focuses on treating the product as a black box, experiencing it only by its operating parameters with respect to customer needs and predicted functionality. Furthermore, this phase includes a full disassembly of the product, a design for manufacturing analysis, functional analysis and the creation of final design specification based on the above. The second phase entails the development of design models, analysis strategies and experimentation. Based on these results, a product redesign is created in the third phase.

Each phase has several steps to follow, where the first phase starts with *Investigation and hypothesis*. Here, the product is treated as a black box where its internal functions and components are to speculation and the product is fully defined by how it is experienced in real

time. In the next step *Product teardown*, the product is taken apart and documented in a structured manner. In the last step that will be followed, the *Function structure* is analyzed, concluding with a morphological matrix and engineering specifications. A diagram of the original method can be found in Appendix A2.

Brainstorm

At the beginning of design processes, the designer often assesses the concepts and solutions it devises itself, instead of submitting the design solutions to external judges (Bonnardel & Piolat, 2003). This only happens later in the design process when solutions are worked out in a presentable manner to be validated. However, the design process can also be assessed by an external audience like future users. Methods like brainstorming or functional analysis can stimulate creativity in early design phases, as well as help provide the designers with clearcut principles and criteria to further their design process (Chulvi, Mulet, Chakrabarti, & López-Mesa, 2012).

Since the design environment of a shaker is inherently narrow, it was decided to use brainstorming to kickstart the design phase, which was created to counteract the tendency to terminate a solution-generating process too early (Osborn, 1953). This is especially necessary, since the start of the project was spent on reverse engineering existing solutions, which already put imaginative boundaries on generating ideas for problems that one has already seen multiple solutions for. To also include more external judges into this design project, it was decided to involve possible future users in this brainstorming session as well, of which the outcomes can later be assessed separately (Nelson, Buisine, & Aoussat, 203). The inclusion of future users is especially important since, as stated in the research into smart functionality, the benefit of this technology is very dependent on how it interacts and supplements the work of the user, which is why the brainstorm would mainly focus on interaction and connectivity of the product.

Analogy and constraint management

The brainstorming session is structured along the Analogy and Constraint Management (A-CM) model, which highlights the roles of two cognitive processes within design (Bonnardel, 2000). Analogical thinking or more specifically idea generation will lead designers to open up their idea space to new solutions, while constraint management allow designers to narrow their focus to assess the solutions and their derived constraints (Bonnardel & Didier, 2020). Based upon these two processes, two brainstorming phases are performed. The first phase, evocation of ideas (IE), focuses on encouraging participants to come up with creative ideas and uses a post-it like creative space to create a word web with possibilities. With the designer acting as moderator, it is important that the participants express all ideas that come to mind and write them down, rejecting any self-censorship. The second phase, evocation of constraints (CE), is intended to evoke the participant to manage the constraints related to the design problem and solutions they have come up with in the first phase. These constraints can be derived from the participants' previous experience (constructed constraints) or from the combination of previously defined constraints and ideas (deduced constraints).

PREFACE

Contents

In the first chapter one will research laboratory work and practices, as well as interview some future users and laboratory technicians to verify the literature research. Furthermore, research into competitive products will be done by performing a reverse engineering analysis on 3 different products. The planning of this phase is discussed up front on the next page, while its eventual course is evaluated at the end of this chapter.

The full diamond of the analysis phase can be seen below (figure 2). It will start with some exploratory research in shakers and orbital shakers, as well as laboratory work in general. In terms of direction, the top half of the diamond is largely meant for research pertaining to a shaker itself, while the lower half pertains the laboratory environment where the product is used in. This includes the laboratory itself, the users as well as any

working guidelines and legislation, but also recent and upcoming innovations that might be useful to be aware with when designing the product.

The analysis is set to span a 3-month period, this to include more in-depth user research and product research (reverse engineering) after the initial literature research, to get oneself better acquainted with the product and laboratory.

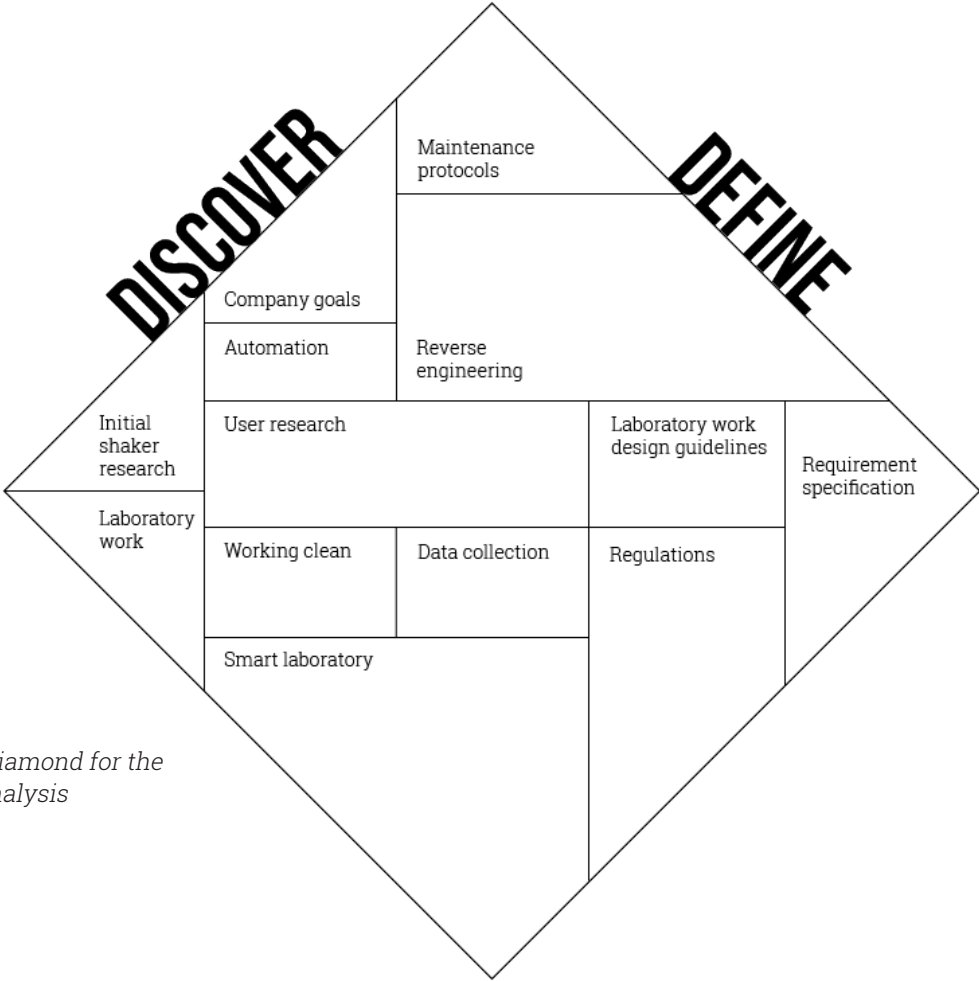


Figure 2: Diamond for the planned analysis

LITERATURE RESEARCH

Laboratory work

In laboratory work, the technician follows a set of steps to complete the required tasks, called a protocol. This protocol is thought out before hand, printed on paper, and brought in the lab or send to the notebook or tablet already present in the laboratory. During the experiment, the technician follows the steps or instructions of the protocol while making notes of the results and parameters in their laboratory journal. This journal can be a notebook exclusively used for this matter or a digital notebook on a laptop or tablet. Laboratory work consists of a lot of different, smaller tasks as preparation for one end result. The laboratory technician (or user) uses a lot of different tools but performs only a handful of operations, just in many different ways. These different operations can be categorized as seen on the right: (Arnstein, et al., 2002):

The orbital shaker falls in the categories of combination and incubation, depending on the exact use in the laboratory. When the shaker is used as a tabletop shaker under laboratory room temperature and conditions, combination is the core purpose of a shaker. When the shaker is used in an incubator for a longer period of time, usually coupled to low rotation speeds, the shakers' purpose is incubation. Thirdly, a combination of both uses is possible as well for when the technician wants to combine entities under specific conditions. Finally, the purpose of a shaker can be expanded by adding smart functions, creating a use in detection.

Design guidelines for laboratory

Following the above summarization, one can write up basic design guidelines on laboratory work (Arnstein, et al., 2002). Since laboratory work already consists of so many different tasks, adding smart functions to products should not result in adding an extra task for the technician to do. For example, having the technician supervise the output of a monitoring system that senses errors, since this will require extra steps to be done by the technician in relation to not having the equipment and thus having to check for sensor errors themselves. Furthermore, experiments done in laboratories can differ from time to time, so any monitoring or smart system should be flexible enough to adapt to a changing layout and/or work. Similarly, technicians needs various types of information during their work, which should be accessible at any times with as little effort as possible. This information can be for example:

- Check the experiments progress against a previously made plan (or protocol)
- Refer and compare results with historical data and experiments
- Capture information in multiple formats
- Share information with other lab workers

Working clean

Evidently, laboratories working with bacterial organisms or reactive chemicals have strict regulations and cleaning protocols while working. The details of these regulations tend to be different in each organization, company, or educational institute the laboratory belongs to, but there are some overarching rules that are applicable in almost every laboratory.

Equipment is usually cleaned with ethanol (75%), killing all bacteria that might react to new experiments. This can be done in between experiments, but sometimes also multiple times during an experiment. New equipment, like a freshly bought shaker, entering the lab undergo a similar treatment. An obvious consequence for the shaker is that the outer surfaces should be resistant to ethanol.

Another way of cleaning is full sterilization in an autoclave, which is mostly done in conjunction with cleaning with ethanol, depending on how strict the protocols are. Sterilizing in an autoclave means that the equipment is placed in a pressurized chamber and heated to a maximum of 150 degrees Celsius. These temperatures are reached by filling the chamber with steam, which is then heated due to the high pressure for a set amount of time (Technical Safety Services, 2020). After the procedure, the equipment is cleaned of any contaminants of biological material. Due to an increases push to working safer, sterilization is used more often, and more types of equipment is asked to be sterilized, including shakers.

COMBINATION

Forming one entity out of two or more.

INCUBATION

Exposing a collection of entities to specific environmental conditions over time.

DISPENSING

Extracting a collection of entities from another non-selectively (same relative distribution).

SEPARATION

Extracting a collection of entities from another selectively (based on some physical property and range).

DETECTION

Recording the properties of an entity or collection and storing the data.

STORAGE AND RETRIEVAL

Naming and storing an entity or collection for later reference and retrieval.

Digitalization

Data collection

As mentioned before, the collected raw data of experiments in a journal is later analysed outside the lab. Recently, there has been an increase in the use of digital notebooks (lab journals) for experiment data collection, especially in the pharmaceutical industry, where this is the current standard (Nussbeck, et al., 2014). In academic life-science laboratories, however, there now exists an intricate mixture between paper-based and digital annotation, which is slowly moving towards a fully digital journal. The UTwente Bioprinting laboratory that is connected to this thesis is currently in the process of transferring to a digital journal called eLabJournal, but it can also be as standard as Microsoft OneNote or GoogleDocs (Guerrero, et al., 2016). Digital annotation will make it easier for the technician to later review their notes of the experiment, as well as serving for a better standardisable and re-analysable collection of notes, tying into the increased need of good scientific process, collecting as much (usable) data as possible. Furthermore, having notes digitally available straight away, makes it a lot easier to share results with other technicians in the lab during work, making information better accessible in less time (Giles, 2012).

Reproducibility of scientific experiments

Another factor pushing the digital journals is the increasing amount of focus on the reproducibility of scientific research. According to a study from 2016, 70% of researchers have tried and failed to reproduce other experiments (Baker, 2016). This rating being especially high in the field of cancer and medicine research, sporting only 10% reproducibility, sometimes resulting in a costly failure later in medicine

trials (Begley & Ellis, 2012). Although main causes are thought to be selective reporting and pressure to publish, 40% of scientist think that the unavailability or inaccuracy of the original raw data also contributes to the problem. This is why there is both a push from research institutes as well as publishing agencies to better collect the raw experiment data in understandable form. Digital data collection can help give a detailed, standardized overview of the raw data from experiments, since no technician is tasked with taking these notes (Groth & Cox, 2017). It also adds to the narrative overview of a protocol with hard parameters, making the recreation of computational models a lot easier to accomplish (Gil & Garijo, 2017).

Smart Laboratory

Apart from an increased need for working clean as mentioned before, there are also numerous innovations happening in the area of digitization in the laboratory. A majority of research is done into creating a safer and more pleasant laboratory environment to work in. By fitting the room with sensors to measure things like air quality, humidity and temperature, the productivity and health of the technicians can be boosted by optimizing the environment for work. However, it can be that the optimal environment for humans to work is different from the optimal environment for the equipment to work reliably (Samonte, Mendoza, Pablo, & Villa, 2021). Combine these sensors with personal RFID tags to monitor technician presence, electricity can be saved when no technicians are present (Poongothai & Subramanian, 2018) (Banagar & Khatrar, 2020). However, when it is visible online when laboratories are staffed or not poses a clear security

risk as well, opening an opportunity to tamper with parameters or damaging experiment equipment and samples, so not all laboratories are interested in such systems. Keeping the laboratory environment more constant is not only beneficial for the long-term health of the technicians but can also benefit the reliability of the equipment and the laboratory samples that are researched, thus increasing the quality of the research as a whole. It can also give the supporting staff better insight in the usage of equipment and their workload, supporting them into better scheduling maintenance and replacing machines before a critical breakdown (Khriji, Houssaini, Barioul, Rehman, & Kanoun, 2020) (Li, Gao, Wang, & Zhang, 2020).

Using smartphones

Since technicians already carry and use their phone during laboratory work, the incorporation of smart phones is a logical step. The usage of IoT and smartphones can let users interacted with the laboratory equipment without having to physically be present (Samonte, Mendoza, Pablo, & Villa, 2021). For example, technicians can check the progress of their cell growth in incubators with a build in camera, as well as the incubator environmental factors in order to spot divergent numbers from the ones set. This can help spot problems with the incubator or indicate when it is time for a service, especially useful when the samples in the incubator are of high value, meaning the loss due to equipment failure is even bigger. Furthermore, lab wide sensors measuring air quality, combined with smart phone connectivity, can directly inform the personnel when a spillage or danger is sensed (Lei, Liang, & Man, 2013).

Remote laboratories

In educational laboratories on universities, smart equipment can be used to facilitate remote laboratory work or interactive experiments for students, especially beneficial when students cannot be on-site or when there is not enough capacity to let every student do the experiment themselves (Garcia-Loro, et al., 2021). However, there are many reasons why such remote laboratories are a very rare occurrence. First off, there is a lack of commercial products that either already have these sensors equipped or services that add these sensors to existing products. This mainly due to the multidisciplinary nature of such a system, integrating hardware interfacing, data gathering, application development, networking, real-time control, and cyber security. Such an intricate combination of systems made-to-measure for every laboratory, means that there is no modular design strategy since each laboratory has different wishes and works with different protocols. Given the complexity of the system, it also means that maintenance personnel are short. Most current systems are managed by interested students or teachers, meaning that every laboratory is forced to reinvent the wheel in making such a smart system. Another downside for educational institutes is the absence of learning management integration in the system, such as Canvas, Blackboard, etc. This because any of these systems are one-offs and it is thus not economically interesting for learning system companies to integrate this. Finally, all of these reasons snowball into the last one, namely that many administrators do not see the direct monetary benefit of such a system (Azad, 2021).

Automation

In terms of automation, technological advances are carried by needs of the pharmaceutical and biotechnology companies (Rutherford & Stinger, 2001). However, existing laboratories are different to renovate. The lifespan of laboratory equipment is so long that equipment can be replaced one by one, meaning that replacing several machines by a single automated machine turns out very costly in existing laboratories. It can however be an option in newly build laboratories, but the market for machines capable of doing a large array of different tasks is small and thus expensive (quito). Therefore, the majority of robotics used in laboratories come into play in analysing samples and recording data. Another big portion of laboratory work where the usage of automated systems is increasing are disposal systems of waste and samples, with the added benefit of doing this work cleaner, since the technician does not have to interfere (Naugler & Church, 2019). Smaller products have shared in these innovations as well, with pipetting systems utilizing automated portioning and dispensing, pipetting can be done with more accuracy than before (Thermo Fisher Scientific, 2021).

A place where automation has not broken through yet is the performance of tasks and following the experiment protocols. The technician can be assisted by, for example, a voice assistant when doing the “dumber” repetitive tasks of certain experiments, since it is these parts of protocols where the most mistakes are made (Gill, 2018).

Affecting the technician

Not only do these added sensors have benefits for the whole laboratory, but it can also change the daily workflow of the technicians for the better as well. Having equipment save their experiment parameters in a cloud-based system, removes the need for technicians to write this down during their work and makes it easier to view this info later on (Perkel, 2017). It can also help increase the productivity of an experiment, since technicians can get an automated notification when a machine is finished with its task, preventing the need for the technician to be present and watch. The biggest benefit however is helping technicians save results in digitized form, removing the step for technicians to convert their paper notes onto a screen. However, fully incorporating the needed sensors in equipment is difficult without help from manufacturers and without dramatically changing the workflow in the whole laboratory, thus changing the role of the technician in a laboratory (Arnstein, et al., 2002).

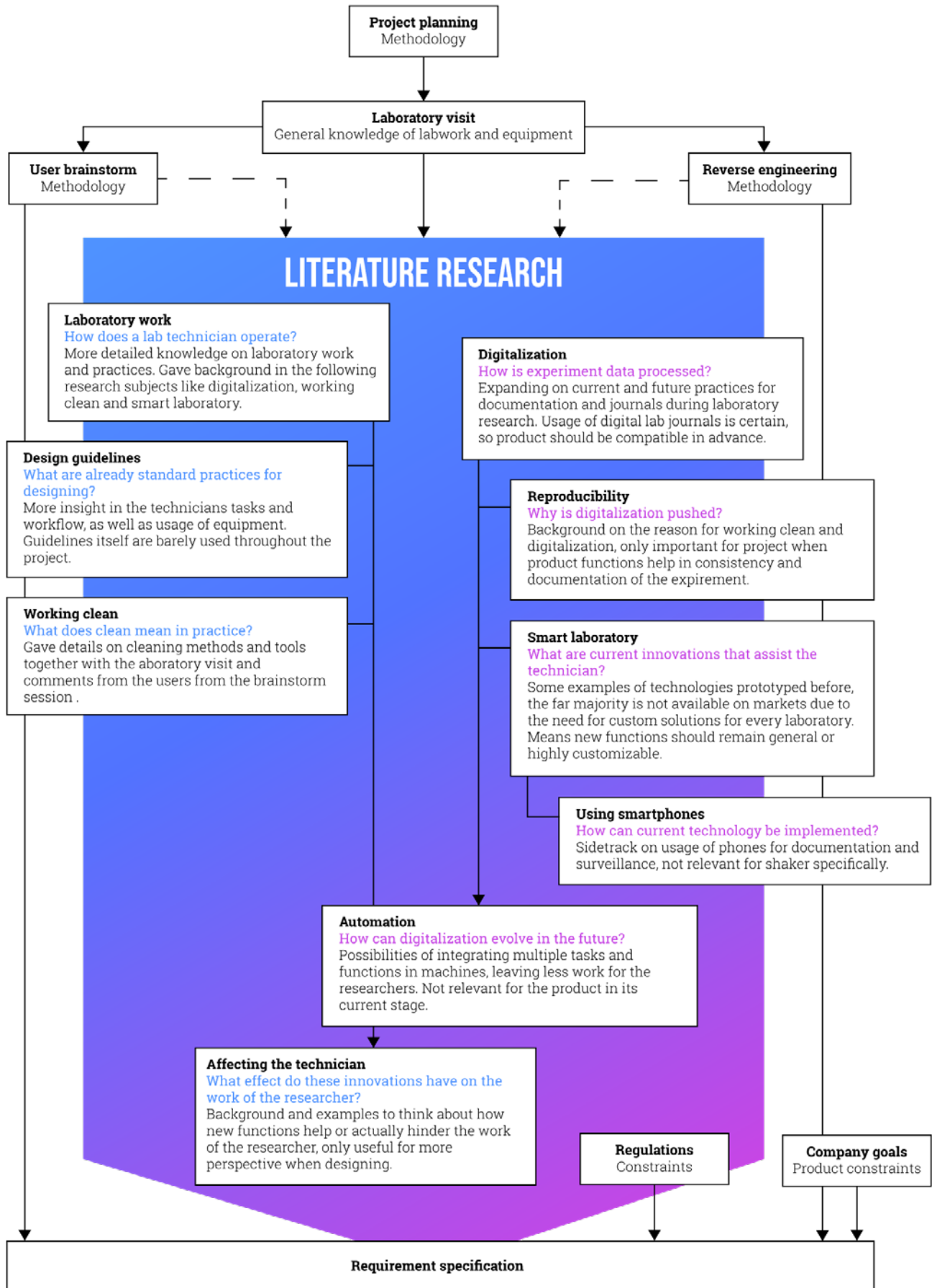


Figure 3: Overview of research performed and how it affected the requirement specification and thus the design of the shaker.

REVERSE ENGINEERING

Adaptation

As mentioned before, this project will use the Product Evolution method (Otto & Wood, 1998) as a basis for reverse engineering some competitor products. However, some adaptations will be made to make the method fit the specific situation of this project. Since this project, the products that are reverse engineered are competitor products and not the manufactures own products as is the case in the method, as well as the newly designed product requiring characteristics that are not present in the competitor products, the main use of this methodology lies in the first phase (reverse engineering). Consequently, the methodology is used as a basis for performing the reverse engineering tasks than that it is strictly followed.

Before actually taking the product apart, an initial problem statement is created, as well as a black box model of the shaker and an overview of customer needs. These steps are the same for all three competitor products and can thus be done once. The research into economic feasibility is skipped, since working on this project has already deemed it economically feasibility in the first place. After the initial problem investigation and creation of a black box model, a hypothetical function flow model is created. Since this model will solely be based on the customer needs, it will again be the same across all three competitor models.

After this the products will be disassembled according to the methods reverse engineering steps, this includes any possible exploded views, lists of steps for disassembly, subtract/operate procedure and simplified electrical schemes. One will not create a BOM of each

product, since this will take up too much time to do thrice, as well as it will not be relevant for the newly designed product. For similar reasons, creating a morphological matrix and function sharing will not be done, while function structure and engineering specifications will be briefly touched in a qualitative judgement. This section will note anything interesting about the product found out during disassembly. The design models and design analysis that follow the product teardown will not be followed, since this project will not make a product that is fully comparable to the disassembled products. A qualitative judgement was added after each product teardown, where remarks and comments on the entire unpacking, disassembling and functioning of the product are noted.

Products

A detailed comparison of features and specifications can be seen in the table in Appendix A1 (N-BioTek Inc., 2021) (Biosan SIA, 2021) (OHAUS Europe GmbH, 2021). Each column of this table is filled in based on the online brochure, meaning terminology can be different for the same type of parts. Furthermore, not every specification or feature can be mentioned in every brochure, while it can still be present in the product.

N-BioTek NB-101S Mini Shaker

This shaker is a basic model, (figure 6) not meant to be used in incubators. It was already present in the distribution company and did not have to be ordered separately, which is why this shaker was disassembled first. Since it is a base model and thus not too complex, it will also be a good introduction to shaker products.

BioSan CPS-20 CO2 Platform Shaker

The second shaker is the BioSan CPS-20 (figure 4). In the laboratory market, BioSan products are known to be as simple and straightforward as it can be, without losing quality, meaning that this product is especially interesting for its low-cost and quality balance. It is a CO2 shaker, meaning it will have a detached interface, unlike the N-BioTek shaker.

OHAUS Extreme Shaker SHEX1619DG

The third shaker is the OHAUS Extreme Shaker (figure 5). This shaker is in a higher market segment compared to the other two, meaning specification wise it is just a little better than the BioSan shaker.



Figure 4: *BioSan CPS-20 CO2 Platform Shaker*



Figure 5: *OHAUS Extreme Shaker SHEX1619DG*

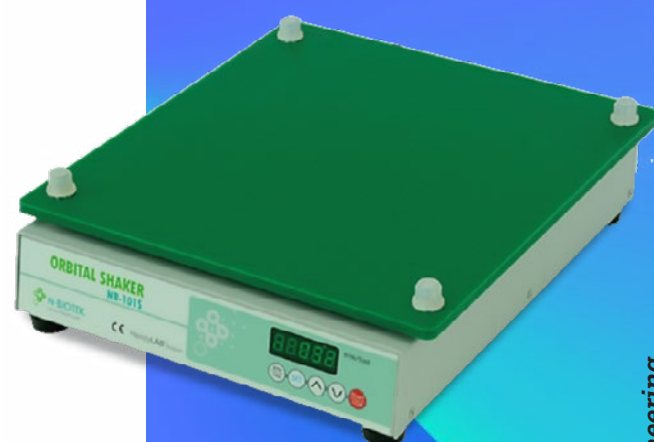


Figure 6: *N-BioTek NB-101S Mini Shaker*

Execution

As mentioned in the methodology, the reverse engineering theory is executed in 3 phases, each with their own number of steps, with the first step being Investigation and hypothesis. One will only perform the first phase, which starts with the step Investigation and hypothesis. Here, the product is treated as a black box where its internal functions and components are to speculation and the product is fully defined by how it is experienced in real time.

Investigation and hypothesis

Initial problem statement

This project was started by the perception of the user need to fully decontaminate a shaker in an autoclave by heating the product to 150 degrees Celsius, enabling correct use of the product in an incubator.

Black box model

The black box model of a laboratory shaker can be seen below in figure 7.

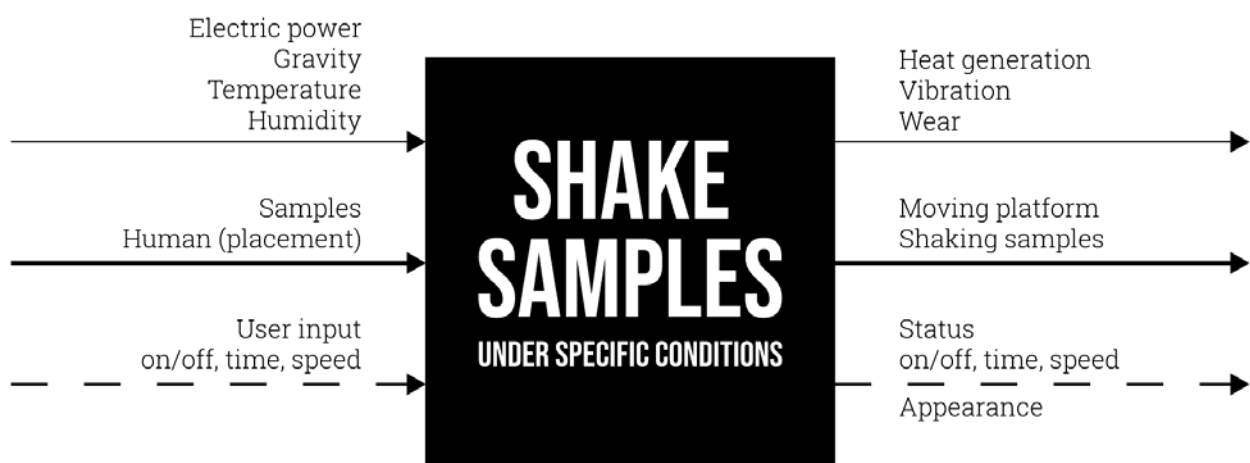


Figure 7: Black box model of a laboratory shaker

Customer needs

The customer needs were created based on the interviews with the laboratory on the University of Twente done before. The table that was the result of these interviews for reverse can be seen in Appendix A3.

Hypothesized function flow diagram

The hypothesized function flow diagram can be seen below in figure 8 which is based on the black box model of figure 7.

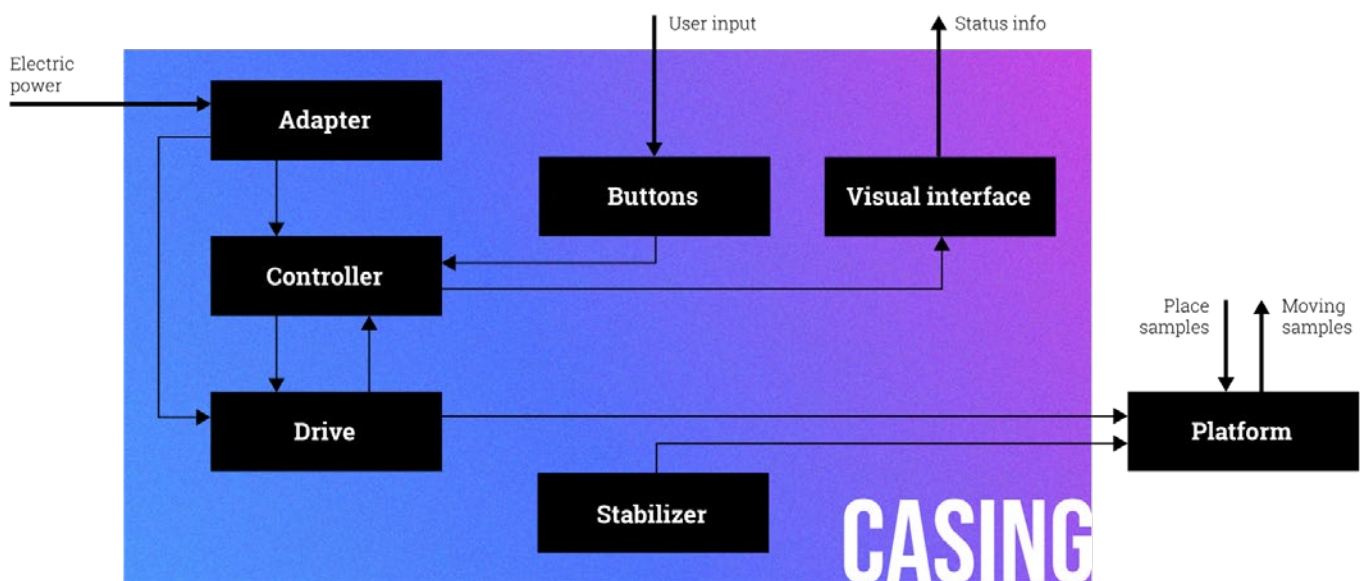


Figure 8: Hypothesized function flow diagram of a laboratory shaker.



Figure 9: Top view of the shaker packaging when taken from the box

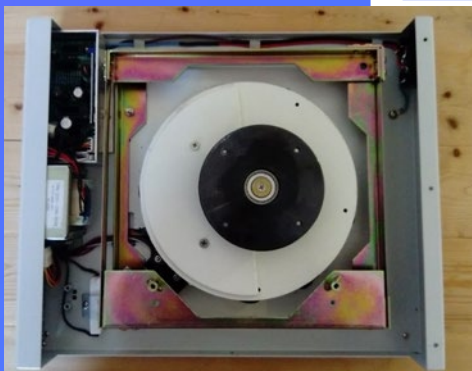


Figure 10: Top view of the internal mechanism

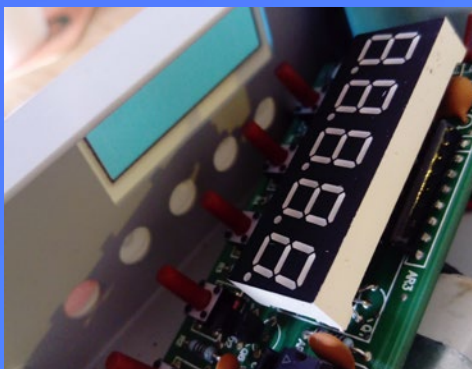


Figure 11: Interface and printplate

Product teardown

During this step, three different shakers are disassembled, starting off with the N-Biotek and after that BioSan. The OHAUS shaker was newly ordered but had a lot of delay in ordering and only arrived 2 months after the planned date, once the project was already well into its ideation phase. However, the reverse engineering was still done so the three shakers could be compared.

N-BioTek NB-101S Mini Shaker

The shaker used a self made motor on a central axis. The stabilizing mechanism consisted of flexible frames in X&Y direction which, for its simplicity, works surprisingly well. A speed sensor is used to create a feedback loop to adjust plate speed when it is weighted down, but it is covered in epoxy so it is not removed. The interface had the basic functionality of speed and time and is understandable without requiring checking the manual. The full qualitative judgement can be seen in appendix B1.

Subtract and Operate Procedure

The main goal of the subtract and operate procedure in this product was to find out the function of the epoxied printboard underneath the magnet on the drive mechanism, since this function could not be determined by its outside appearance. As start, some basic parts were taking off like the metal covers and top plate to make the inside of the shaker visible and better reachable when testing. When it was determined these removals had no effect on the actual operation of the shaker, functional parts were removed one by one to determine the printboard functionality, as can be seen in appendix B3. Eventually one concluded the printboard was an external speed sensor for creating a feedback loop to the motor control.

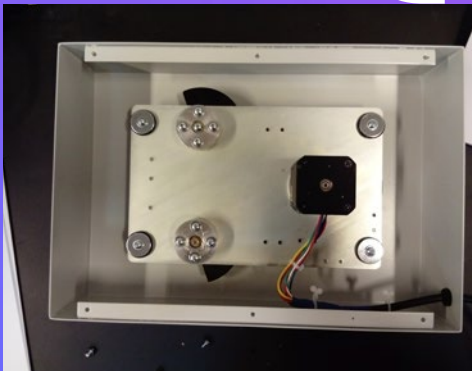


Figure 12: View of the mechanism from the bottom



Figure 13: Top view of the mechanism separated from the casing



Figure 14: The controller casing and printing plate

BioSan CPS-20 CO2 Platform Shaker

The detailed qualitative analysis of the BioSan shaker can be found in Appendix B4. The shaker appeared very well optimized to its usage and very compact. The only screws in the casing are on the bottom, leaving the top and sides clean and leak free. The mechanism uses 3 independent axes with counterweights where one is powered. The top plate that can be exchanged by the user is not fixed with fasteners but uses a rubber friction fit. The controller casing was 3D printed and consisted out of 4 parts; the front and back and their respective inside and outsides, probably to increase thickness and reduce printing time.

Subtract and Operate Procedure

Since the electrical components were all integrated in one circuit board, there was little to subtract in that part. Certain parts in the printing board could of course be disconnected or purposefully broken, but such detailed knowledge of the competitor circuit was not deemed necessary in this project.

Furthermore, the drive mechanism was understandable without having to disassemble it and the function of certain parts in that subassembly have already been showed in the previous SOP of N-BioTek. This is why this SOP was rather small with this product.



Figure 15: Top view of the complete OHAUS shaker

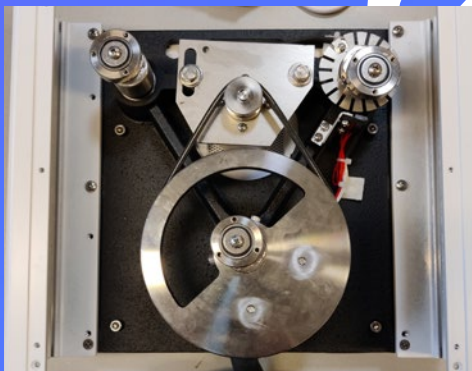


Figure 16: Top view of the mechanism, with the casted base in black



Figure 17: View of the controller, with a lot of plastic and little interface

OHAUS Extreme Shaker SHEX1619DG

The qualitative analysis of the OHAUS shaker can be found in Appendix B7. In general, this design is more excessive in complexity than the BioSan shaker, using a scaled down drive mechanism as usually found in larger table shakers.

Subtract and Operate Procedure

No subtract and operate procedure was done on this product, since the understanding of previous products was enough to not create any questions on the operation or parts of this shaker.

Function analysis

The function flow structure diagram can be seen in appendix B9. It uses the setups discovered in the reverse engineering of the three competitor shakers to create a comprehensive overview of an orbital shaker.

Morphological diagram

A diagram similar to a morphological diagram was made to summarize the different solutions found in the three disassembled products. Instead of showing the possible solutions, the columns show the solutions to each function chosen by the competitors. This diagram will serve as basis for a proper morphological diagram made afterwards. The comparison table can be found in appendix C1 and the morphological diagram that followed in appendix F1.

Conclusion

To conclude, the reverse engineering research was great to get better acquainted with orbital shakers, especially considering all three shakers were quite different in use and design. A summarized comparison of all three shakers can be seen in appendix C1. One learned the most from the BioSan shaker since it felt the most well efficiently designed and optimized for its use purpose. The mechanism was compact and reliable, as well as having material choices and thicknesses suited for its intended purposes and lifetime. The 3D printed casing was a surprise, but it makes sense considering the smaller number of units yearly compared to injection moulded plastic products. BioTek was a good example on how simple and functional the design can be, while OHAUS was the other way around. It felt overengineered with too much safety factors in the design, like it was originally made for larger shakers and scaled down to tabletop, instead of designed specifically for tabletop shakers.

REQUIREMENT SPECIFICATION

The requirement specification table can be seen in Appendix D1 and relative regulations in Appendix D3. Some general constraints and requirements for the product are explained in more detail below.

Temperature

Since the shaker has to be heated to 150°C, all parts in and on the shaker should be resistant to these high temperatures. This excluded the controller and interface casing, since when heated, these parts will not be present in the autoclave. Some specific parts of interest are explained below in more detail, like general structural materials, the motor and anti-vibration mounts.

Motor

Using an electric motor that can withstand heating to this temperature is extremely important. Motor temperature resistance is standardized in the NEMA Insulation Classes (National Electrical Manufacturers Association, 2022). This regulation classifies electronic motors in 4 different classes and their respective characteristics seen in Appendix D2. There are a couple of notes that one can make on how the temperature ranges in these classes are relevant to the project. First off, the classes are meant for operation temperatures. However, when the product will be heated, it is not in operation and not plugged in. Furthermore, the winding temperature is usually 20°C lower than the outside surface temperature ((HECO Inc, 2022)). So, when the product is heated for a short while, one could practically add 20°C to the temperature resistance. This means that for heating the shaker to 150°C a Class B insulation could suffice, but a Class F insulation is preferred.

O-rings and anti-vibration mounts

Due to the circular motion of the product, anti-vibration rings and o-rings will be present in connections between the mechanism and casing, to help prevent the casing from vibrating. These parts are generally made from rubbers or silicones. Rubber is the most common material used, but due to the temperature constraints in this project, silicone is considered as well.

Liquids

Alcohol

As mentioned in analysis (part), a mix of 75% alcohol is frequently used to sterilize the surfaces of the equipment in laboratories. This comes with the obvious consequence that all outside surfaces should be resistant, which is why one focussed from the start of the project on primarily using stainless steel 403 for the casing. This also means that the plastic used for the controller as well as any rubber or silicone for seals and vibration mounts should not react with alcohol. Moreover, the shaker, both casing and controller, should leak proof to a certain degree in order to prevent the alcohol from short-circuiting the electronics or reacting with any materials inside the casing and controller.

Other chemicals

The shaker could also be used to mix chemicals instead of biological components, which is why it is important that the materials of the outer body are resistant to chemicals as well as being leak-proof to some extent. As mentioned before, laboratory products are cleaned with ethanol, reinforcing the need for chemical resistance, and preventing leakage.

General humidity

When used inside an incubator, humidity is often 95% RH, meaning any electronics need to be well insulated and covered. Furthermore, the casing will have to be leakproof, due to mixing of liquids on top of the product.

Fatigue

Due to the long lifetime of products in this market and shakers specifically, an important constraint is the resistance to fatigue of parts in the product. As mentioned in the research, shakers can sometimes run 24h a day instead of 8h of a standard working day, amounting to 87,600 hours in 10 years instead of 29,200 hours for 8h a day, meaning parts should be designed with a strong emphasis on reliability.

SUMMARY

In general, the analysis took a little longer than was planned. Firstly, the reverse engineering research was added midway, basically replacing, and expanding the competitor research. This meant that the methodology had to be research in detail, adapted and executed. While the shaker from N-BioTek could be

done immediately, the shakers of BioSan and OHAUS both met a delivery delay of 2 weeks and 3 months, respectively. Luckily, other work in the thesis could be done in between, so no time was lost on waiting, but it did mean that his topic was closed at a very late stage in the thesis (while designing the final concept).

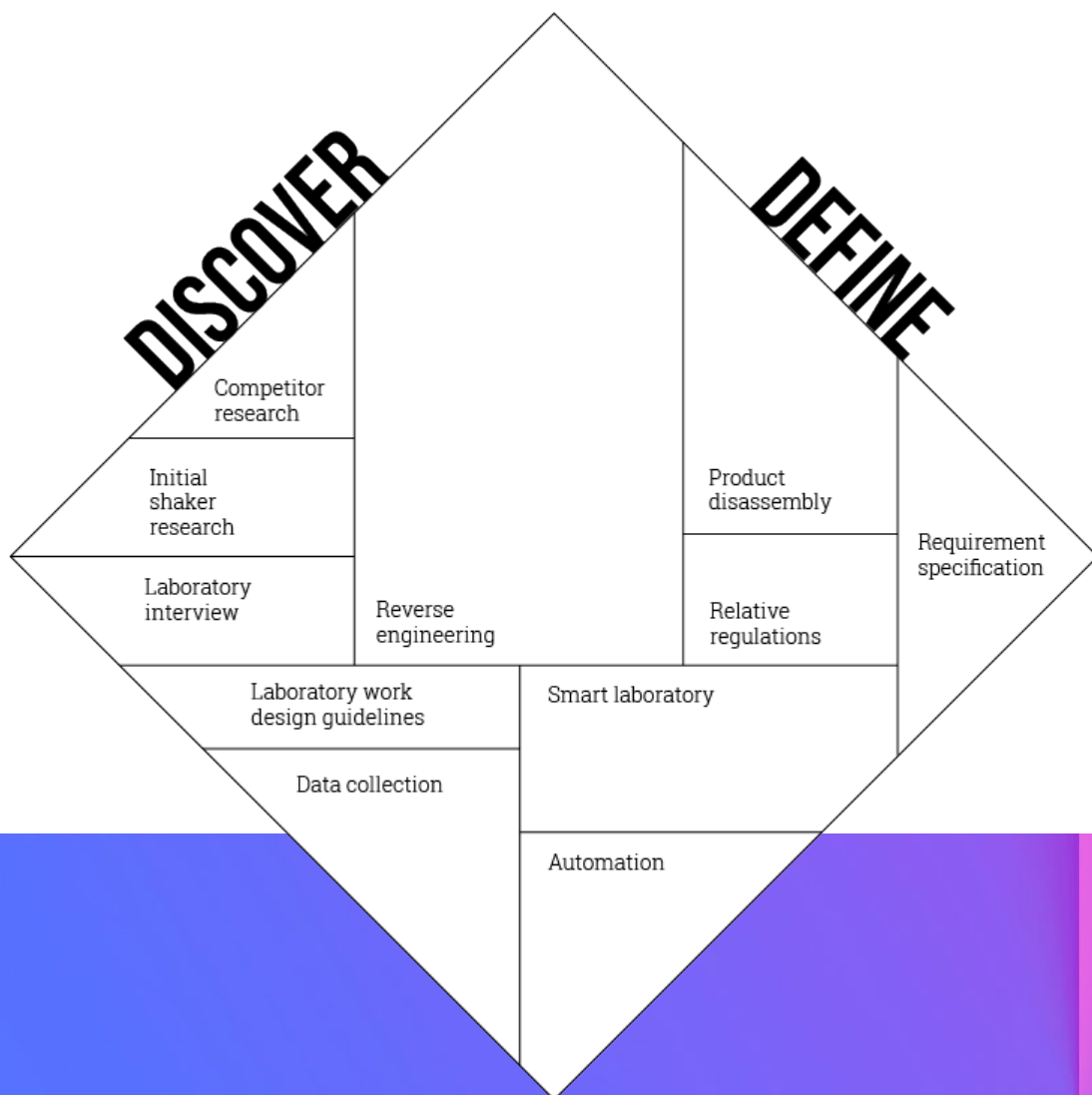
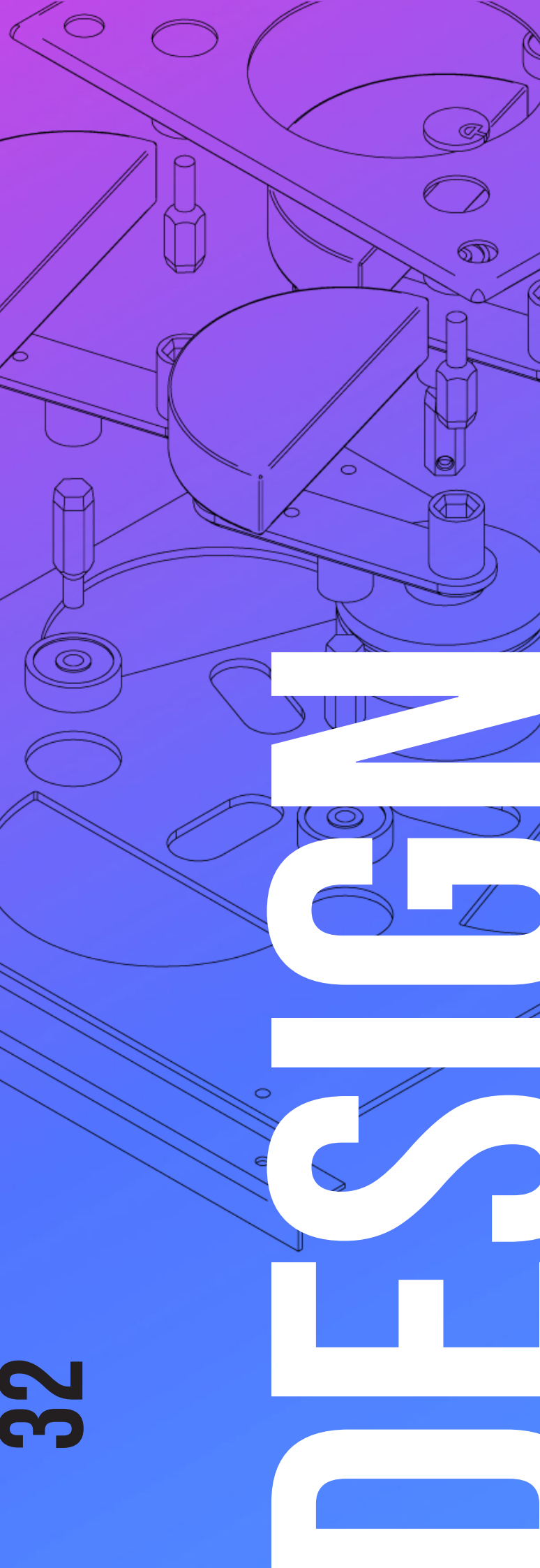


Figure 18: Research diamond as it was actually performed, with more emphasis on the reverse engineering research and product disassembly and less on the components of the literature research.





DESIGN

Contents

In the second chapter the ideation and design process for the conceptual design is documented. Once the concept was selected, a prototype was designed and build in tandem with the final design, but this process is documented separately in the next chapter.

PLANNING

After analysis, the designing phase was set to span roughly 4 months, after which the rest of the project would be spend on prototyping and testing. The subjects that were expected to be worked on can be seen in figure 19. The halfway point would mark the creation of 3 concepts, after which one would be worked out in more detail to be ready for a prototype design. The function flow and morphological diagrams all follow from the reverse engineering research

done before, while a user brainstorm session is organized to involve the users in the laboratory in the process as well as facilitate a way to apply the literature research. The phase will be finished with a conceptual design and complete CAD model of which the parts are ready to be adjusted to a prototype design.

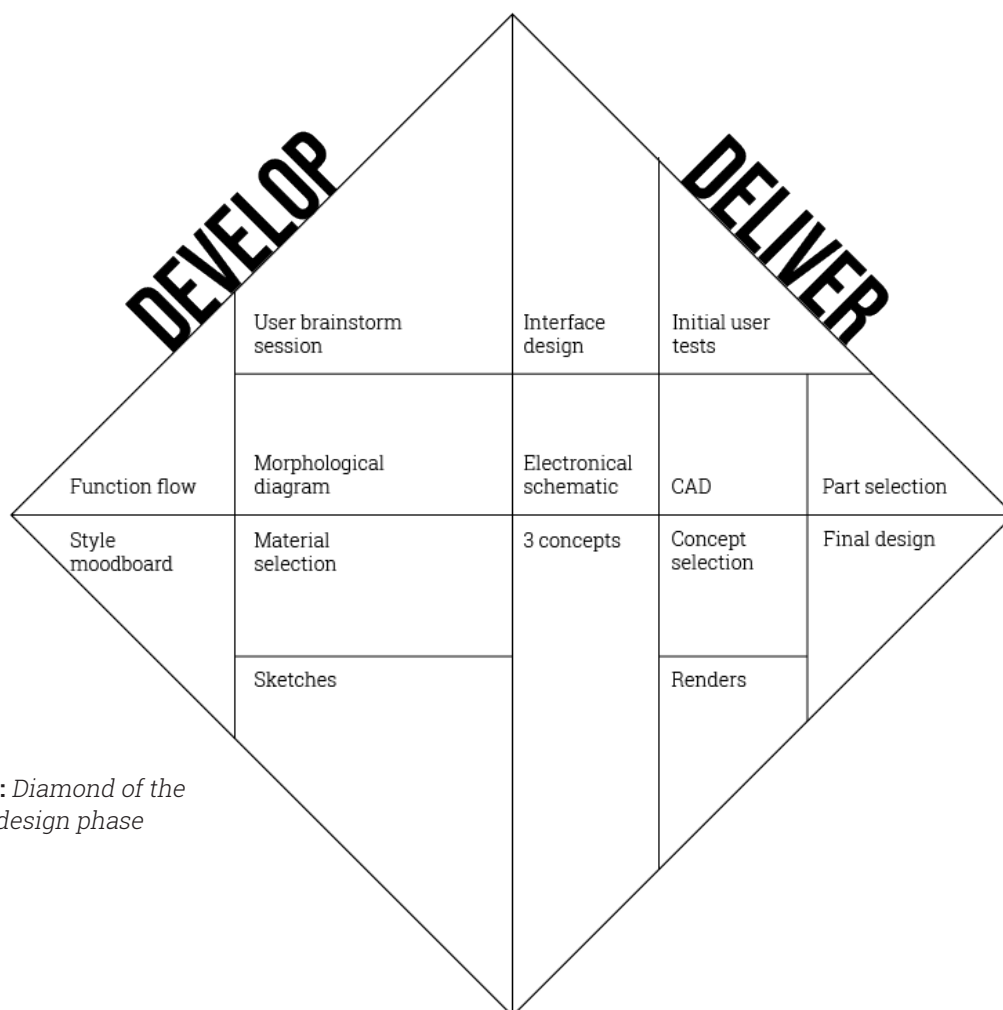


Figure 19: *Diamond of the planned design phase*

USER BRAINSTORM SESSION

Execution

The brainstorm sessions are done online and one-on-one with the moderator, which in this case was the project designer. First, the participants are explained the general premises of the project, after which they start with the EI word web. The goal of this starting point is to focus the idea generation on extra functions for the shaker. After this session, the created IE web is used as basis for the CE web, where the constraints are added on top of the IE web. Finally, the session will be concluded with a small discussion going over some of the most interesting ideas or constraints. The whole session will take roughly an hour maximum, so roughly 30 minutes for every phase. The full word webs can be seen in appendix E1 for the first participants and appendix E2 for the second participants.

Results

While some ideas mentioned in the brainstorm were already known via research or the initial interview, there were also new ideas that pushed the idea generation in different directions. An overview can be seen on the right. It was decided to include the history list in the final design and prototype, since this is a addition that could heavily change the workflow of setting up the shakers, it would be beneficial to change the user interaction with the interface. Although the addition of multi-functionality is interesting and worth mentioning, it would most likely be too advanced as a first product when also including the requirements set by the company, so this is ignored in the rest of the project.

HISTORY LIST FOR SETUPS

- Streamline repetitive tasks during an experiment
- Creates better reproducible research since the parameters are guaranteed equal
- Exact setups can be retrieved later for documentation

ALARM/NOTIFICATION WHEN FINISHED

- Shakers are not always situated close to where one works

MULTI-FUNCTIONALITY, REPLACING OTHER INSTRUMENTS

- Weight to replace scales
- Timer without shaking function to replace separate cooking stopwatches
- Connection to digital lab journals or computers to remove intermediate step of logging shaking parameters

Conclusion

The user brainstorming session was rather successful. During the first session the idea generation was sometimes difficult to keep flowing and one had to mediate the discussion back to new ideas, but this happened less in the second session. To prevent the discussion from slowing down, some standard questions could be thought of beforehand by the moderator and kept close during the session as a fallback option. Furthermore, the background graphic worked well doing what it was meant for, namely boosting the start of the discussion, but is ignored once the participants had come up to speed. During the first phase, it was often necessary to mention to participants to not think about constraints just yet, since it became clear new ideas were often followed by "but ..." and a number of constraints.

Ideally, the session would be repeated with more participants than two, as was currently the case. It would have also been beneficial of including researcher of the biolaboratory of the university. However, during the time the project required a brainstorming session, a lot of researchers from that laboratory were unavailable due to it being the Christmas period, so alternative options had to be found to prevent any delays. On the positive side, one can say that this inclusion of different researchers and their protocols makes sure that a wider array of users is represented in the research and design of this product, instead of a single laboratory.

IDEATION

Building on the user brainstorm session and reverse engineering results, one had a strong basis to start designing the actual product. One largely focused on 3 distinct parts of the product, namely the outside casing, the internal orbital mechanism, and the separate interface, since these 3 systems function largely independent of each other and also adhere to separate requirements.

Morphological diagram

A morphological diagram of all sub-solutions, combining findings of reverse engineering phase and the user brainstorm sessions can be found in appendix F1.

Moodboard

A moodboard on how the the design of the shaker should be perceived and feel can be found in appendix F2. It is worth noticing that the moodboard include a lot of mass-produced plastic products, enabling a lot more design freedom in comparison to the hand assembled metal shaker this project is about. Therefore the moodboard largely functions as for the design for the controller and interface.

In terms of design, the shaker should build a bridge between older equipment in a laboratory, while still fitting in with modern products and their more complex functions. Due to the requirements on cleaning and sterilizing, the laboratory product will have limited form and material freedom in its parts, so the design will take that as granted and play into that more instead of trying to do the opposite. This concludes to a rather minimal-retro look with only single curved surfaces and simple shapes to make it easy to clean.

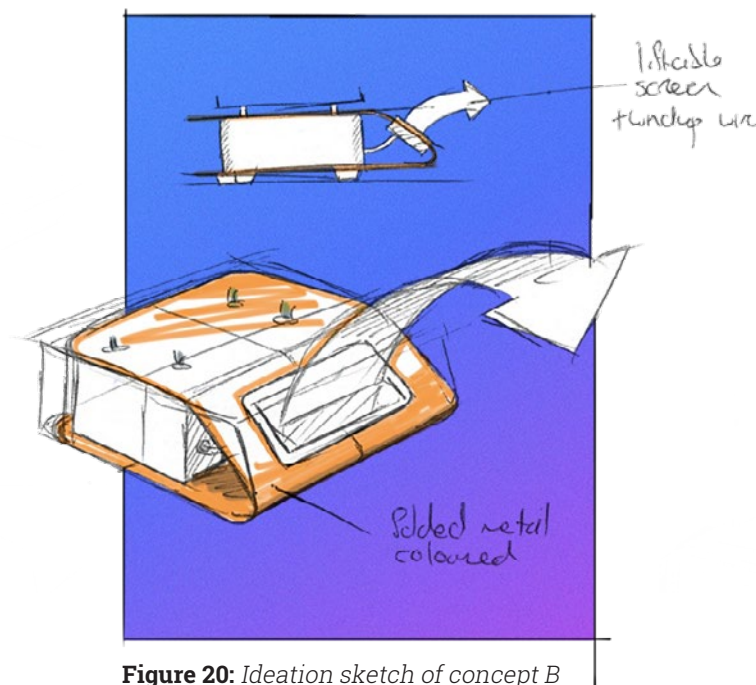


Figure 20: Ideation sketch of concept B

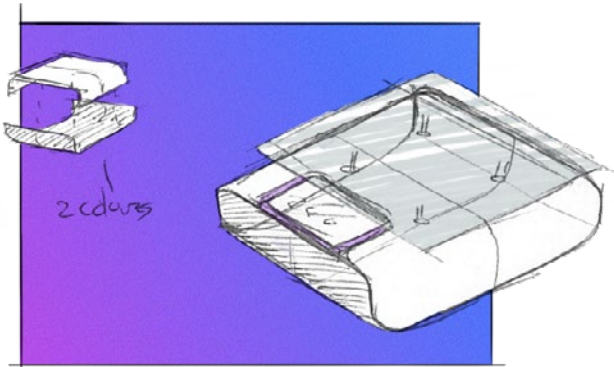


Figure 21: Ideation sketch of concept C

Company constraints

Although the previously mentioned morphological diagram assumes a total freedom of selection of solutions, the company has limits to developing the product and its parts in its current state. To start, this product will be their first manufactured product, thus for some parts it is preferred to use a third party part rather than reinventing the wheel themselves. Consequently, manufacturing will largely be an assembly of pre-manufactured or ordered parts, which with the limited number of products expecting to be sold when starting (roughly a 100), will be done by entirely by hand. This means that for electronical components like motors, displays, buttons or print boards, the design and the prototype will be limited to what is available by third parties.

It was also discussed that further focus on clever connectivity functions, like the multi-functionality that appeared in the brainstorm, should be secondary to the core mechanical design of the shaker. Later (software) functions and extra sensors can always be added later to compliment the shakers use once a baseline reliable model has rolled out. However, when some functions can be included in the prototype to be tested by users, this is only encouraged.

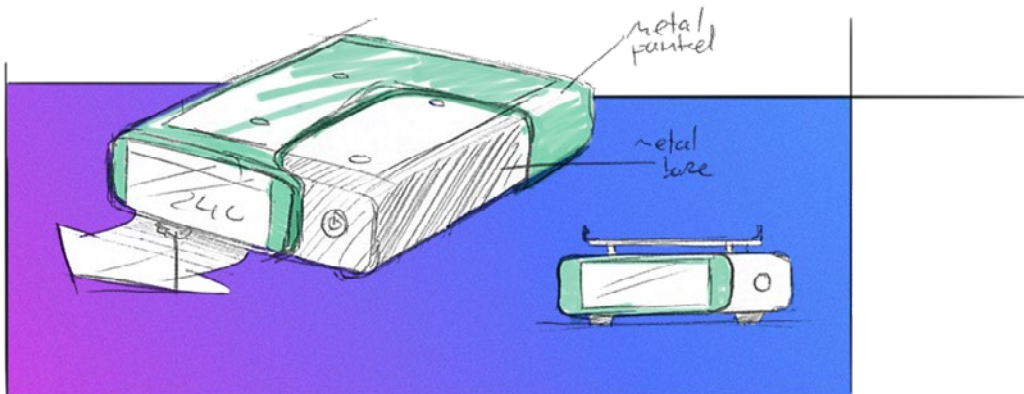


Figure 22: Ideation sketch of concept A

CONCEPTS

The ideation concluded in three concepts, each with a different internal mechanism, controller design and shaker body. Although the concepts are presented as one, the mechanism can be judged separately from the body, since it can be implemented in every casing body with small adjustments to the fitting. The same follows for the design of the interface, specifically the screen and digital user interface. This is why any ideation on design for this feature is done after the selection of a concept, once the screen size is known, which could already be seen in Appendix G1.

Morphological diagram comparison

Using the morphological diagram made previously, a comparison of all three concepts is created by connection the different solutions. This comparison can be seen in Appendix G2.

Presentation

On the following pages, the concepts in figure 23 are presented like they were to the company. A discussion paragraph and a strengths/weaknesses table is used to summarize the comments following the discussion of the concepts.

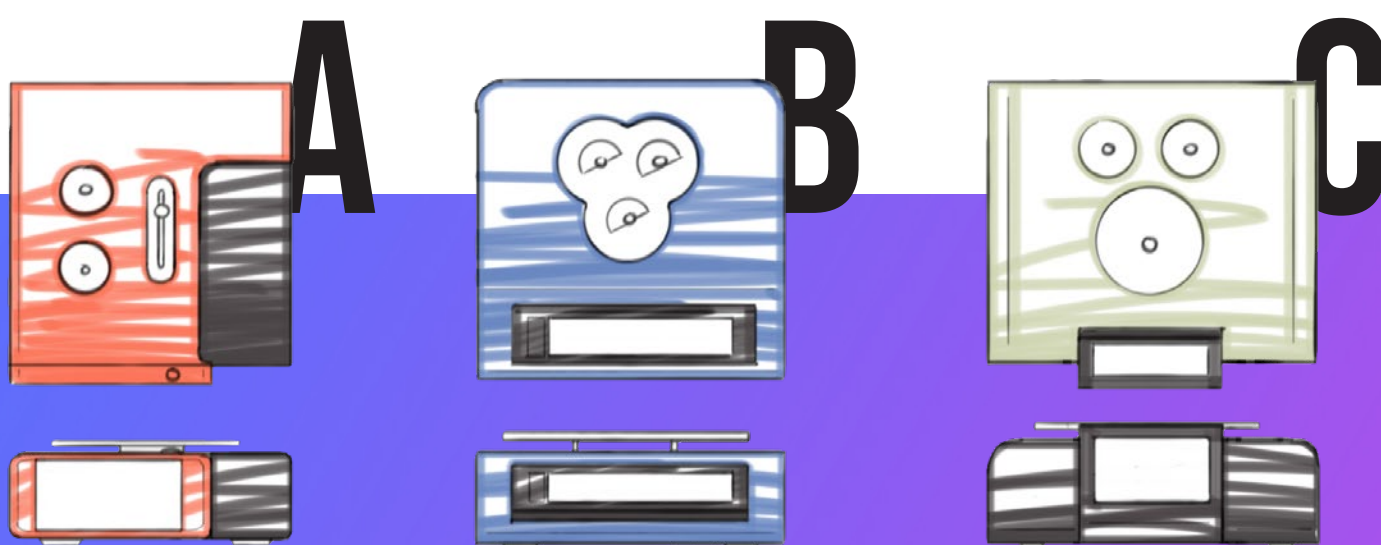
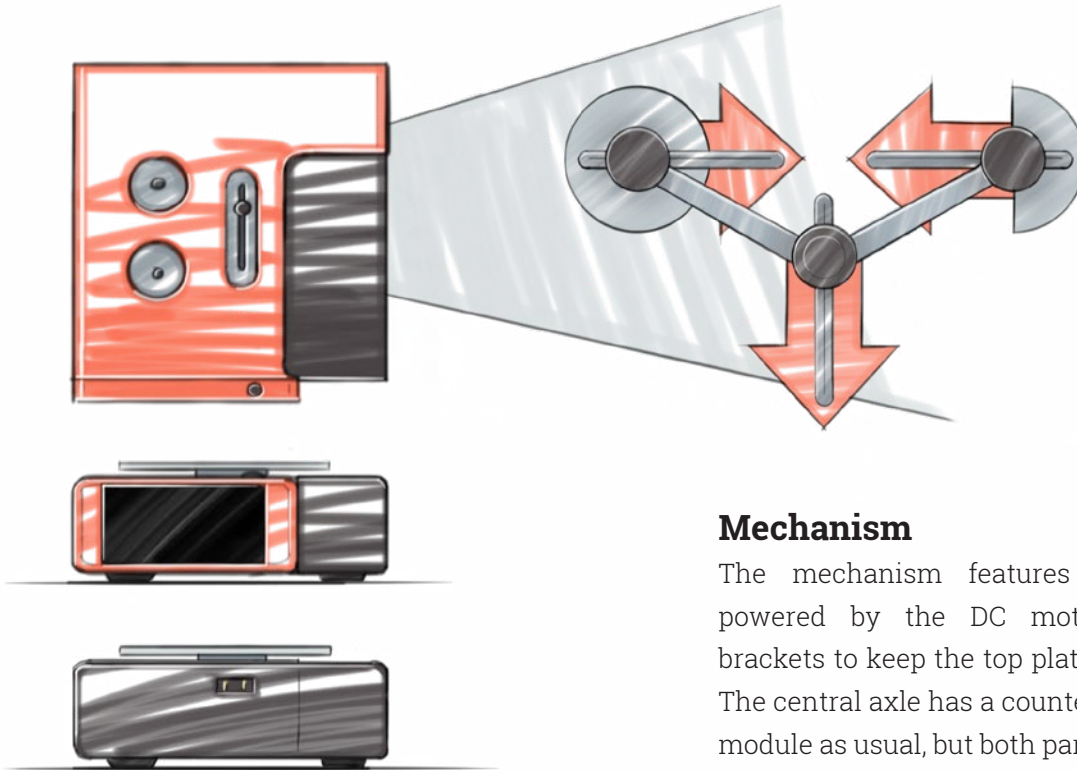


Figure 23: Top and front views of concepts A, B and C



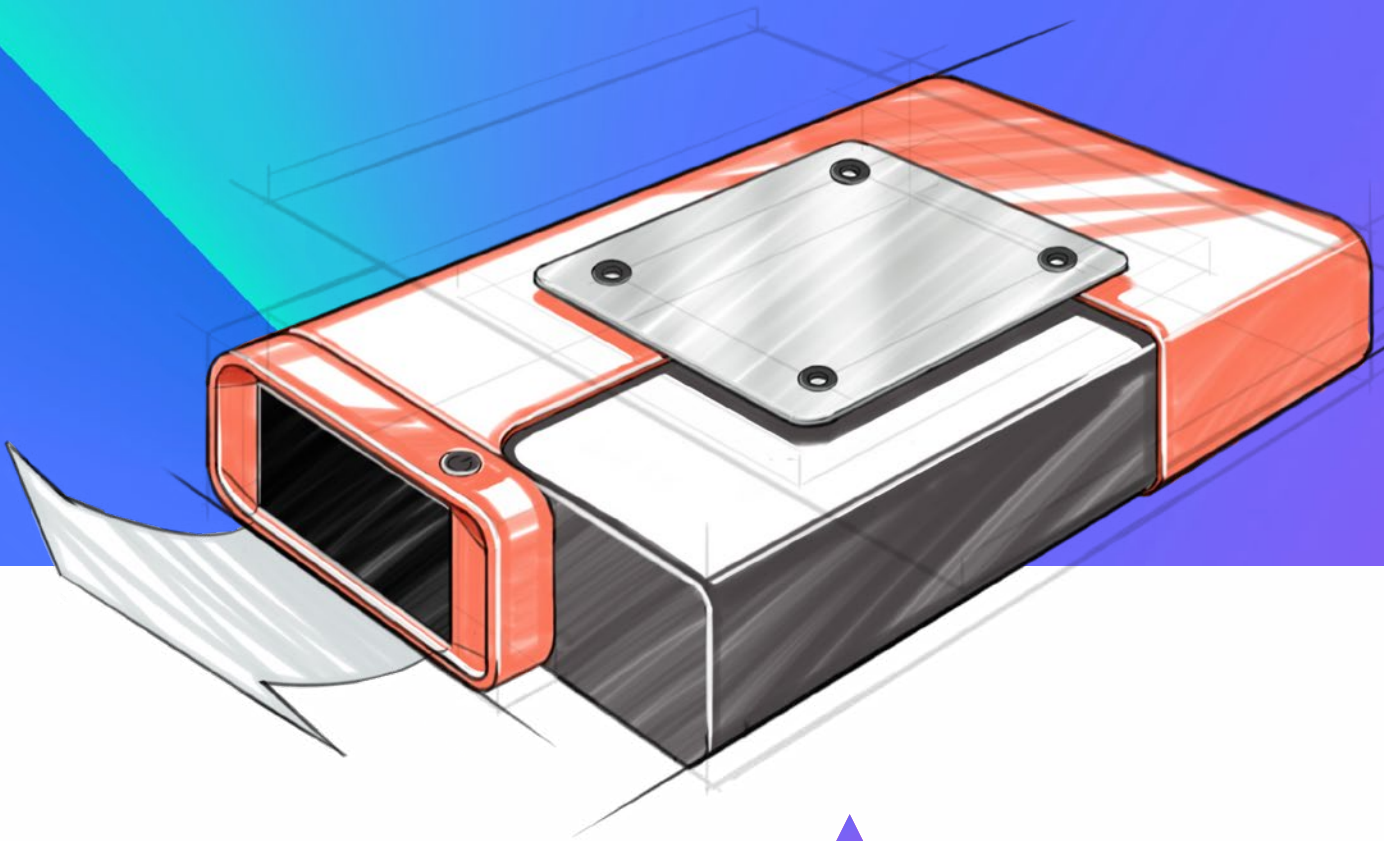
Concept A

The first concept features a black underbody with a red asymmetrical wraparound sheet on the left and right sides. The screen is mounted flush on the front left, accentuating the red body. The controller will connect in place to the body by both magnetic connection as well as an electronical male/female fit. Both body parts are painted stainless steel, while the controller would be plastic.

Mechanism

The mechanism features a central axle powered by the DC motor with flexible brackets to keep the top plate stable (Nbiotek). The central axle has a counterweight and orbit module as usual, but both parts (counterweight and connection to top plate) are attached to a perpendicular slider. When moving the slider outward, both parts are pulled together, and the orbit is reduced. When moving the slider inward, the parts are pushed away, and the orbit is increased. The slider (and thus the connection parts) can be locked at set intervals of 20mm, 25mm and 50mm, creating an adjustable orbit. No change in counterweight is needed since the arm of the counterweight is adjusted as well. Due to the flexible brackets as stabilizer, the same bracket can be used for different orbits.





Discussion

Having a directly changeable orbit is what took the most focus in this concept, but uncertainties were expressed on how reliable this mechanism is for longer runtimes and/or its entire lifespan. To be able to give an adequate answer to that question, more testing would be needed, which would likely expand beyond the time scope of this project. One concluded with this mechanism possible being detailed and implemented in a future version of the product. The outward design was considered good looking, but only due to the coloured casing. Another potential issue is the question on how precise the researcher would setup the product across different experiments, especially regarding the research on the reproducibility of experiments. For this context, a manufactured set orbit is preferred, for it being more reliable the correct distance.

STRENGTHS

Adjustable at any time, without tools or extra parts

3 possible orbits, with possibility to add more or have custom

Possibility that the slider gets loose due to vibration during operation

Introducing moving parts on moving parts will affect reliability

Unergonomic viewing angle of interface when used as tabletop shaker

Slider would require big hole in top of body to be used (since it turns), which impacts the liquid resistance

When used as tabletop, set of connection wires are loose/unused

Flexible bracket might be vulnerable to fatigue on 50mm orbit

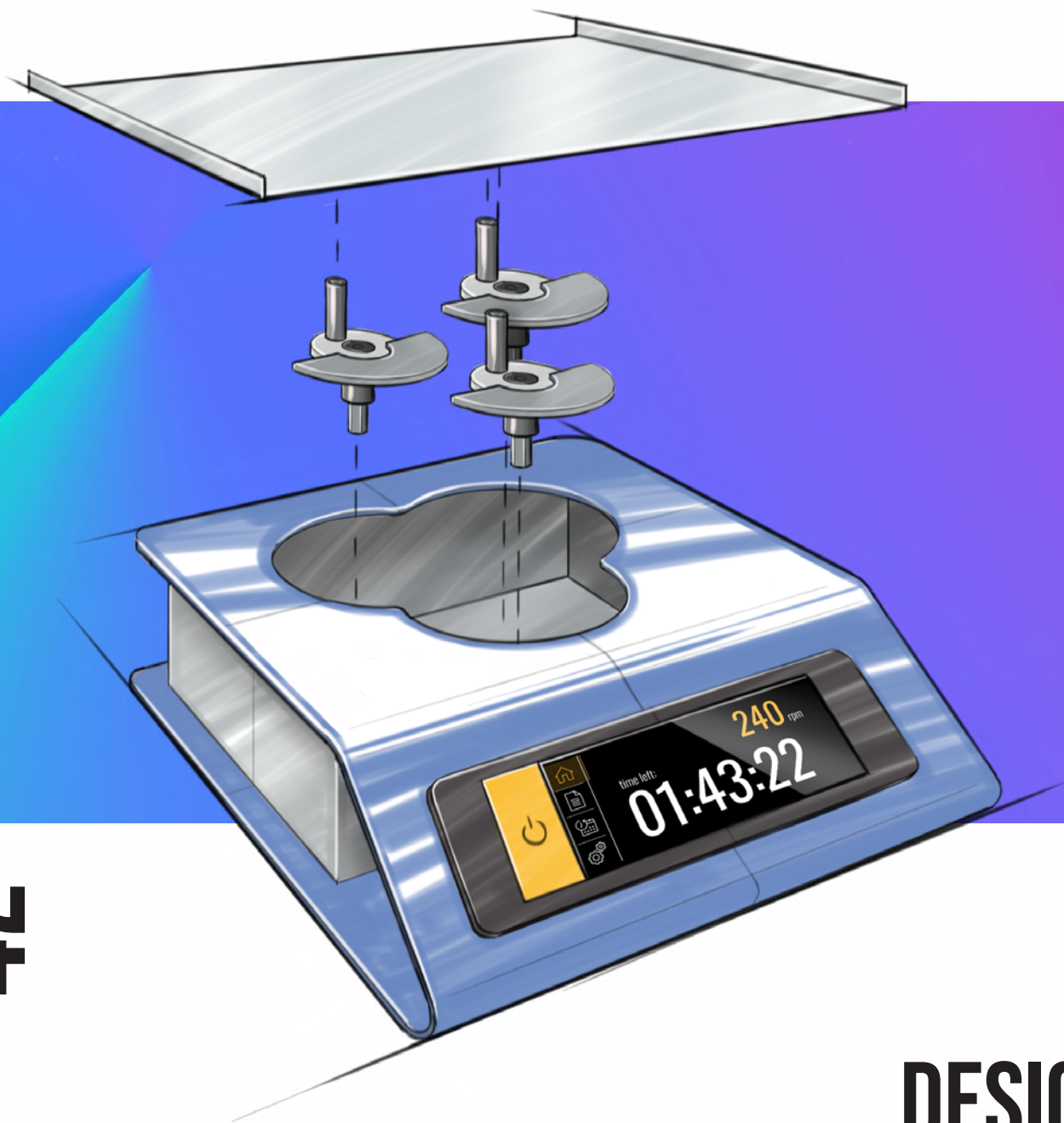
WEAKNESSES

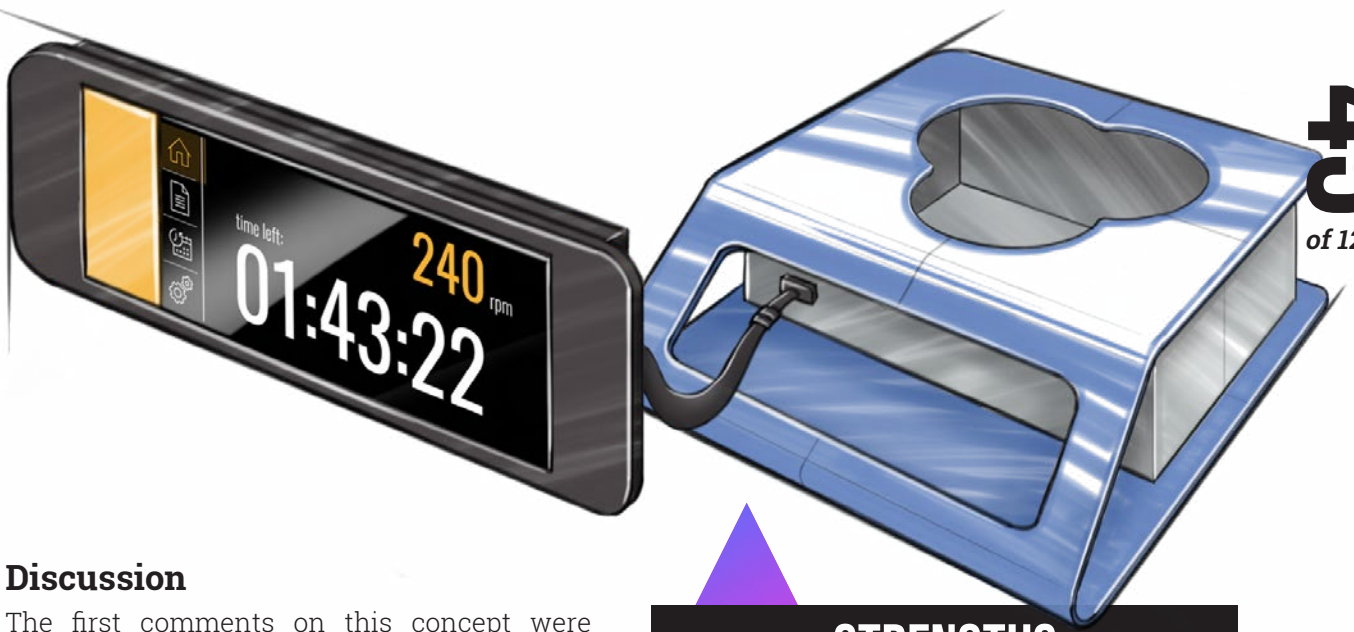
Concept B

The second concept continues on the wrap-around sheet metal trend to create more interesting looking shapes by using a standard box with a large U-shaped sheet around the top and bottom. In the front, there is a cut-out in the wrapped sheet where the controller resides. Just as concept A, the body is fully sheet metal while the controller casing is plastic.

Mechanism

Unlike concept A, this mechanism features 3 separate axes with counterweights. One axle is powered by a DC motor, while the other 2 function as stabilizers, spinning on a bearing at the bottom. The novelty in this concept lies in that each part that changes the orbit and connects the top plate and counterweight (later referred to as "module") is identical and removable, creating a modular mechanism with swappable modules for different orbit distances. On the top and bottom of the modules, hexagonal fits connect the modules with the bearing on the top and bottom plate.





Discussion

The first comments on this concept were the industrial and innovative casing design in comparison to other shakers, conveying correctly that this product would also have innovative functions. The controller looks more intuitively removable than concepts A and B. The idea of modular orbits was received positively, especially mentioning that this can be ordered extra. This means that the change of mechanism only happens behind the scenes and thus keeps the customer experience when buying and using it for the first time as expected. It was also mentioned that the modular parts can most likely still shrink in height when detailing, so the whole product will not be that tall.

STRENGTHS

Creates a modular structure in the shaker mechanism, meaning easy to replace parts as well

Does not force changeable orbit on users that might not need it; orbit module packs separate to buy

Ergonomic viewing angle on controller even on tabletop

When used as tabletop, excess wire can be folded and tucked in cavity below controller to be out of sight

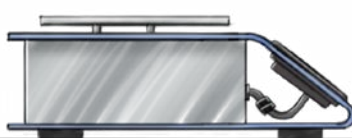
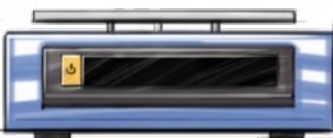
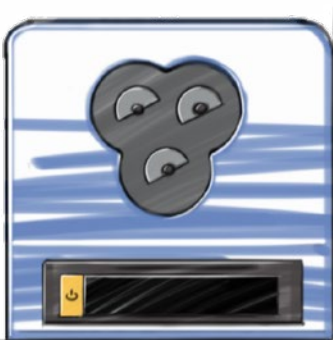
Aligning all modules to attach top plate bearings might be a hassle due to all parts spinning freely

Hexagonal fits should be tight enough to prevent any vibration

Requires customer to keep spare parts for different orbits

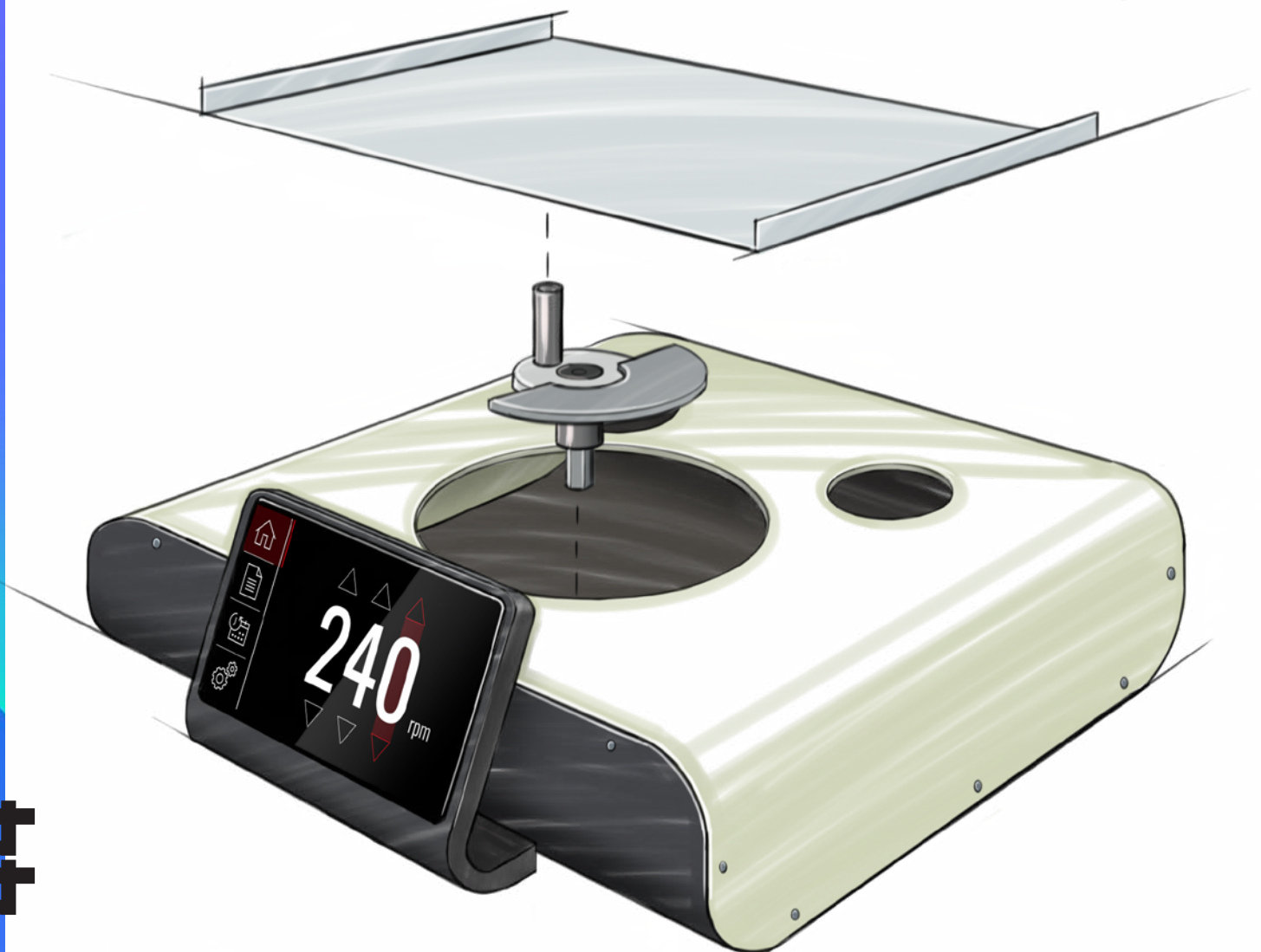
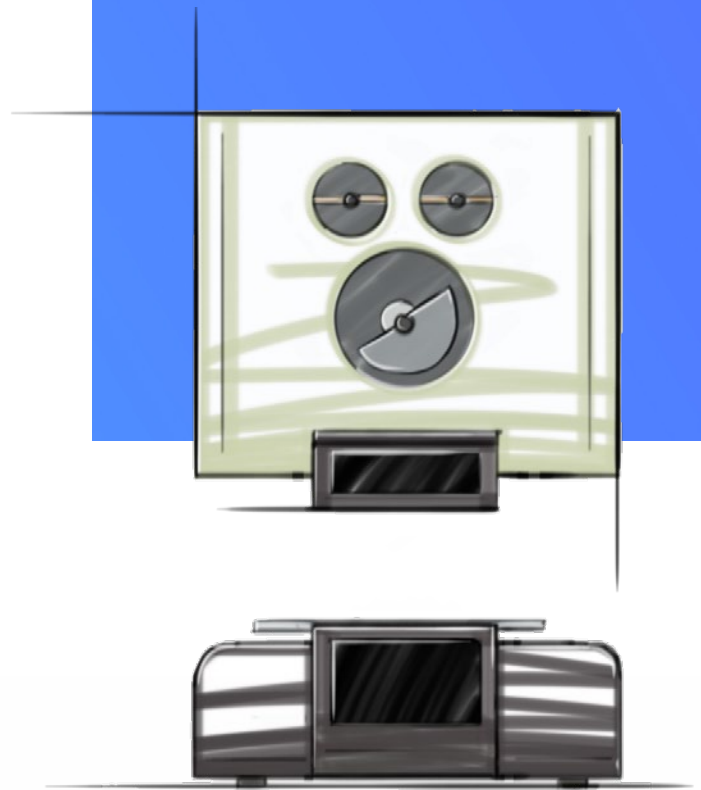
Requires clear visibility to distinguish modular sizes (20mm, 25mm, 50mm)

WEAKNESSES



Concept C

The final concept consists of two U-shaped sheet metal parts attached to each other. The top and bottom part are painted in respectively light green and black stainless steel. The plastic controller is snap-mounted under an angle for a better viewing angle on the interface.





Mechanism

The mechanism is a mix of concept A and B. It uses the stabilizing bracket of concept A and the modular orbit and counterweight of concept B. The orbit module is mounted on the central axle with a DC motor. This means that the orbit can be changed, while only 1 separate module has to be kept in storage. Since the size of the casing is a lot bigger than the necessary space for the mechanism, there will be space to store these parts in the product itself.

Discussion

Due to the dual tone painting of the concept and the minimalistic interface, it was perceived as sleek/modern. However, this would turn into plain and boring when the casing is plain stainless. Using a flexible stabilizer as in nBioTek is smart, but doubts were cast on the flexibility and fatigue of this metal when having to accommodate 50mm of flexing. That said, 50mm could be left out of the product range entirely, but it is still a con for this concept. Furthermore, a more integrated screen solution would be preferred than the current loose clip-on solution.

STRENGTHS

- Only 1 modular element
- Smooth, edgeless body shape makes it easy to clean
- Enough space inside the casing to store excess parts from the modular mechanism

- Flexible bracket might be vulnerable to fatigue on 50mm orbit
- More difficult to attach top plate after exchange (user will have to bend frame correctly to orbit distance)
- Requires customer to keep spare parts for different orbits
- When used as tabletop, set of connection wires are loose/unused

WEAKNESSES

Selection

During the concept presentation, the design and mechanisms were discussed on the spot while presenting and any comments were noted down by oneself. After having discussed each concept individually, a discussion was held on which concept would be continued with and why, which is summarized in "Qualitative results". After the session and based on the discussion, one rated the concepts based on weighted requirements in "Quantitative results".

Qualitative results

One of the first comments on the concepts was the mention that the entire casing will most likely be plain stainless steel without paint. This is not because the paint would not survive the heating in an autoclave or the humidity, but because the researchers would, from experience, a plain stainless product that is built for these circumstances. In other words, painting the product would signal the wrong use case to new users. With that, comes the decisions to have the power cable connect to the controller first, not the casing. Thus, the only connection between the casing and the controller is the motor control cables. This enables the use of a flat cable for said connection, making the product universal for all types of incubators. Furthermore, the touchscreen control is definitely preferred, but any functions would preferably be tested in a prototype. This, however, is in line with what was planned. Finally, as a general comment, the interface design could be more colourful, especially now it is decided the casing will most likely be plain stainless steel.

Quantitative assessment

To complement the qualitative assessment, a quantitative assessment was done afterwards to compare each concept on statements based on the initial requirements. The weighting was done by me, taking the research done, requirement weighting, and information learned from the user interviews in mind.

Method

Each criterion was given a score from 1 to 5, where 1 means not important and 5 means critically important. The concepts then got a score based on their performance on said criterion, ranging from 1 to 10, where 1 is 'bad' and 10 is 'good'. These scores were then multiplied by their respective weights, and all added up to a total score. The result can be seen in Appendix G3, the criteria were grouped by their relation to the product, so the in-between group results are visible as well. For reference, a perfect product would score 10 on each criterion, resulting in a maximum score of 500.

The result of this assessment was more used as a way of summarizing all points mentioned in the qualitative discussion and as a confirmation of those being on the right track. During that discussion it was already clear that the casing of concept B and C were both liked, which is solidified by the quantitative score. Based on this, it was decided to create visible prototypes of these two designs to compare both concepts from a physical model. In terms of mechanism, the design of concept B scored the best and was liked the best as well in the discussion. Since the mechanism is almost independent of the casing, one would continue with this mechanism design and both casing concepts B & C.

Revision

In retrospect however, it is clear that having the quantitative results be fully dependent on a qualitative weighting is not the most solid assessment. Which is why a revision to the weighting was made. The participants of the user brainstorm were contacted again and asked to fill in a weighting table of the criteria based on their point of view, which is then all averaged in a revised weighting. Since the original weighting is not fully senseless and still based on the research done beforehand, it will still be included in the average. The new weighting and how each criterion differs from their old rating is seen in Appendix G5.

Differences

The weighting differs the greatest in the cleaning, where the users rate the importance higher, while the overall design is rated slightly lower. The importance in the different uses of the shaker that this project focusses on, namely heat ability in an autoclave, a user changeable orbit and user friendliness, have all been gained lower importance by the user. This could be due to the users not being well informed on the newer functions this product is supposed to have or simply the bias oneself had when making the weighting list at the start, re-emphasizing that this revision on the weighting was indeed necessary. As with the user-brainstorming, a better representative result could be had when one consulted more user instead of just two. However, the users participating in the brainstorm were the same users giving this weighting, meaning they were already introduced to this project, probably giving a more grounded weighting since one knew to what extent the weighting was used. Secondly, some sections like manufacturing were possible for oneself to judge the concept on, but difficult for a user to estimate due to their lacking background knowledge. The weighting table with the revised weighting can be seen in Table 1.

Results

Even though the weighting greatly differed at points, the final scores are still similar, with the scores of Concept A and B only being increased 1.4 and 1.2, respectively. A slightly larger increase of 8.6 is seen at Concept C, now being the highest scoring concept, largely due to the design scoring better in the cleaning section.

A B C

Table 1: Revised quantitative assesment of the concept selection

Criteria	(1-5) Weight	(1-10) Score	Total	(1-10) Score	Total	(1-10) Score	Total
Design							
Overall looks	2.3	6	13.8	7	16.1	8	18.4
User friendliness	3.3	6	19.8	9	29.7	7	23.1
Stand out from competitors	2.7	7	18.9	9	24.3	5	13.5
Performance							
Predicted reliability	5.0	3	15.0	9	45.0	8	40.0
Predicted vibration/stability	5.0	4	20.0	9	45.0	7	35.0
Cleaning							
Easy to clean	3.7	7	25.9	6	22.2	10	37.0
Cleaning "prevention" (not look dirty too quickly)	2.7	5	13.5	5	13.5	6	16.2
Liquid/leaking resistance	3.7	8	29.6	6	22.2	9	33.3
Heatability in autoclave	3.7	10	37.0	10	37.0	10	37.0
Flexibility of use							
User changeable orbit	4.3	10	43.0	7	30.1	8	34.4
Incubator use	4.0	7	28.0	8	32.0	9	36.0
Tabletop use	4.3	5	21.5	8	34.4	7	30.1
Manufacturing							
Predicted costs	2.3	4	9.2	7	16.1	9	20.7
Predicted difficulty/stability of quality	2.7	6	16.2	8	21.6	7	18.9
Weight							
Within 9 kg	2.0	6	12	6	12.0	7	14.0
Max score = 517	Total		323.4		401.2		407.6

DESIGN

Conclusion

During the discussion, it was clear there was a clear preference for the internal mechanism of concept B, due to it being predictably more reliable in the long term than the mechanism of A, as well as being better adaptable to bigger orbits than C. For outer shell design though, both B and C were favourites. Concept B was generally liked for its different design from current shakers and integration of the screen in both use cases, while concept C scored better on cleanability, having effectively a fully smooth outside surface. Since the final design would most have an unpainted stainless steel surface, it was decided to have both the outer casing of concept B and C be made physically to compare.

Once these physical prototypes were in, it was decided to continue with concept B for the project, even though concept C in its current stage was a better product. This due to the fact that one expected that concept B had more room for improvement to be better on the areas it lacked, namely cleaning and leaking resistance, while concept C was already as good as it could get. If these aspects would be fixed and improved, it would turn out into a better product than concept C can grow.

Continuing this chapter is the further detailing and conceptualization of the final design. Parallel to the final design, a prototype was made as well, which transcript of design and assembly can be viewed in the next major section "Prototyping". The following chapters are only relevant to the final design.

MATERIAL SELECTION

Based on the constraints mentioned above, a selection of usable materials was made. This paragraph will make it sound more complex than it actually was, since the majority of decisions boil down to going for the safest option in terms of fatigue; “material X has been used for years and has proven sufficient, so there is no reason to try something different”. However, one will explain some specific parts in more detail by grouping them in their corresponding material below.

Stainless-steel type 403

As mentioned in general constraints, stainless-steel is the standard for laboratory equipment and often required by regulation as well. For the majority of projects, type 403 is used, with in some odd cases type 416, due to its extra chemical resistance which might be requested by the customer. The project shaker will use type 403 as well for the outer casing as well as any parts in the mechanism.

Furthermore, the decision was made that for now, the stainless-steel casing will not be coated/painted. This because products on the current market that can be sterilized in an autoclave are all made of plain stainless-steel, meaning that when painting the product, the user might not realize that the product can be heated. Especially since the end-user is often not the person deciding on ordering the product, so it is not necessarily aware of its features.

Aluminum

By using anodized aluminum, similar heating and chemical resistance compared to stainless-steel can be achieved, but for a lower weight. This material will be used when possible for any plates and parts on top of the revolving mechanism to consequently, keep the counterweight weight as low as possible. As a bonus from an aesthetical standpoint, the aluminum can be anodized in various colors, so these can be different from the bare metal finish of the stainless-steel parts.

Rubber and silicone

Due to the moving parts of the products, as well as the environment where the shaker will function (incubator), it will require some anti-vibration buffers, rings, or feet to keep the impact to its operating environment to a minimal. Usually, natural rubber or isoprene is used for these parts, but this material has a maximum temperature limit of 210 °C which is very close to the heating target of 200 °C (Mykin Inc, 2022). For this reason, buffers were selected from Nitrile/NBR rubber as well as edge trims of silicone that have a maximum temperature of 250 and 450 respectively (see figure 14).

CONTROLLER CONCEPT

Since the controller will be a largely separate part of the product, it required a separate design attention. Certain interface style concepts were explored in Appendix G1. Of these, a design that is less minimalistic and closer to a app style interface is chosen. Since the interface had to be made as a functional touchscreen for the prototype, several screens were designed were expected to be present in the prototype. These screens would show of different functions of the program, like saving setups and settings. The screens were used in a quick Adobe XD interactive prototype to think through the program map and necessary information and confirmation windows, which would later serve as the baseline start for the prototype program. With the touchscreen designs as reference, some detailed variations of the controller can be seen on the right in figure 24, while the final conceptual design is visible in figure 25.

Figure 24: Variations on the controller casing, with several screens designed for the prototype.



Figure 25: Conceptual controller design used before the CAD implementation.

FINAL DESIGN

After the concept was selected, the design was detailed and refined in CAD. When the dimensions and measurements for the casing and its internals were clear, a prototype was built in tandem. As mentioned before, a report of the design and assembly of that can be seen in the section "Prototyping". A full exploded view of the CAD model and all its components can be found in appendix XX. The following chapters will explain the final proposed design, according to the subassemblies shown in figure 26.



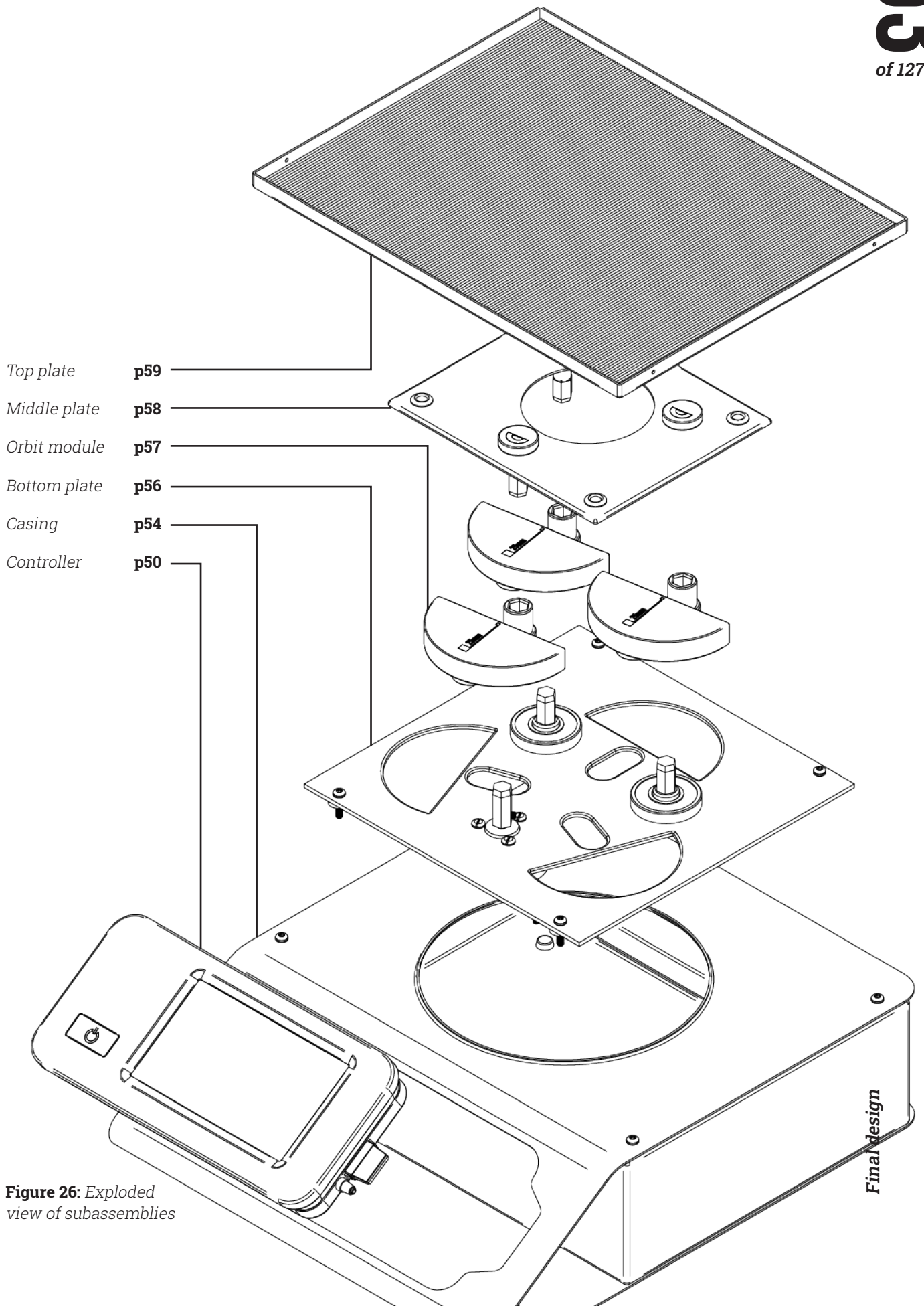


Figure 26: Exploded view of subassemblies

Controller

As mentioned before, the interface would consist of a touchscreen and a flat on/off button. The button will be a flat FPC membrane button for their leaking resistance and are thus often used in laboratory equipment. A full covered, smartphone-like, enclosure was also considered for the controller, but due to the expected limited number of products sold yearly, a separate plastic casing was preferred.

Color wise, it was quickly decided to double down on the modular theme of the mechanism in this design. The casing is plain black, with accent colors present in the touchscreen interface. A silicone band is used to fit the controller snugly in the casing, which has the benefit of being available in multiple colors that can be included in the person. This might not be necessary for the actual release of the product, where a single accent color is picked to complement the accent color in the interface. Alternatively, the casing could be printed in that color as well.



Manufacturing

The casing will be made from FDM printed ABS, instead of injection molding the plastic parts. The casing consists of 4 parts: 2 for the top and 2 for the bottom. The top and bottom casing parts consist of an inside and outside printed casing, this to be able to create a stronger and thicker casing without being bound to longer printing times. The outside surface of the 2 outer parts will be sandblasted afterwards for a smooth finish.

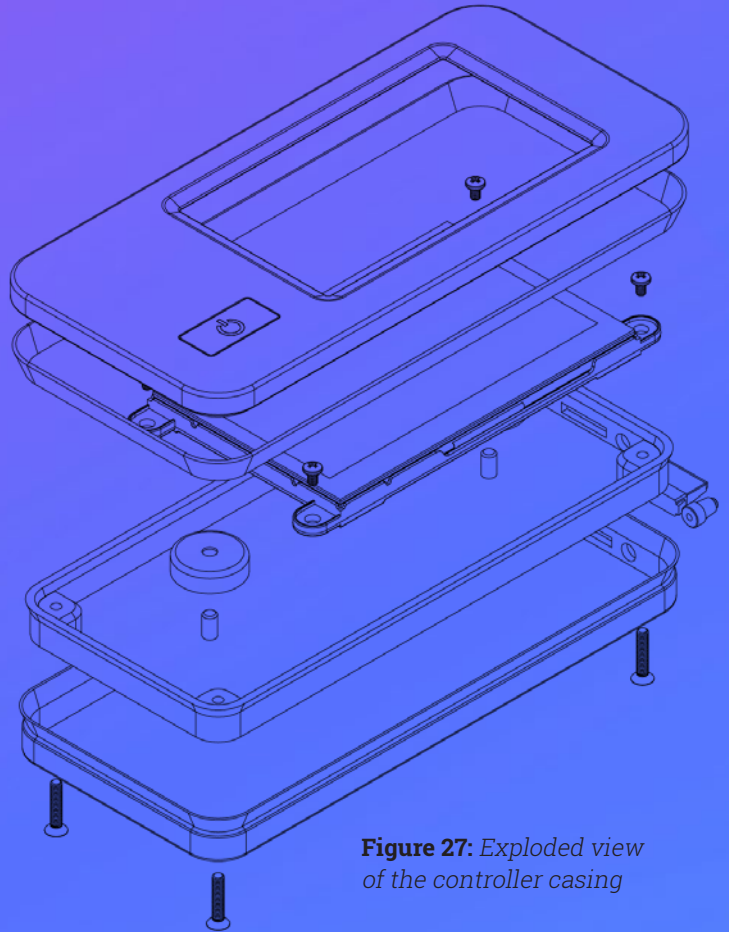


Figure 27: Exploded view of the controller casing



SILICONE BAND FOR PRESS FIT
AND POSSIBLE CUSTOMIZATION

Final design

Interface

The interface features a clean and clear aesthetic with customizable accent colours in the settings. On the home screen, the speed and time can be set. It can be decided to save the setup in the memory under a 3 letter identifier. If not, the setup will standard be saved in the history list, being 5 setups big, for easy selection when the setup has to be repeated

multiple times. The history setups can be found in the history tab and the saved setups in the saved tab, navigated to via the panel on the left side of the screen. In the settings, the language can be changed, as well as the accent colour of the program. The accent colours in the interface match with the replaceable silicone bands attached to the controller casing.

Figure 28: User interface flow diagram of the touchscreen interface. These screens are designed and were slightly altered to fit the prototype.

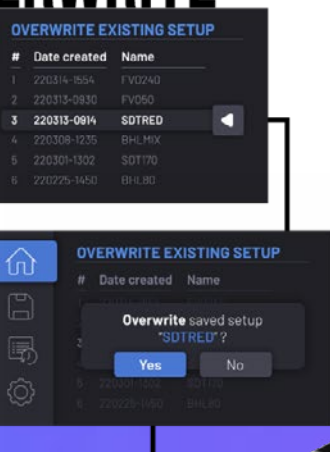


Future possibilities

The images showing the design of the interface are made before the prototype was built. In the final chapter of Prototype, one can read on some improvements of this original design. Having a touchscreen interface and more processing power in a shaker also enables more integration possibilities with software and other laboratory hardware in the future.

For example, a connection to the incubator could be made, using the temperature and air-flow sensors to notify the researcher when the shaker is obstructing the airflow too much or creating too much heat. However, this requires collaboration with numerous different manufacturers, so the achievability for this is small, especially in the starting stages of this product. Something that is more attainable is integration with digital lab journals by means of an add-on and connection. This could help the researcher by sending the selected shaking parameters straight to their digital journal where it is visible afterwards, relieving the researcher of the task of noting down the setups themselves.

ERWRITE



Casing

The casing is built up of a basic sheet metal box and a bend cover. The two are connected by screws in the top and the bottom of the casing cover. Two L-brackets are spotwelded inside the box to hold the bottom plate. Contrary to the prototype, the sides of the cover and box area flush in the final design to improve cleanability, while still keeping the offset at the back and the front. This also signal to the user that the product is either lifted comfortable by grabbing the casing on the bottom instead of the less sturdy top cover. The bottom of the casing has 4 feet inserts made from NBR rubber.

Manufacturing

All components are laser cut and bend. The hole on top of the cover is pressed to create a small upstanding edge that prevents any leaked liquid from entering the shaker. The holes in the L-brackets and casing box require threading. The cover is brushed while the box and L-brackets are left large untouched.

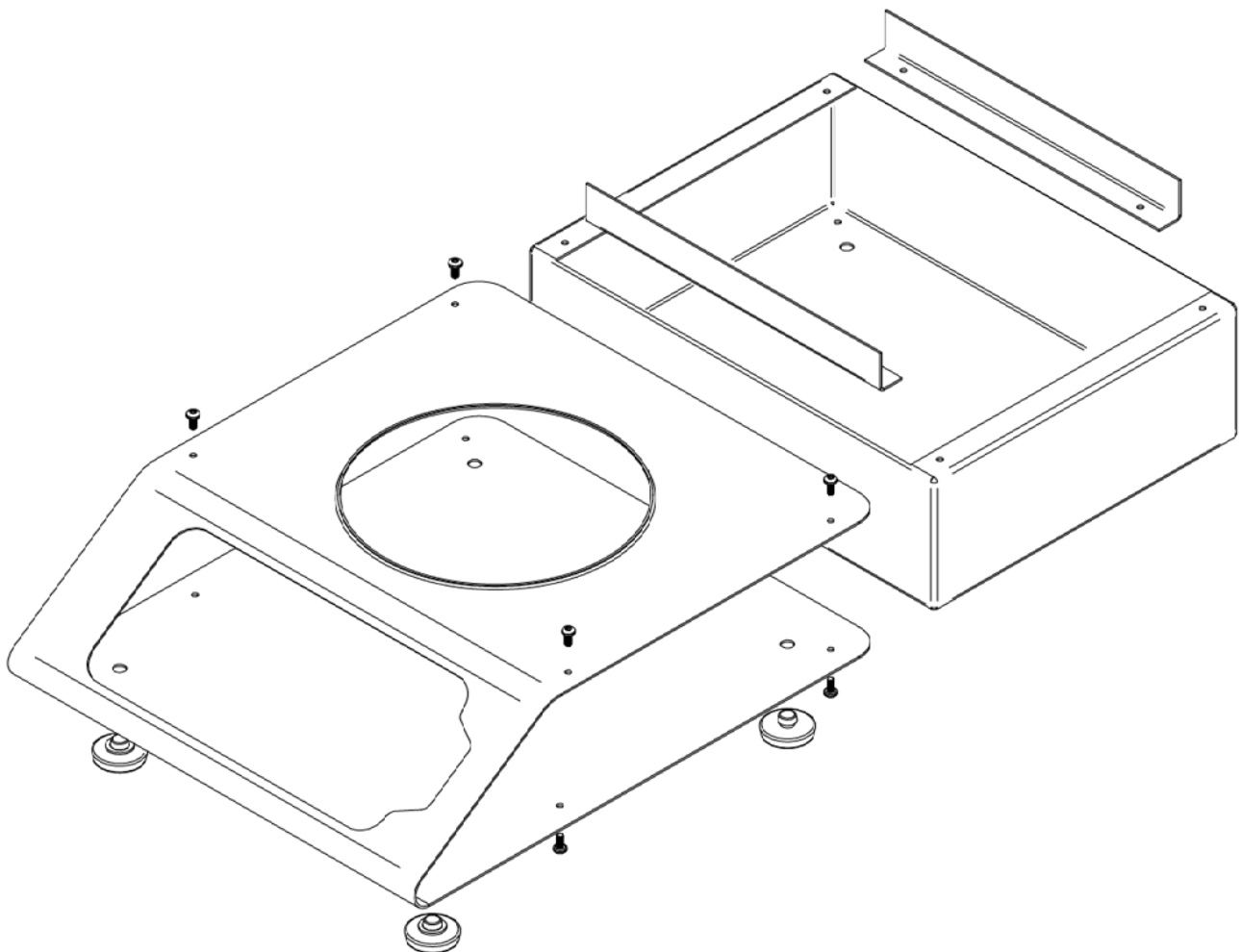
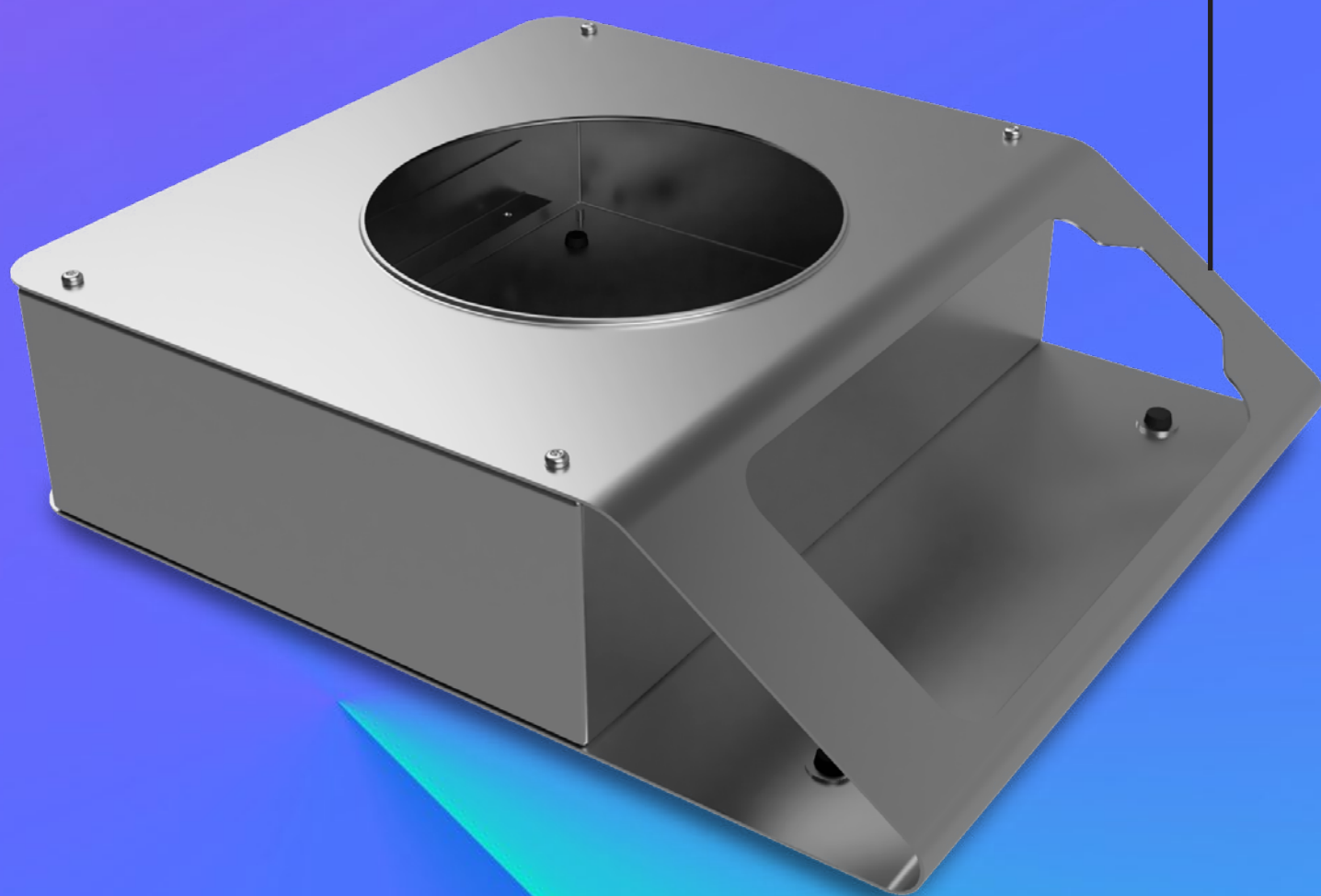


Figure 29: Exploded view of the shaker casing, including fasteners and feet

PLACE FOR CONTROLLER
DURING TABLETOP USAGE



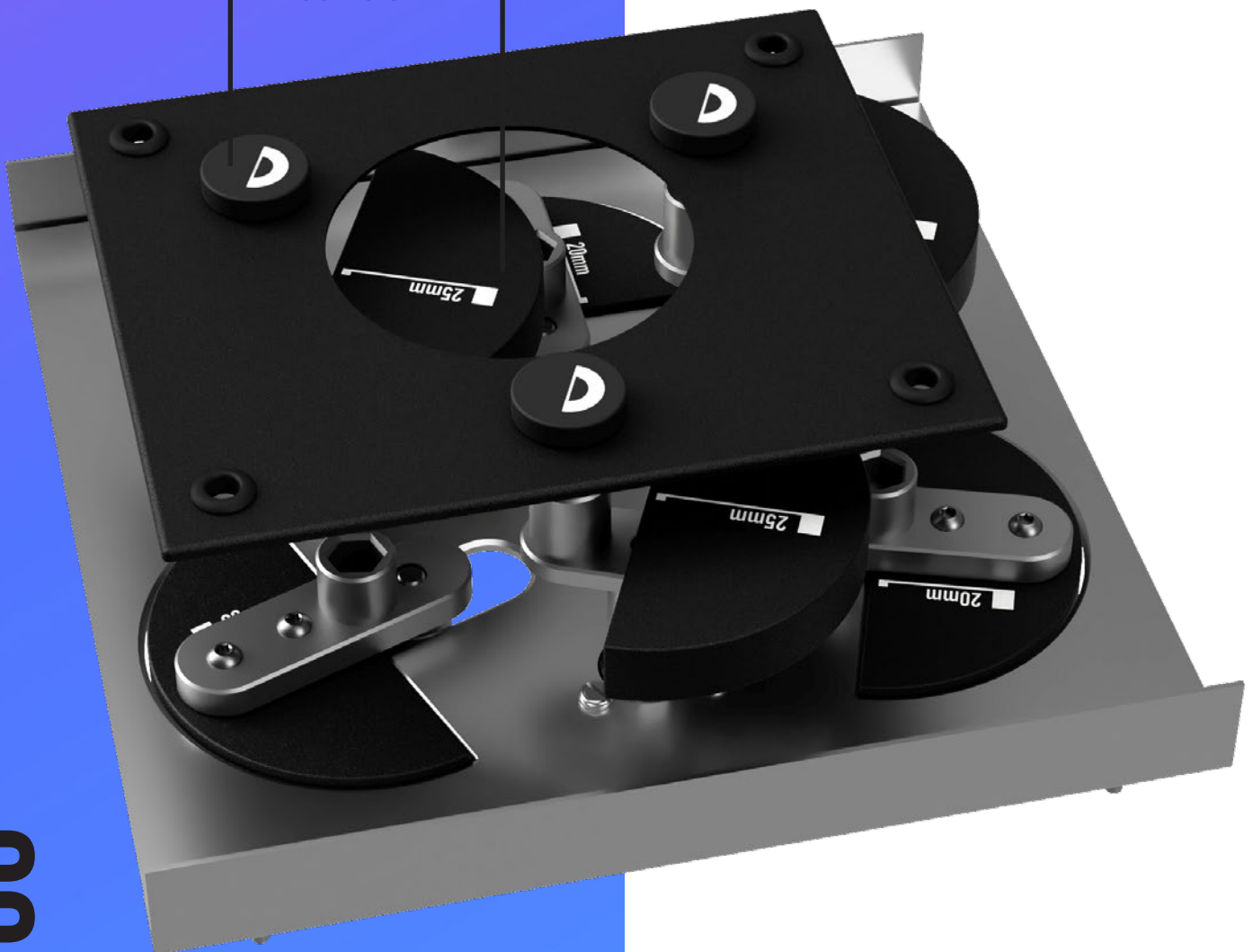
Final design

Internal mechanism

The internal mechanism is made up of 3 plates with the orbit modules in between. An exploded view can be seen in figure 30. The bearings and motor are not manufactured new and will be bought. Continuing in this chapter is an explanation of all parts in the mechanism, starting on the bottom that is connected to the casing and working towards the top, that hold the product.

INSCRIBED ORBIT ON
COUNTERWEIGHT FOR
IDENTIFICATION

PLASTIC CAPS ON TOP TO
EASE ALIGNMENT AND
FITTING OF MODULE



Bottom plate

The bottom plate is attached to the casing by L-brackets and hold the motor for the driving axle and 2 bearings for the 2 stability axes. It also facilitates extra cut-outs to place an unused set of modules. The bearings and motor both hold a transfer piece that end in a male hexagonal M5 shape. Similar to the prototype, the bearings are friction fitted to the bottom plate. In the prototype, the transfers to the orbit modules are fitted to the bearings by a precise fit and Loctite. However, it is more reliable to use bearings inserts for this purpose in the final design.

Manufacturing

The plate is a 2mm lasercut sheet metal piece of type 403 stainless steel with no threaded holes. The flexible trims holding the extra modules can be either silicon or NBR rubber.

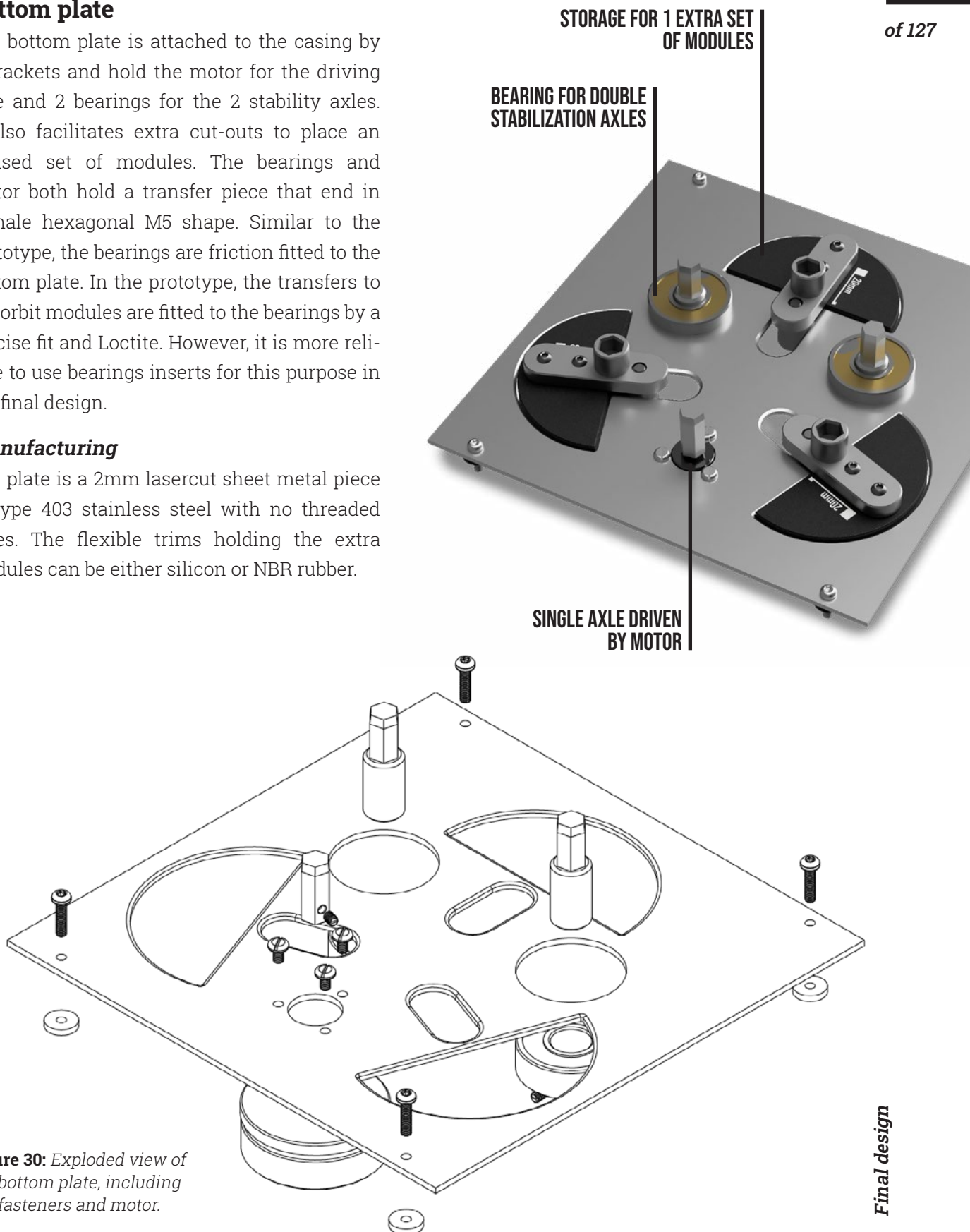


Figure 30: Exploded view of the bottom plate, including the fasteners and motor.

Orbit module

On top the hexagonal fits, the orbit modules are placed. Each module is made up of a plate with a M5 female fit in the middle on the bottom and on the required orbit distance on the top. The fits are mounted to the plate by a threaded hole in the plate and fitting a M5 bolt through the fit, as can be seen in figure 31. The counterweight is made of a solid piece of brass and fitted to the plate by 2 screws. The brass piece has a black coating with a white painted stamp signaling the correct size it fits to. Since the orbit module needs to be made in different sizes, the plate features holes for all sizes (20mm, 25mm and 50mm), so the hexagonal fits are only placed on different places. The counterweights are placed on the same place but are made in different height for different orbits.

Manufacturing

The plate can be lasercut and requires threaded holes, while the hexagonal fits and counterweights will have to be milled. As mentioned before, the counterweight is made of brass, while the fits and plate are stainless steel. Both the top and bottom hexagonal transfer connections are milled a solid stainless steel.

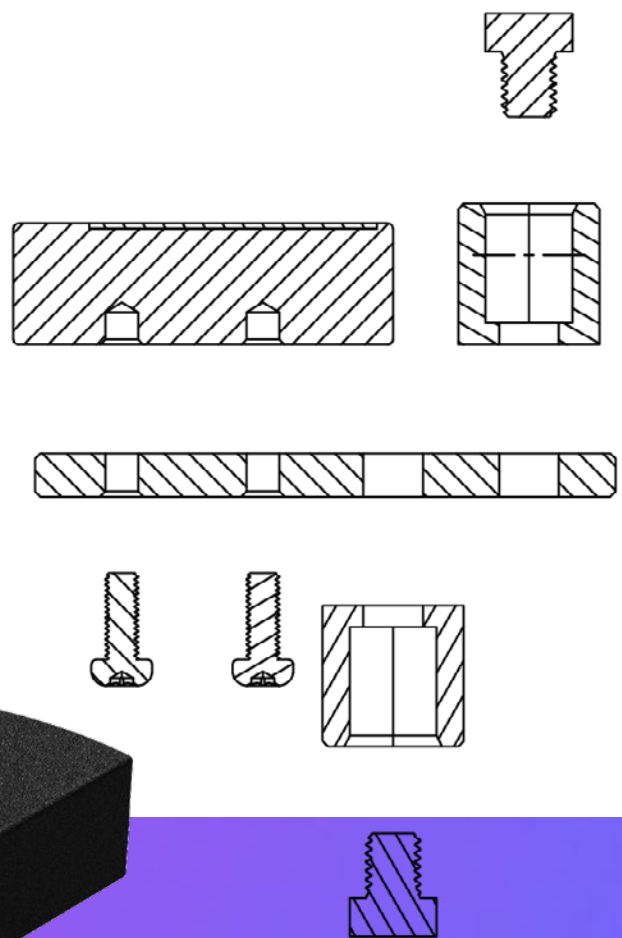
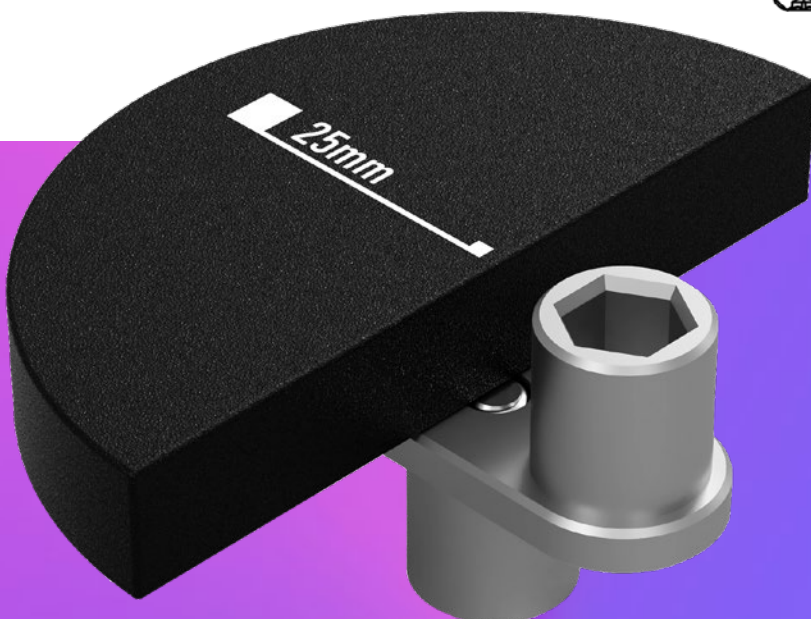


Figure 31: Cutthrough of the exploded view of the orbit module and fasteners.



Middle plate

The middle plate connects the 3 independent orbit modules together and holds the friction fit connection to the top plate. The plate has 3 places where the bearings with insert can be friction fitted to the plate. Rubber or silicone grommets are used in the holes in the corner of the plate to create the friction fit connection to the top plate. Since this plate fits loose on the orbit modules, a plastic cap fitted on top of the top transfers and bearings will help with positioning the freely rotating modules and transfers correctly.

Manufacturing

In the prototype, the middle plate was made from 2mm lasercut aluminium sheet to save weight for the moving parts of the shaker. In retrospect however, this meant that placing object on the shaker will have a greater percentual weight change than when the moving parts are initially heavier. This is why the middle plate is now a 1mm lasercut sheet metal piece from type 403 stainless steel, so the difference between a loaded and unloaded shaking mechanism is marginally smaller. The plate gets a black coating for aesthetic purposes.

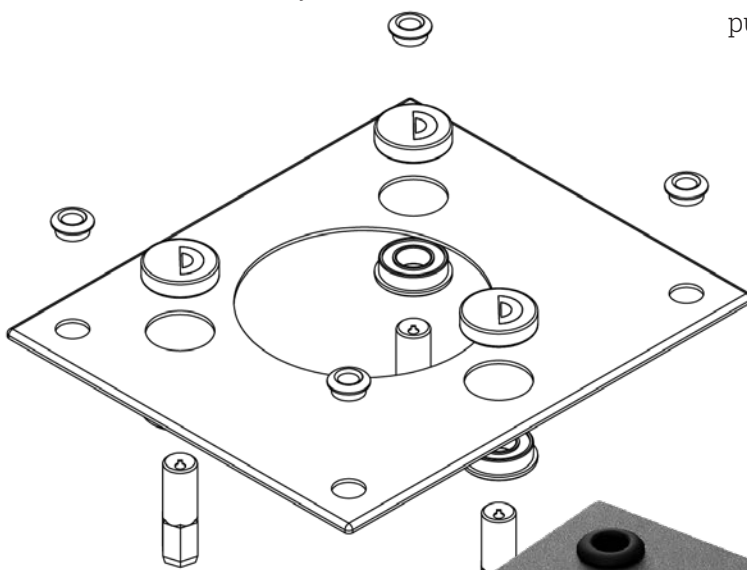


Figure 32: Exploded view of the top plate

GROMMETS FOR FRICTIONFIT
CONNECTION TOP PLATE

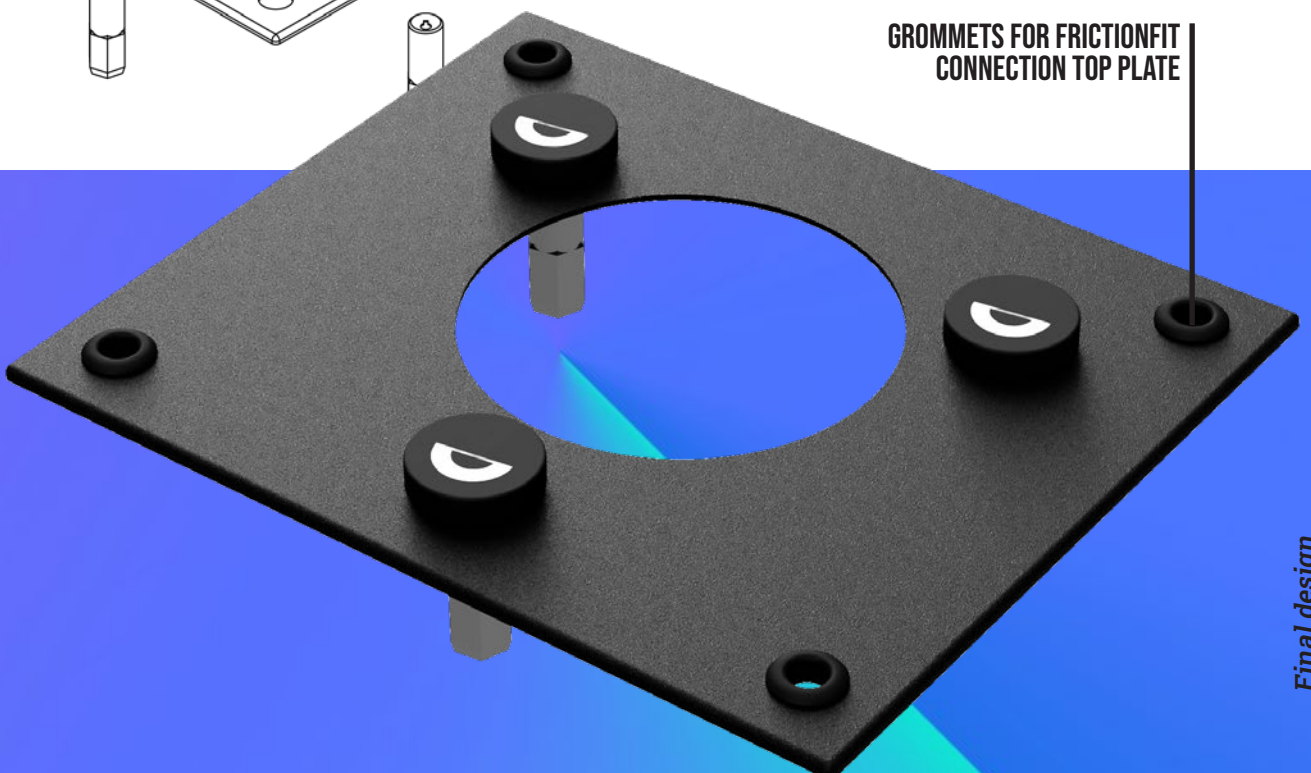
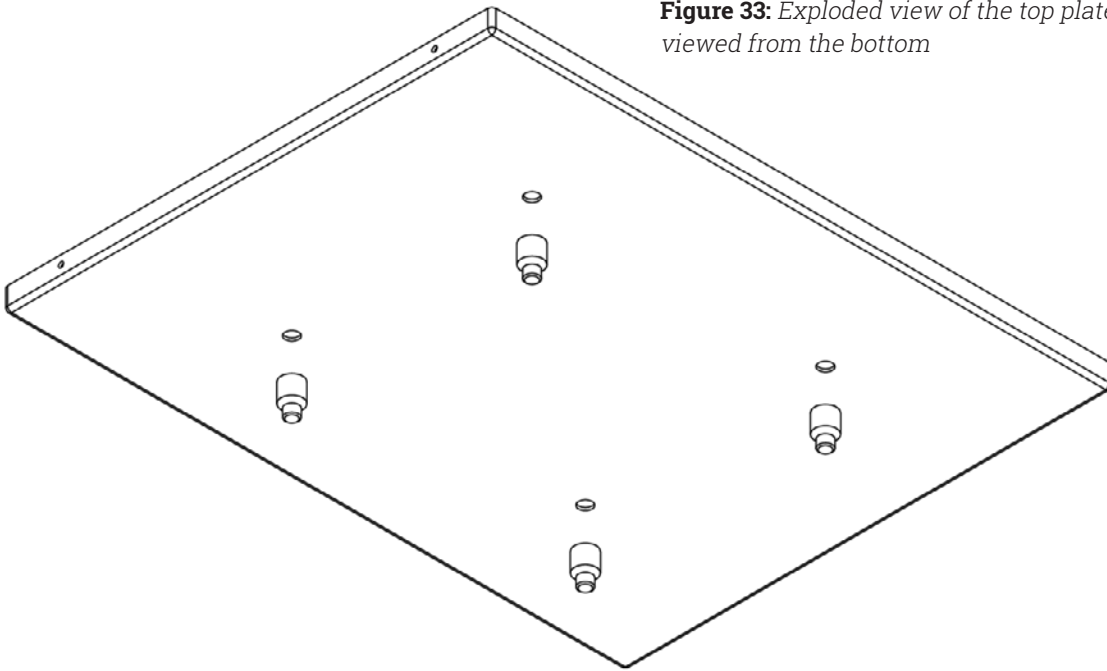


Figure 33: Exploded view of the top plate, viewed from the bottom



Top plate

The top plates of orbital shaker can come with many different attachments, all of which require no redesigns for the functioning of this project. This is why one only designed the basis plate to which these attachments are fitted. This basic plate is inserted with studs on the bottom into the friction fit grommets on the middle plate. The initial plate is lasercut with holes to help positioning the studs, which are welded on the top. Since the plate will stay largely untreated, a silicone matt lays loose on top covering the welds, as well as increasing traction for any objects being placed upon the shaker.

Manufacturing

The plate is lasercut and bent from type 403 stainless steel, while the studs are milled and weld. The silicone matt can be bought on roll and cut to size.



SUMMARY

To start with, the ideation went quicker as expected, taking roughly 3-4 weeks instead of the 2 months planned. The reverse engineering gave a lot of detail to the product beforehand, making the ideation quicker in the sense it was a lot more focused on the useful problems to solve straight away. Downside of this is probably that the design is more compartmentalized towards those problems, e.g. orbit change, incubator usage, touchscreen controller, without having taken the time to take a new look at the product as a whole.

Benefit of this however, is that there was more time left to spend on conceptualizing and finalizing the design afterwards. Once the 3 concepts were presented, the design changed very little when towards the final design. Since the concept design was already build in CAD to make the prototype casings from, one continued from that model to detailing and adding parts. This meant that compared to the original planning, more time was spent on CAD than expected. A lot of designing was done in CAD that could and should have been done on paper before, creating times where one was running in circles in the CAD model, solving fittings and dimensioning issues that eventually turned out unnecessary for the final model.

On the other hand, this extra time in Fusion 360 did speed up the learning curve that comes with learning a new CAD program, making the designing of the actual final version and the prototype quicker in general.

Finally, the actual 'end' of this diamond, like drawing, exploded views and renders, were dependent on incorporating the improvements of the prototype, but since the prototype took a lot longer than expected, this was also done much later than initially planned.

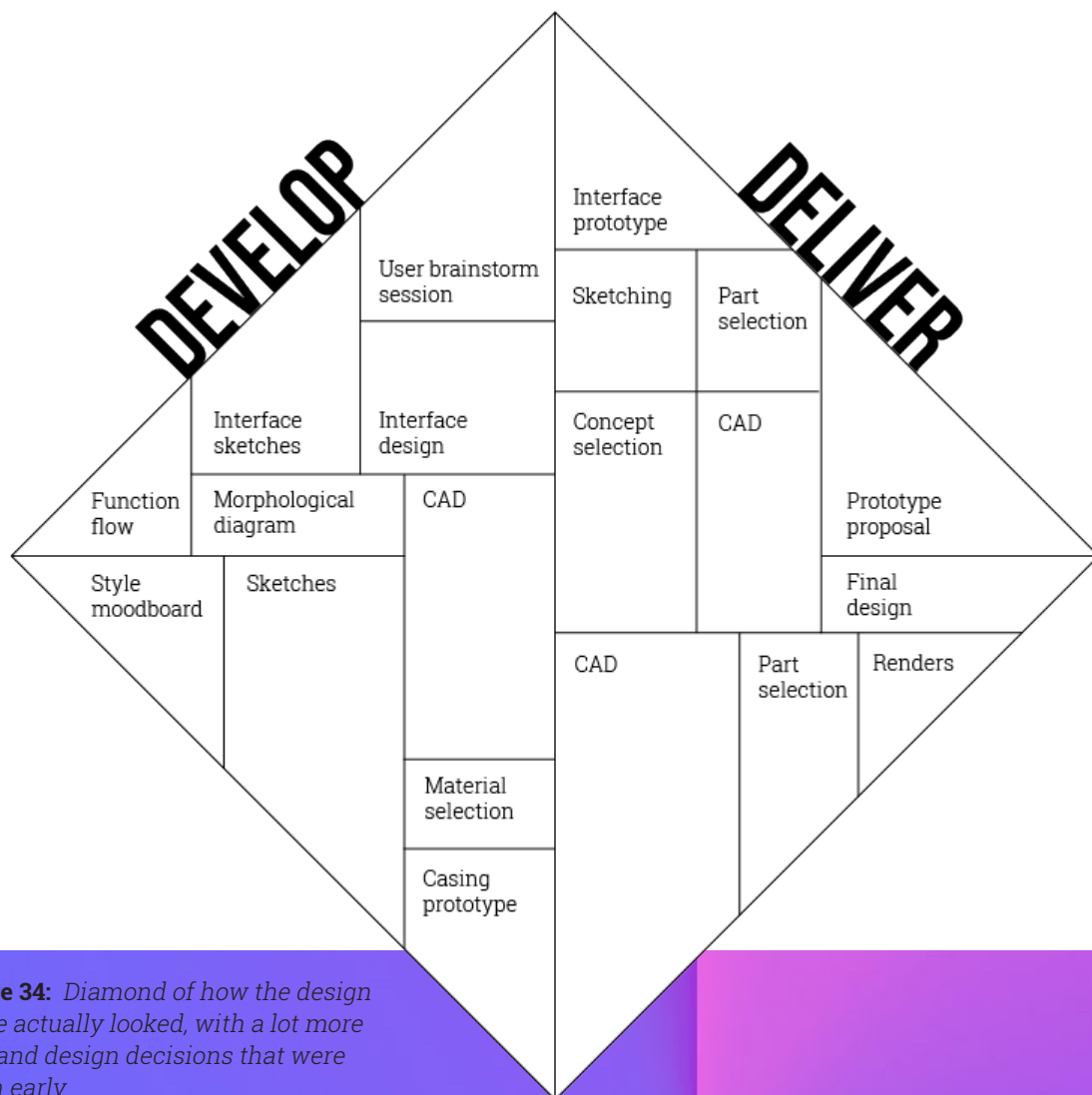


Figure 34: Diamond of how the design phase actually looked, with a lot more CAD and design decisions that were taken early

PROTOTYPING

Contents

In the third chapter the conceptual design is redesigned into a high fidelity prototype. The prototype was built up from building lower fidelity prototypes of the casing and the software first. The chapter closes with a list of improvements implemented in the final design.

All photos shown in this chapter are photos from the actual prototype and its finished parts.

As one can see in figure 35, the prototype will be designed in CAD first, based on the final design and adjusted to the concept casing that was built earlier. The majority of parts will be made in the UTwente metal workshop, while some other parts will most likely have to be bought. One expects the necessary software development and electronics to take one month, with another month being spend on manufacturing and assembling all physical parts. Once the prototype is complete, one will have 2-3 weeks to test it with users and evaluate the results.

Goal

The main reason one wanted to build a prototype was the ability to test said prototype with a group of users present in the University of Twente Biolab. With this in mind it was decided to try and create the touchscreen interface as close to the final product as possible, since the usability and newly added functions can be tested properly. This would be done by an in-depth user test where a user would be asked to navigate the interface and activate a certain function or setting with a test supervisor present answer any question.

Furthermore, the shaker would be placed in the lab and use independently by lab technicians and students with explanation or a test supervisor present, to see how intuitive the interface is. This also includes that the reliability of the new internal mechanism will be tested this way.

Lastly, depending on how the shaker electronics end up being assembled, the shaker will be put in an autoclave and sterilized, since this was one of the main goals in improving this product.

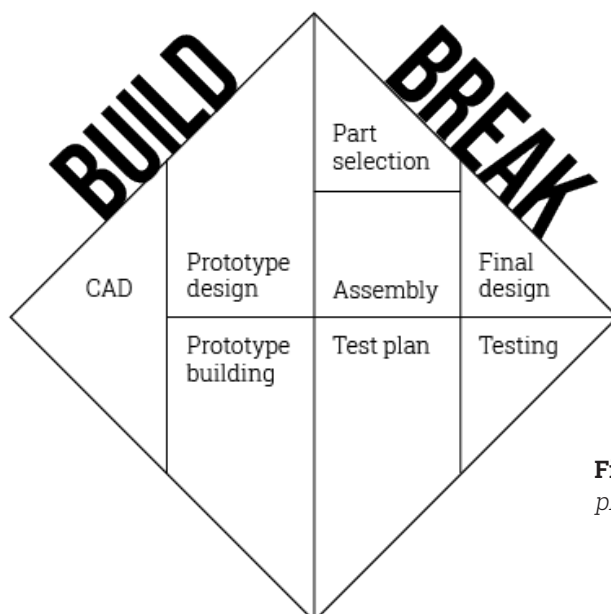


Figure 35: Smaller diamond of the planned prototyping phase

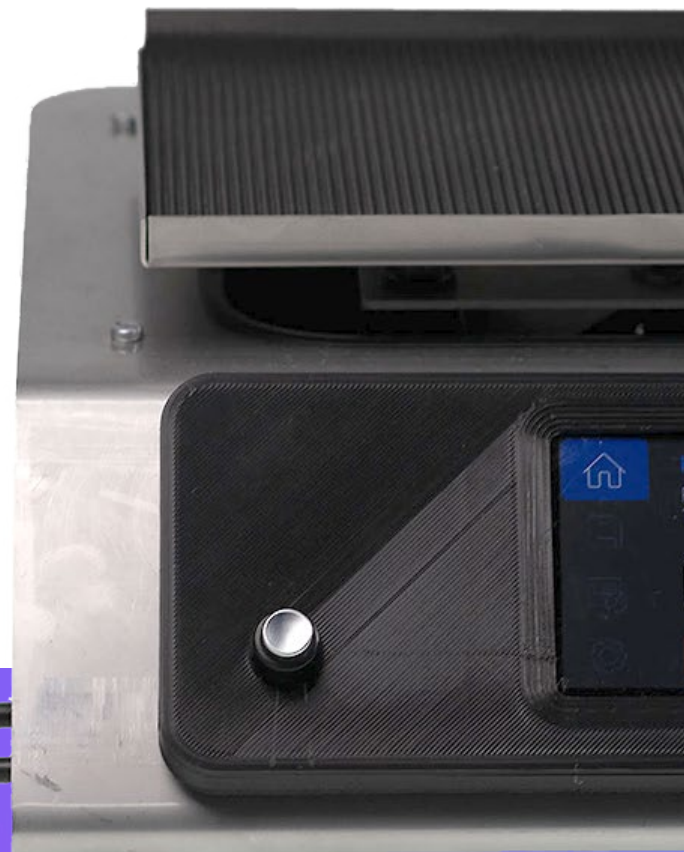
DESIGN CHANGES

With an outside casing already existing (build after the concept selection), it was decided that this would be the basis for the prototype of the internal mechanics. The interface would initially be done separately since the screen could rather easily be fitted to the casing prototype once this was finished.

Interface design

The interface could be closely mimicked from the original design. However, since the knowledge of programming a graphical interface from scratch was lacking in this project, it was decided to use a screen and controller with accompanying design software, namely 4D workshop. This meant one was dependent on the capabilities of the software. Luckily, the initial design did not need major changes after the basic components like fonts and colouring could be replicated in the software.

During designing the interface and interaction through the menus however, certain features were added, most notably extra confirmation messages on saving and loading, as well as a changed input method for speed and time variables. When programming the saving and loading of setups, it was also decided to simplify the on-screen appearance of these files in order to simplify the background steps in the code, as well as the communication between interface and controller.





Program features

One decided to scrap certain features of the full feature list for the controller to speed up the prototyping process. Firstly, any settings in terms of language, keyboard style, accent colour, etc, were left out of the prototype since these are rather basic and do not influence the daily use of the product. The setup saving function will be included in the prototype, but since saving a setup on user input follows the same principle as saving an input history, the first holds priority in realizing.

Motor control

Furthermore, detailed motor control, namely gradual speed increase on start-up and decreases at stop are left out as well. The selected motor did not have an internal speed sensor to create a feedback loop for controlling the rotation speed, so the only control on speed will be the initial speed selection. One could have added an external speed sensor and create a feedback loop in the Arduino control, but due to the work to realize it, it was left out.



Casing

This casing was a little bit bigger than the evolved CAD model, so the existing design had to be changed a bit for this to fit nicely. Another change was the lasercutter gap for the interface which was done using old dimensions (very wide and low), before a screen size was selected. It was not possible to widen this hole neatly to the new size, since that hole would be bigger than the available slanted area. As a result, the 3d printed box holding the screen, will be expanded upwards to hold the screen on top of the slanted area instead of inside the whole. This resulted in a bulkier interface casing but at least made it fit to the existing case.

Wiring

As expected, the wiring of the prototype will be very different to that of the final design, due to the inclusion of separate printing boards for the interface control and motor control, Arduino, and usage of breadboard cables. The electrical schematic for the prototype can be seen in appendix X.

Mechanism subassembly

The casing that will be used for the prototype is slightly bigger and lower than the final designed version, meaning the internal mechanism needed to be resized to fit this space. Furthermore, the module subassembly cannot be made from one piece like the original design, so it would be made from a flat stainless steel piece and grinded down hexagonal pieces, which are bought parts originally meant for imbus toolkits. Due to the dependence on the third party parts, the height of the subassembly will be a bit higher than the original design.

Additionally, the bottom set of bearings is mounted by means of a friction fit, instead of a proper insert. The top bearings would also be friction fitted, but due the fit being too frictionless, metal-on-metal glue (LocTite) was used, which for the short lifespan of the prototype would function fine.



PROTOTYPING

Apart from the casing, all parts were manufactured in the metal workshop of the university in the Horst building. The CAD model of the final design was adjusted to dimensions of the prototype and all parts that had to be made and assembled in the workshop were exported as technical drawings, available in appendix I.

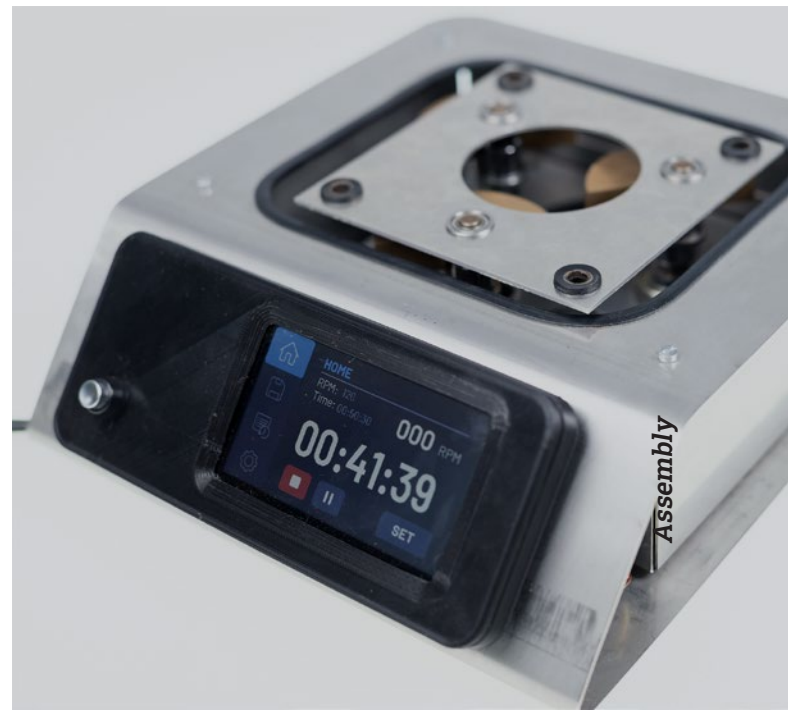
Coding

As mentioned before, an Arduino Uno is as base controller with a 4D systems display. The display comes with an internal processing unit and coding program as well. The whole interface was designed in this program. The majority of processing is still done in Arduino, apart from some basic button functionality, which is done in the interface processor. A summary of the code structure can be seen in appendix J1.

Doing the majority of processing in Arduino instead of the interface processor was decided because one had previous experience in Arduino, but none in 4DGL (the display's native language), so this was expected to be quicker to realize. However, as it turned out, this also made finding example projects for basic interface functionality that is usually done in the 4DGL language a lot more difficult, since these had to be translated to Arduino language. The interface was initially built with Workshop4D, which has pre-built elements that one can use to quickly build up the basic interface. The coding practice had several specific hurdles that had to be overcome when programming, which are detailed more below.

Keyboards

The interface uses a total of 3 keyboards; 2 numpad styled keyboards for speed and time and one QWERTY for setup name. Examples of keyboards in the documentation were only available in 4DGL language, so it was decided to handle these inputs in the interface processor initially. However, these examples were very outdated in respect to the current version of Workshop4, so one eventually rewrote these in Arduino. It meant they handled a little slower due to the extra communication but did make it easier to manipulate the values further in different sections.



Storing values in memory

The program had to store values for saving the setups, namely name, speed, and time. These could all be saved as a single string, to make showing these on screen a bit simpler as well. There were locations where the values could be stored, a simple text file on the uSD card already present in the interface, or in Arduino's build-in EEPROM memory. The uSD saving seemed like the better option, since EEPROM only holds 1k bytes and can be written to a maximum of 10,000 times. One could get the separate saving to uSD from Arduino script to work, but once implemented in the full code it would slow down the communication so much it timed out before saving anything. Eventually it turned out the function writing to the uSD card could not exist in the same function handling interface events, meaning the saving function to be moved outside this function into the main loop, which also meant the keyboard handling had to be moved back into 4DGL. Since one was working on the programming for a while now, it was assumed the problem with the keyboard could be fixed with the improved knowledge now. However, that did not turn out the case and after several days of troubleshooting it was decided to abandon the uSD integration and move to EEPROM definitively. EEPROM was very easy to set up and was integrated in the main branch in a single day, which left a sour aftertaste on how much time was wasted on getting the uSD to work.

At first, having a history of used setups that were not saved was meant to be added as well, since this would be largely the same as the saving functions. However, there were many smaller issues and bugs that arose when adding this into the main branch, so it was eventually removed altogether.

Timer

A timer was obviously needed to time the motor and use the user input. There were several prebuilt libraries available for Arduino, so one decided to use these. They worked fine on itself, but not when implemented in the main code. After more visits to forums, it became clear the timer library used the same hardware timer on Arduino as the interface communication library, thus creating an incompatibility. After trying some other timer libraries which all seemed to have the same incompatibilities, one found a countdown library running on a software timer where the main code was responsible for calling and checking. This worked well, although the input and output of the library were seconds, while the input and required output of the user were hours, minutes, and seconds, so 2 functions calculating conversions for both ways were added as well.



PROTOTYPING

Motor control

Before doing the timer and saving, one wanted to build the motor control first. However, this required an extra controller for the motor, which had to be ordered. Luckily, other features could be worked on while waiting for delivery. When arrived, one could not get it to work straight away. After doing some troubleshooting with a basic analogue circuit described in the data-sheet, it worked, and the hardware connections were one by one replaced by connections via the Arduino. The motor programming was fairly straight forward, with requiring a digital output (HIGH voltage) from the Arduino to enable rotation, speed selection (range of rpm being used) and direction. Actual speed control within the speed range was done by means of a PWM (Pulse Width Modification) signal of 0-5V from an Arduino pin. The necessary conversion formulas were all present in the datasheet, however a small edit had to be made, since the motor control had a resolution of 1024 steps, while Arduino pins could only manage 256 steps.



Mechanical assembly

Not everything went smoothly in assembling the prototype due to mistakes made in designing the parts but also during assembly. The size of the counterweight required some adjustments after seeing the inventory of the workshop for available materials. The counterweight turned out a bit heavier than expected due to this. Furthermore, the laser cut middle plate needed 3 iterations before it held the bearings and motor properly and even then, the holes with which it is attached to the casing brackets needed some adjustment before assembling. These adjustments were all done in the company workshop after having manufactured the parts in the metal workshop.

A full list of improvements and mistakes can be seen in Appendix J2, while some will be discussed in more detail here.

Improvements

Slots

Firstly, since working with parts that are bent and lasercut, not all holes will align fully like in a CAD model, meaning some parts need slots to account for these inaccuracies. However, this was forgot in the making of parts, meaning that when one had problems when trying to assemble, especially for the middle plate, where the holes eventually had to be drilled out.

Threaded holes

A minor mistake is not correctly looking up the size of holes required before threading, meaning some holes (notable the top casing attachment to the box) required an extra round of drilling before threading, meaning these holes are also one size bigger than they were planned to be. It did not matter much for the prototype's functionality, but it just more work that could have been prevented.



PROTOTYPING

Module assembly

Another part that took a lot of time where the modules that held the counterweights. These were made up from a piece of sheet metal and a hexagonal screw bit. The piece of sheet metal would have a threaded hole the same size as the bolt that fits in the screw bit, by which both could be fixed.

This method worked well but required a massive amount of metal grinding to get all 6 screw bits (for both sides of the 3 modules) on the same size that could be used. Moreover, due to the nature of the screw bit being a little oversized, the top plate feels a bit loose when speeding up or slowing down. This was lessened a bit by using a small piece of silicone in the screw bit, but this is not a solution that can be used in the final design. Finally, the selected sizes for these screw bits; M6 on the top and M8 on the bottom, turned out a bit too extreme, creating more issues on spacing in respect to the counterweight. These can be reduced in the final design to M5 on both sides respectively.



SUMMARY

The prototype phase took a lot longer than planned, for numerous reasons. Firstly, the amount of work that was the programming of the interface and Arduino was severely underestimated at the start. The problem was not the actual complexity of the work that had to be done, but more the time it took to collect the necessary understanding of programming basics and the communication between the interface design software and Arduino before one could start to tackle the actual problems. Once the basics of the interface was coded, motor control had to be included, which compared to the other features, did not take much more time than expected. Manufacturing the metal parts was largely according to planning, although as mentioned before, some mistakes were made that caused delays. Finally, with how long the project was already taking, it was decided to leave out the final user testing. Although a loss, a lot of improvements are appeared when making the prototype as well as using it themselves.

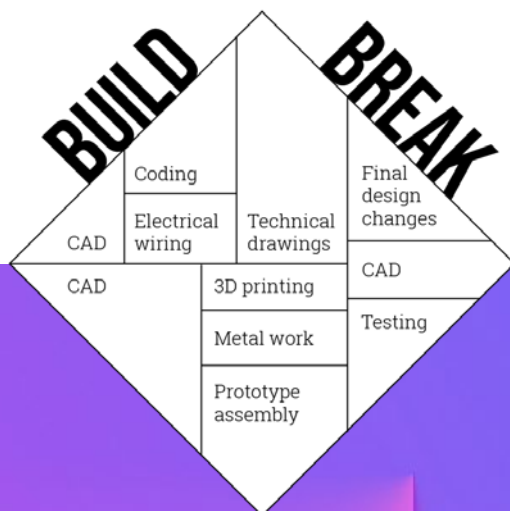


Figure 36: Diamond of how the prototyping phase actually looked, with in general more time spent on designing and building the prototype and less on testing



closing

DISCUSSION

For the company, the project has achieved its goal of having a high-fidelity prototype and CAD model on which an educated decision can be made whether to continue the development of this product or not. The prototype is fully functional, and it is clear what parts need extra work before the finished product, namely a properly programmed interface and more advanced motor control, while the casing mechanism could use some optimization for manufacturing but will work as is.

This project started with the research question “How can an orbital shaker be redesigned to be better adapted to future laboratory usage?” and is answered in this project. Future laboratories will be different on two main points, namely increased digitalization, and stricter cleaning regulations. Both of these culminated in more stable experiment results and better reproducibility. To prepare for further digitization in shakers, the implementation of a digital interface creates a basis for further implementation and connection to other laboratory products as well as digital laboratory managements systems, even though the current design does not have any of that. Future features could be connectivity to the incubator the shaker is placed in, or integration with digital lab journals, so shaker setups are accessible by researchers from their offices. In terms of stricter cleaning, the shaker casing and mechanism is designed to fit and be heated in an autoclave, unlike existing shakers. The physical cleaning of the shaker is at most equal to existing shakers, held back by the cavities in the body necessary for the placement

of the controller. These potential drawbacks, however, were addressed and minimized in the final design and can be expanded upon even more.

Research

The literature research was interesting to find and read, but only appeared useful on rare occasions in the project. In hindsight, the work put into this section could have been less broad to leave more time for deep diving into the user. The interview and visit with the laboratory and its researchers were of great use, but that use could have been better reflected in user-scenarios or another form of direct deliverable, instead of the background acknowledgement that it turned out as.

By far the most knowledge was gained from the reverse engineering, especially since all three products had very different internal mechanisms and design philosophies, giving a great context to the use and philosophy of this project. It also showed a large number of details in the design that came in useful when designing and assembling the prototype. One can say however, that starting a new project with disassembling competitor products in the same market will already put boundaries on your creative thinking when designing. This is true, but not a disadvantage for this project, since the goal of this project was not to create a new, innovative definition of what an orbital shaker is, but to improve the existing definition through a different scope. In this light, looking at an existing product from that specific scope is only beneficial, because it forces oneself to look at the product from an angle it is probably not designed for, thus laying bare more flaws and improvements to make.

Design

A downside of building two separate CAD models of a single design was keeping both up to date and actually separate. Where the prototype model was built catered towards the manufacturing capabilities of the company and the UTwente workshop in mind, the final design was built for larger scale. Sometimes, a problem was found in the prototype model during manufacturing which needed fixing, after which the change is also implemented in the final design model, only to realize that the prototype problem is unique to the prototype due to the difference in manufacturing or assembly. This is of course a human error, but it is made more likely by both models being made by the same person at the same time.

Another problem both designs ran into was the dependability on bought parts and their dimensions and implementation, like bearings, motor, and screen. These had to be found and ordered but could differ for both designs. It was decided to try and find parts as close to the final design specifications as possible for the prototype, which is why the final design is built with these parts in mind.

Prototyping

One major improvement point for prototyping that would have prevented a large portion of the delays and problems one ran into is to have defined the starting low-fidelity prototypes clearer. The final prototype is the combination of a multitude of smaller systems, namely the internal mechanism, the exterior casing, the plastic controller design and the interface programming and electronics. Although they were basically multiple low-fidelity prototypes developed separately, all were developed with the final prototype in mind and thus had no little evaluation that could be useful before starting a more detailed prototype. Separating the prototypes this way would have also given the possibility to test separate parts independently, meaning user tests for the interface and stability and setup tests for the mechanism.

On a positive note, the project went from researching working competitive products to a working prototype very close to what the final product would be like, which is a very solid basis of results to build on for the actual future product.

The project took a lot longer than first planned, namely from starter research to finished report a time of 14 months, including holidays. This due to a number of factors, of which some were outside of one's power. To start off, as mentioned in the planning revision of the research, this phase could have been less extensive to save some time, as well as to have less time being spent reporting it. Furthermore, the majority of allotted time in the design and prototyping phase was spent focused on the design project and not per se on the design report, meaning that more work was done for

the project that would be reported on afterwards. It would have been better if one would have better separated working times on project and report or spend select hours updating the report. That there would be some delay in the manufacturing and assembly of the prototype was expected, but it was bigger than one had margin planned for. As mentioned in the planning revision of the prototype, the programming was a lot more work, in terms of hours required to establish the basics. The assembly took a bit longer due to delivery times of supplied parts as well, but the time spend waiting was still spend on the project and report, so it is not a direct loss. Finally, the prototype design had some design flaws that had to be solved on the spot when assembling, but these could be fixed in the final design straight away. After all, those problems are the reason a prototype was made in the first place.

With small adjustments to the prototype, it could be tested to still meet the requirements that are currently uncertain. In retrospect, the project followed an almost complete design process from orientating research on the product to creating a high-fidelity prototype of the new design. It required oneself to fit into multiple multidisciplinary roles of designer, mechanical engineer, electrical engineer, programmer, and probably more, while also managing the time and direction the project took largely by oneself. Although it was not smooth sailing at times, I hugely enjoyed the variety of the challenges I had to face and the many different angles it opened up to critique my own work.

CONCLUSION

The project used the Double Diamond approach to structure and plan the different phases. Research was conducted on the use orbital shakers in a laboratory environment. Literature research was carried out into the laboratory environment and current and future innovations in digitization and laboratory work and equipment. By means of reverse engineering – according to Product Evolution – of competitive products these findings were related back to an orbital shaker, while also getting a better understanding of the mechanics and electronics this project. Additionally, a laboratory visit and interview, as well as a user brainstorming session, helped relating the literature research back to the technician, as well as give usable input from a technician point of view in shaker usage and interface interaction.

These findings then culminated into the design of 3 concepts, each with an authentic mechanism and casing. After a quantitative evaluation of the concepts and a discussion with the company, a single concept was selected to continue with. This concept was developed into a detailed CAD model, while a high-fidelity prototype was designed in tandem. Not only did the prototype showed improvements necessary for the final design, but it also illustrated to the company, together with the research and design of the project, what time and capital investment would still be necessary to develop this product to a final, sellable state which was the original goal of this project. The company now has a detailed report of design and prototype, as well a functioning proof of concept and detailed CAD model to make an educated guess on continuing this product design further or halting it.

Recommendations

As mentioned in the discussion, the main recommendation for continuing this project is testing and improving the prototype, specifically user testing. While any mechanical problems dealing with cleaning and heating can be fixed without further research, the interaction between the user and the interface might require multiple versions before a design is found that satisfies the current requirement for features and is intuitive to use for the user. Once this baseline is reached, integration with different software for digital journals or connectivity with incubators can be implemented, with the goal of further reducing the number of tasks a technician needs to perform when working with an orbital shaker.

In terms of the mechanism, the current modular approach is a step towards customizability in comparison to the fixed setups modern day shakers use. In time, this direction can be expanded by reducing the need for extra components via modularity and building a shaker with fully adjustable orbits and counterweights. Furthermore, the cleanability of the shakers can be improved from its current form with the implementation of chemical resistant or anti-bacterial paints and surface treatments used in some high-end laboratory products.

Evaluated requirements

In terms of requirements, the design met a large portion of the requirements that function in the prototype. Detailed requirements that were uncertain can be seen in table 2, while the full table is visible in Appendix K1.

Most requirements not met, would theoretically be passed, according to all temperature and humidity constraints that were taken into accounts when designing the products and building the prototype. Additionally, the vibra-

tion is excessive during operation of the prototype, but the issue – too heavy counterweights and too light top plate – is known and can be fixed in a later version. Since no users have yet tested the prototype, it is uncertain if the new interface is as intuitive as it is designed as, but this can be tested with the current prototype still. Finally, since no detailed cost analysis was done, one cannot make an estimate on the cost price, thus this requirement remains uncertain.

Table 2: Selection of evaluated requirements

Index	Requirement	State
1	<i>The shaker should be operable at max 37 °C</i> Not tested, however the prototype was tested and deemed functional at room temperatures (21 °C), although not in an incubator. Since the prototype is designed to be able to handle these conditions, it could be tested rather simply in the future.	Likely
2	<i>The shaker should be operable at 95% Relative Humidity (RH)</i> Not tested, but since the prototype is designed for this it can be easily tested in the future.	Likely
5	<i>No heat should be generated during operation</i> Not tested, this can be included in aforementioned future testing.	Uncertain
6	<i>The shaker cannot create vibration in the placement surface</i> The current prototype does have vibration beyond acceptable boundaries. Some vibration can be eliminated by a different top and bottom plate, a general lower center of mass and wider feet that absorb more vibration.	Failed
11	<i>The shaking mechanism should, when turned off, withstand heating to 150 °C</i> Not tested, but since the mechanism uses materials and components all resistant to these temperatures, it is likely it will pass.	Likely
12	<i>The electronic components should, when turned off, withstand heating to 150 °C</i> Not tested, and with a temperature resistance of 160 °C for the motor, this might succeed in singular tests but fail in long-term usage.	Uncertain
13	<i>The material casing should, when turned off, withstand heating to 150 °C</i> Not tested, but as like the mechanism, the materials are capable of handling these temperatures.	Likely
18	<i>The shaker interface should be understandable without manual</i> Not tested, the increased complexity of the interface likely will make it less intuitive compared to basic existing shakers. However, the basic operation of setting time and speed has remained as close to the original interaction flow as possible.	Uncertain
27	<i>The cost price should be under 2.000,-</i> No calculations were done	Uncertain

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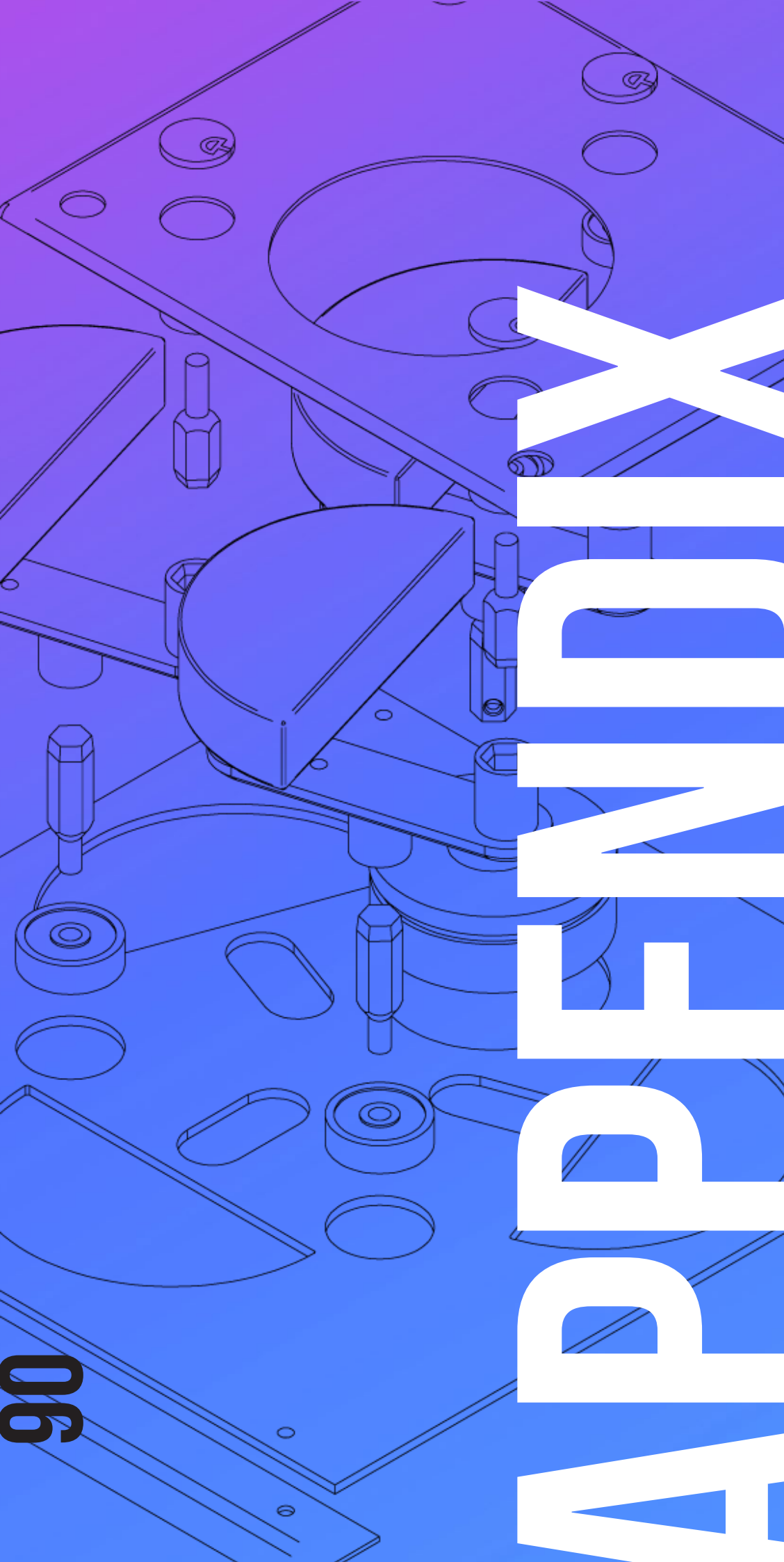
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EXPLODED VIEW

APPENDIX

Appendix A: Reverse engineering	92	Appendix H: Final design	115
A1 Brochure comparison	92	H1 Final design exploded view	115
A2 Product evolution: reverse engineering methodology	93	Appendix I: Prototype technical drawings	116
A3 Customer needs table	94	I1 Casing bracket	116
Appendix B: Product disassembly	95	I2 Bottom plate	117
B1 Qualitative judgement: NBiotek	95	I3 Middle plate	118
B2 Electrical diagram: NBiotek	95	I4 Transfer upper bearing	119
B3 Substract and Operate procedure: NBiotek	96	I5 Transfer motor	120
B4 Qualitative judgement: BioSan	97	I6 Transfer lower bearing	121
B5 Electrical diagram: BioSan	98	I7 Module 50mm	122
B6 Substract and Operate Procedure: BioSan	98	I8 Assembly exploded view	123
B7 Qualitative judgement: OHAUS	99	Appendix J: Prototyping	124
B8 Electrical diagram: OHAUS	100	J1 Summary of code	124
B9 Functional flow structure diagram	101	J2 List of design improvements	126
Appendix C: Competitor comparison	102	Appendix K: Discussion	127
C1 Competitor morphological diagram	102	K1 Evaluated requirement specification	127
Appendix D: Requirement specification	103		
D1 Requirements table	103		
D2 NEMA Motor insulation classes	104		
D3 Relative regulations	104		
Appendix E: User brainstorm sessions	105		
E1 First participant	105		
E2 Second participant	106		
Appendix F: Ideation	107		
F1 Morphological diagram	107		
F2 Moodboard	108		
F3 Ideation sketches	109		
Appendix G: Design	111		
G1 Interface design concepts	111		
G2 Concept morphological diagram	112		
G3 Quantitative assesment - Concepts	113		
G5 Quantitative assesment - Weighting table	114		

Appendix A: Reverse engineering

A1 Brochure comparison

Feature	N-BioTek NB-101S Mini Shaker (1)	BioSan CPS-20 Compact CO2 Platform Shaker (2)	OHAUS Extreme Shaker SHEX1619DG (3)
Motion	Orbital	Orbital	Orbital
Cost	€ 495,-	€ 997,50	€2.310,-
Speed range	30-300 rpm	50-250 rpm	15-500 rpm
Speed increment	1 rpm	10 rpm	1 rpm
Time range	Continuous or up to 48h	Continuous or up to 96h	Up to 160h
Time increment	1 min	1 min	1 sec
Temperature range operability	4 – 60 C	Shaker: 4 – 45 C Controller: 4 – 40 C ***	Shaker: -10 – 60 C Controller: -10 – 50 C
Relative humidity operability	-	Shaker: 98% RH Controller: 80% RH ***	Shaker: 100% RH Controller: 80% RH
Orbit	25 mm	20 mm	19 mm
Controller	Digital microprocessor	-	Digital
Motor	Plate type brushless DC motor	Brushless motor	Brushless DC motor
Drive system	Beltless direct drive	Triple eccentric	Triple eccentric
Operating panel (interface)	Touch button	-	-
Display	5-digit LCD	-	-
Platform size	300 x 330 mm	-	279 x 330 mm
Dimensions casing	305 x 350 mm	255 x 255 mm	294 x 355 mm
Height	75 mm	100 mm	149 mm
Weight	5 kg *	3,4 kg **	21,8 kg
Power consumption	15 W	5,7 W	30 W
Power supply	110-220 V, 50/60 Hz	100-240 V, 50/60 Hz	230 V, 0,3 A, 50/60 Hz

(1) (N-BioTek, 2021)

(2) (BioSan SIA, 2021)

(3) (OHAUS Europe GmbH, 2021)

* The brochure mentioned a weight of 5 kg, but when weighing the actual product this was 9,5 kg.

** Online brochure mentioned 3,4 kg, but the user manual that came with the product used 4,2 kg.

*** Not mentioned online, but mentioned in the accompanied user manual

A2 Product evolution: reverse engineering methodology

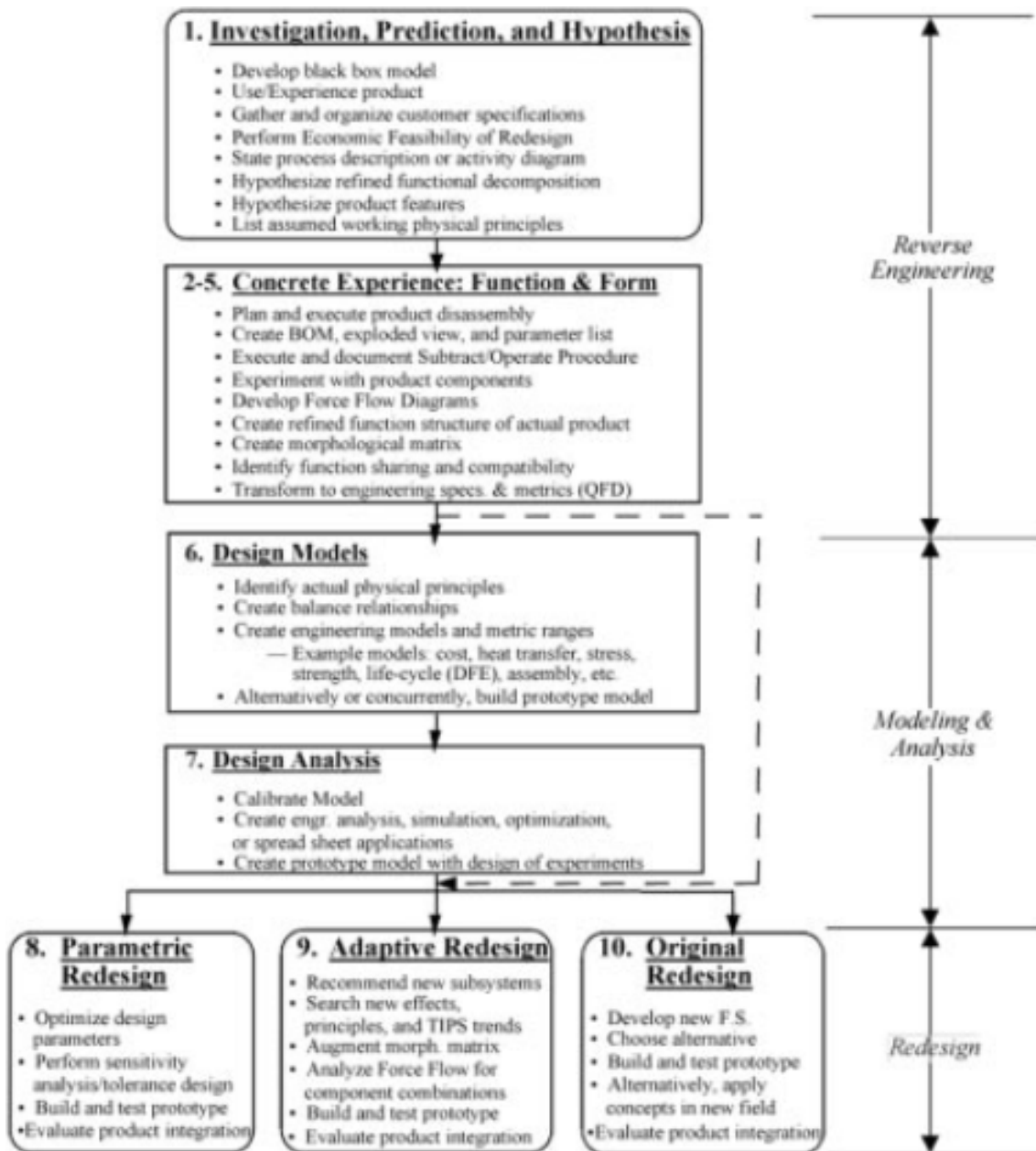


Figure 37: Otto & Wood reverse engineering and redesign methodology

A3 Customer needs table

Customer need	Weight	N-BioTek	Biosan	OHAUS
<i>Cleanable</i>				
<i>Washable surface</i>	6	Y	Y	Y
<i>Alcohol resistant surface</i>	9	Y	Y	Y
<i>Heat able in autoclave</i>	9	N	N	N
<i>Aesthetics</i>				
<i>Look pleasing</i>	2	N	Y	Y
<i>Size</i>				
<i>Compact to fit in incubator</i>	7	N	Y	N
<i>Compact to fit in autoclave</i>	6	N	Y	N
<i>Low weight to not bend incubator shelf</i>	4	N	Y	N
<i>Low height to not move incubator shelf</i>	3	Y	Y	N
<i>Stability</i>				
<i>Does not create vibration on shelf</i>	8	Y	Y	Y
<i>Does not move during use</i>	6	Y	Y	Y
<i>Temperature</i>				
<i>No heat generation during use</i>	8	Y	Y	Y
<i>Cost</i>				
<i>Cost</i>	5	Y	Y	N
<i>Interaction</i>				
<i>Understandable interface without manual</i>	3	N	N	Y
<i>Easily reachable buttons</i>	5	Y	Y	Y
<i>Speed visible</i>	4	Y	Y	Y
<i>Operation time visible</i>	4	N	Y	Y
<i>Long power cord</i>	6	Y	Y	Y
<i>Detachable interface</i>	8	N	Y	Y
<i>Capacity</i>				
<i>Easily exchangeable top plate</i>	6	N	Y	
<i>Interactivity</i>				
<i>Connected to digital lab journal</i>	2	N	N	N
<i>Remote start and stop</i>	3	N	N	N
<i>Remote status visibility</i>	3	N	N	N

Appendix B: Product disassembly

B1 Qualitative judgement: NBiotek

Packaging

- Packaging materials required the shaker to be lifted from the box with foam, meaning it is difficult to handle for one person

Usage

- Interface was understandable for simple usage
- On/off switch at the back was difficult to reach
- Shaker will immediately shake at set speed without ramp
- Fast feedback loop with shaker plate weight

Design

- Epoxy on electromagnet coils and speeds sensor printing plate to prevent reverse engineering
- Tighten-only screw on main bearing to prevent taking it apart

- Fabricated metal box around main printing plate, preventing removal of printing plate to check backside

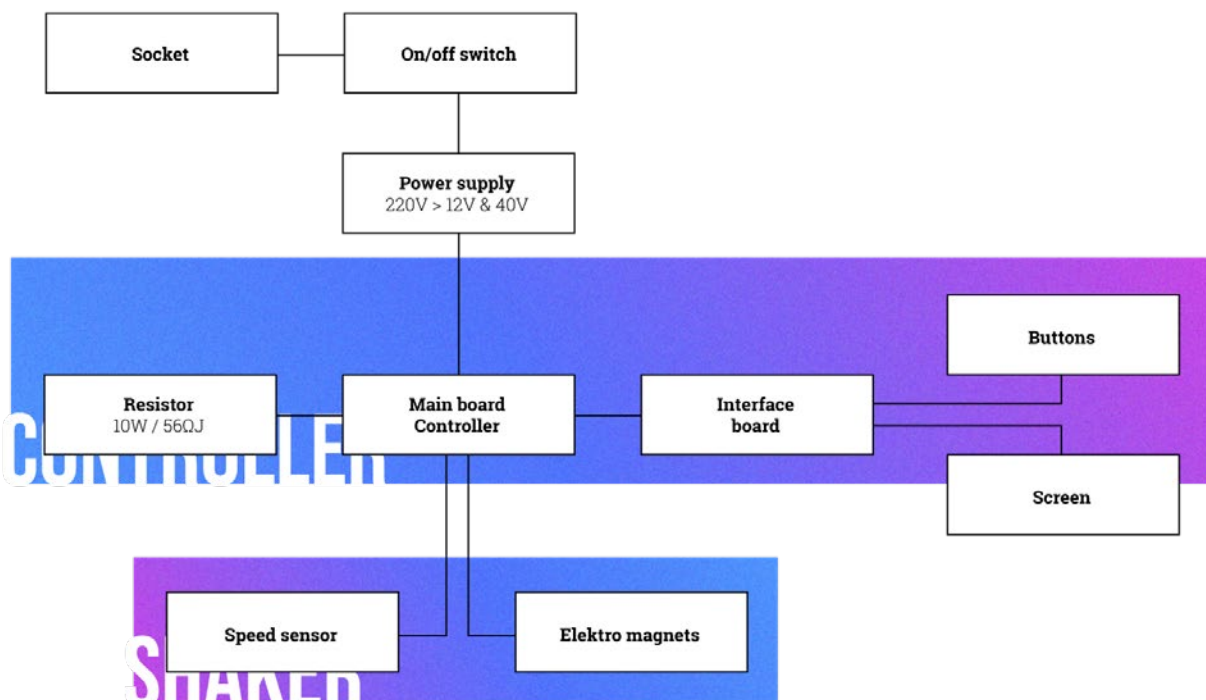
Electronics

- Separated printing plates for speeds sensor, main controller, and interface
- Included large resistor mounted on casing separate of controllers
- Brushless motor was custom made by using coils and magnets on the moving mechanism instead of using a third party motor
- Probably why the sensor had epoxy on it

Materials & fabrication

- Sheet metal casing
- Assembly by hand, no clear hierarchy of assembly
- Stabilizer structure and rotating mechanism as subassembly

B2 Electrical diagram: NBiotek



B3 Substract and Operate procedure: NBiotek

Part and action	Effect	Deduced function
Removed cover	No effect noticeable Electronics visible and fully functionable	No effect on operation, thus can be left off for further testing
Removed stabilizers	Top plate starts to rotate	Keeps plate from rotating
Removed counterweight	Shaker stays still, but table starts to shake Shaking gets worse at higher speeds (300 rpm)	Prevents the surface where the shaker is placed from moving
Removed speed sensor, but kept it connected (At this point the part's function was unknown)	When turning on, screen gives error message Buttons do not work Cannot make shaker move	Requires part to be in place for operating Buttons not working prevent shaker from moving
Removed speed sensor during operation	Shaker started fine Speed readings on screen quickly changed when removing According to the screen speed changes, the plate started turning faster as well Once sensor was removed the plate stops moving Error message on screen Controller requires speed reading to operate	Part is used to sense the speed of the plate (placed underneath magnets on turning part)
Moved speed sensor around during operation	When moved outwards the speed reading drops on screen and the turning slows as well When moved inwards the speed reading increases and the turning speeds up as well	Sensor senses magnetic field of the magnets passing by and adjusts speed accordingly Feedback loop to drive mechanism and controller

B4 Qualitative judgement: BioSan

Packaging

- Similar foam packaging as N-BioTek, cannot remove without dropping the product
- Top plate rubber mat was bent in bag
- Wires of controller were intertwined with shaker foam
- Controller casing was already loose on one end

Usage

- Shaker slowly builds up to set speed, takes roughly 15-20s
- Feedback loop with weight a bit slow, overshoots or undershoots often
- Cannot turn product off without unplugging, no on/off switch
- Rubber "friction" fit for top plate, very simple to use

Design

- General look and feel of product are old fashioned, especially controller/interface (unnecessary curvy elements)

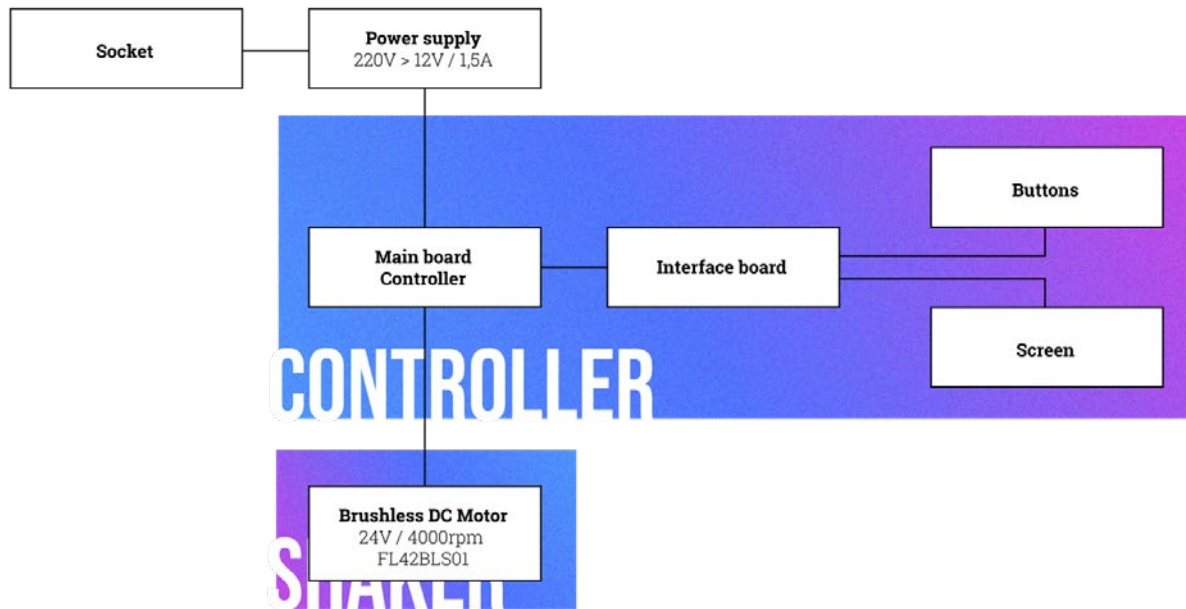
Electronics

- Controller houses 1 whole circuit board, integrating everything
- No separate speed sensor visible, so probably integrated in motor

Materials & fabrication

- Shaker and casing only consist of metal parts, except of rubber and plastic wire clips
- Controller casing was 3d printed, layers and some printing strings on the inside clearly visible, while the outside had some surface treatment
- Each part consists of 2 shells, so 4 printed parts in total, probably to increase thickness, but print multiple parts at the same time
- Metal casing of sheet metal: cut, bend, welded and painted
- Rest of shaker is "simple": clear assembly hierarchy for assembly by hand

B5 Electrical diagram: BioSan



B6 Substract and Operate Procedure: BioSan

Part and action	Effect	Deduced function
Removed controller cover	Electronically still works fine Does not magnetically connect to incubator anymore	No effect on operation Houses magnet in shell
Shaker casing	Still works stable	No effect on operation, except for initial stability/placement

B7 Qualitative judgement: OHAUS

Packaging

- Similar foam packaging as N-BioTek and Biosan, due to this shaker being way heavier it required 2 people to lift the product from the box to prevent it from falling.
- Packaging comes with EU and UK plug, as well as a UK to EU converter plug

Usage

- Light next to on/off button turns on when plugged in, so it was unclear if it was already on or not.
- Buttons for up/down could not keep up with fast presses
- Shaker makes high pitched noise when turned on but stationary, probably the transformer
 - Shaker makes even more noise when moving
- Slow build up to target speed, but almost instant brake when switching off
- In the promotional images it looks like the controller can be attached to the shaker casing, but this is not the case.

Design

- Wires from controller to shaker are bonded flat, enabling pushing them through the rubber insulation of an incubator door.
 - Wires are very sturdy
- Motor powers V snare that includes a counterweight and powers a middle plate. Middle plate has 2 other offset bearings attached as stabilizers, one which includes a speed sensor.
- The controller casing is rivetted into plastic

- The entire shaker casing consists of 6 parts + internal casted iron parts, quite a lot for the size of the product

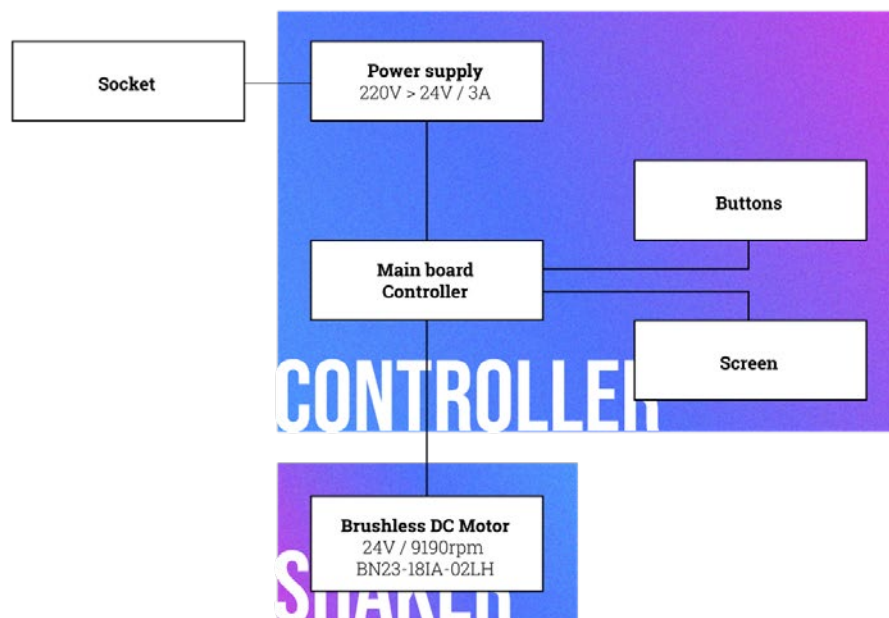
Electronics

- Controller houses 1 circuit board which includes the screen.
- Only other electrical part is the transformer from 220V to 5V
- One stabilizer bearing includes a speed sensor, so there is not one included in the motor

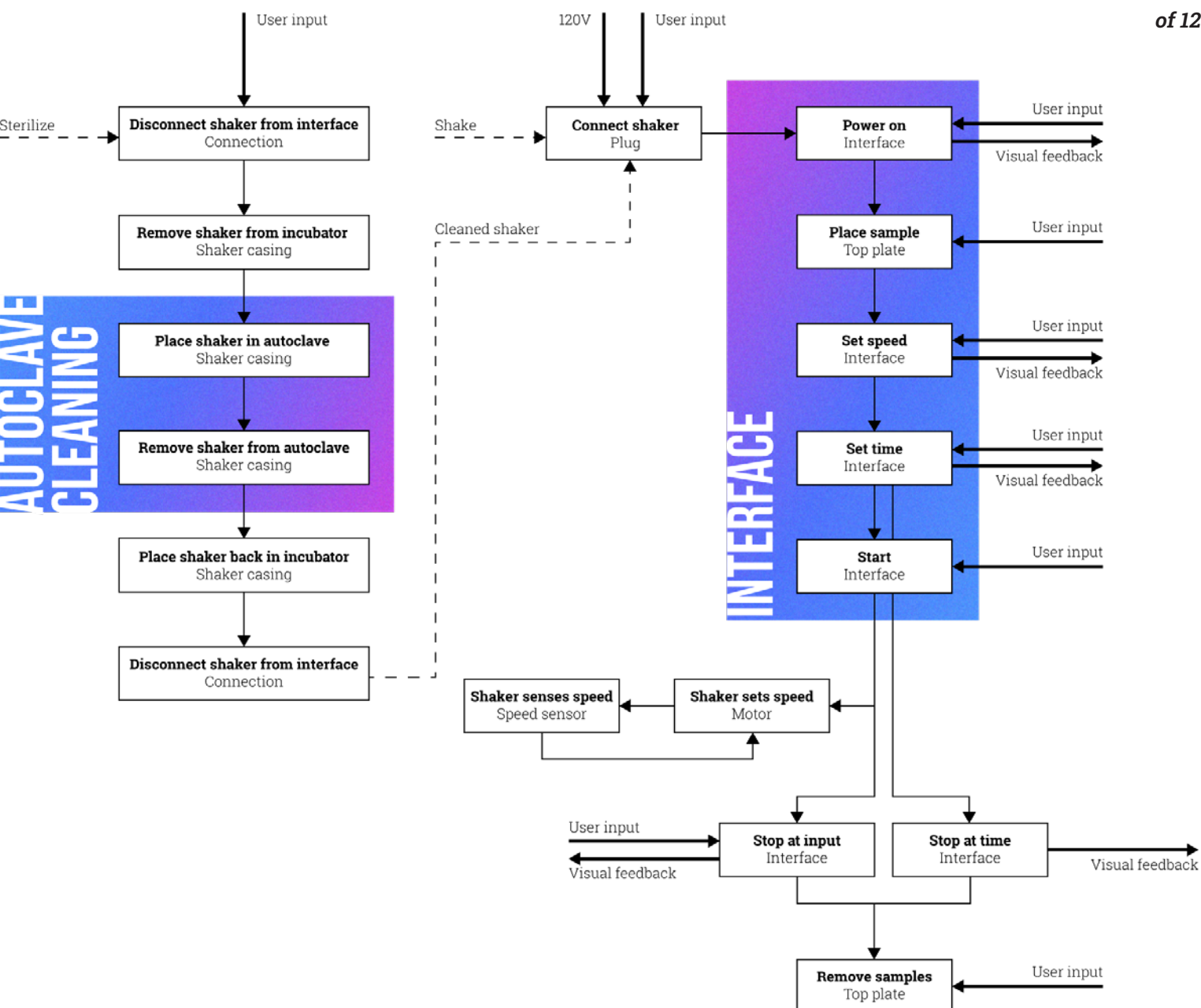
Materials & fabrication

- Shaker top plate is a bended aluminum plate
- Casing front and back, top and bottom panels are flat aluminum sheets
- Side panels are casted aluminum parts, wall thickness of 4mm
- Parts holding the mechanism in place is casted iron, which creates most of the weight.
 - Probably done since this is normal for large shakers (>1m wide), so this product was most likely an adaption from a bigger shaker to a smaller one. For a smaller shaker however, this method is a bit overkill
- Plastic injection molded front of the controller is very thick (3mm)

B8 Electrical diagram: OHAUS



B9 Functional flow structure diagram



Appendix C: Competitor comparison

C1 Competitor morphological diagram

Function	N-BioTek NB-101S Mini Shaker	BioSan CPS-20 Compact CO2 Platform Shaker	OHAUS Extreme Shaker SHEX1619DG
Turn on/off	Switch on back of casing	No switch	Membrane button on front of controller
Change speed & time	4 membrane covered buttons: 1 time/speed selection, 2 up and down, 1 confirm setting	3 membrane covered buttons: 1 time/speed selection, 2 up and down	6 membrane buttons: 2 on/off for time/speed and 2x2 for up/down
Show information to user	5 digit, 7-segment LED display	LCD display	2 LED displays: 1 for time and 1 for rpm
Start/stop shaking cycle	1 membrane button	1 membrane button	1 membrane button, the same for on/off
Connection of shaker with interface	Internally connected interface board with controller board	Interface board fixed to controller, externally connected to drive mechanism	Controller connected to power and casing with motor and sensor
Drive shaking mechanism	Self-made brushless DC motor, directly driving plate, extra mounted speed sensor	Third party brushless DC motor (FL42BLs01, 24V/80W) on main axle, speed sensor incorporated in motor	Third party brushless DC motor on axle, driving the main axle with counterweight via a V snare.
Keep top plate stable	External stabilizing beams attached to casing and top plate	2 extra, non-powered bearings	2 extra, non-powered bearings, one includes the speed sensor
Measure speed	Sensor on bottom counterweight main axle	Sensor in motor	Sensor on unpowered axle
Attach interface to incubator	- (fixed interface)	Magnet in the back of the casing	- (interface too big)
Support multiple top plates	4 metal attachment points on the corners of the top plate	4 holes with rubber sides where different plates can be inserted ("smooth friction fit")	4 screws that have to be unscrewed and fitted

Appendix D: Requirement specification

D1 Requirements table

Index	Requirement	Priority	Origin
1	The shaker should be operable at 37 °C	1	Company
2	The shaker should be operable at 95% Relative Humidity (RH)	1	Company
3	The shaker should allow for a changeable speed of 50 to 350 rpm	2	Company
4	The shaker should allow for setting a timer for operation	1	Company
5	No heat should be generated during operation	2	Company
6	The shaker cannot create vibration in the placement surface	2	Company
7	The weight of the shaker cannot exceed 9 kg	2	Company
8	The width of the shaker cannot exceed 400 mm	2	Company
9	The length(depth) of the shaker cannot exceed 300 mm	2	Company
10	The height of the shaker cannot exceed 100 mm	2	Company
11	The shaking mechanism should, when turned off, withstand heating to 150 °C	1	Company
12	The electronic components should, when turned off, withstand heating to 150 °C	1	Company
13	The material casing should, when turned off, withstand heating to 150 °C	1	Company
14	The orbit of the shaker can be changed to 20 mm by the user	2	Company
15	The orbit of the shaker can be changed to 25 mm by the user	3	Company
16	The orbit of the shaker can be changed to 50 mm by the user	3	Company
17	The shaking parameters can be changed without opening the incubator	1	User
18	The shaker interface should be understandable without manual	2	User
19	The shaker should save operation parameters set by the user	3	User
20	The saved operation parameters should be accessible by the user	3	User
21	Any outside surfaces can withstand daily cleaning with alcohol (75%)	1	Legislation
22	Different types and sizes of flasks can be placed on the top plate	2	User
23	When exchanging top plates, the user should not need extra tools	3	User
24	The power cord should be at least 2000 mm long	2	User
25	The powersupply should be 12V or 24V	2	Company
26	The costprice should be under 2.500,-	1	Company
27	The costprice should be under 2.000,-	3	Company
28	The shaker should comply with regulation EN 61010-1:2011	1	Legislation
29	The shaker should comply with regulation EN 61010-2-051:2015	1	Legislation
30	The shaker should comply with regulation EN 61326-1:2021 Class A (EMC 2014/30/EU)	1	Legislation
31	The shaker should follow directive RoHS 2015/863/EU	1	Legislation
32	The shaker should follow directive WEEE 2012/19/EU	1	Legislation
33	The shaker should comply with the compliance mark CE	1	Legislation

D2 NEMA Motor insulation classes

	Class A	Class B	Class F	Class H
<i>Maximum Temperature Rise (°C) *</i>	60	80	105	125
<i>Hot-spot Over Temperature Allowance (°C) *</i>	5	10	10	15
<i>Maximum Winding Temperature (°C) *</i>	105	130	155	180

*for an ambient temperature of 40°C (HECO Inc, 2022) (National Electrical Manufacturers Association, 2022)

D3 Relative regulations

- **Regulation BS EN 61010-1:2010**
 - Safety requirements for electrical equipment for measurement, control, and laboratory use – part 1: General requirements (European Union, 2010).
- **Regulation BS EN 61010-2-051:2015**
 - Safety requirements for electrical equipment for measurement, control, and laboratory use – part 2: Particular requirements for laboratory equipment for mixing and stirring (European Union, 2015).
- **Regulation BS EN IEC 61326-1:2021, Class A certified**
 - EMC requirements for electrical equipment for measurement, control, and laboratory use – part 1: General requirements (European Union, 2021).
- **Directive RoHS 3 2015/863/EU**
 - Addition to Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic equipment (EEE) (European Union, 2015).
- **Directive WEEE 2012/19/EU**
 - Addition to Directive 2002/96/EU on waste electrical and electronic equipment (WEEE) (European Union, 2012).

Appendix E: User brainstorm sessions

E1 First participant

Brechje Hooglugt, Soil Biology, Master Student Wageningen

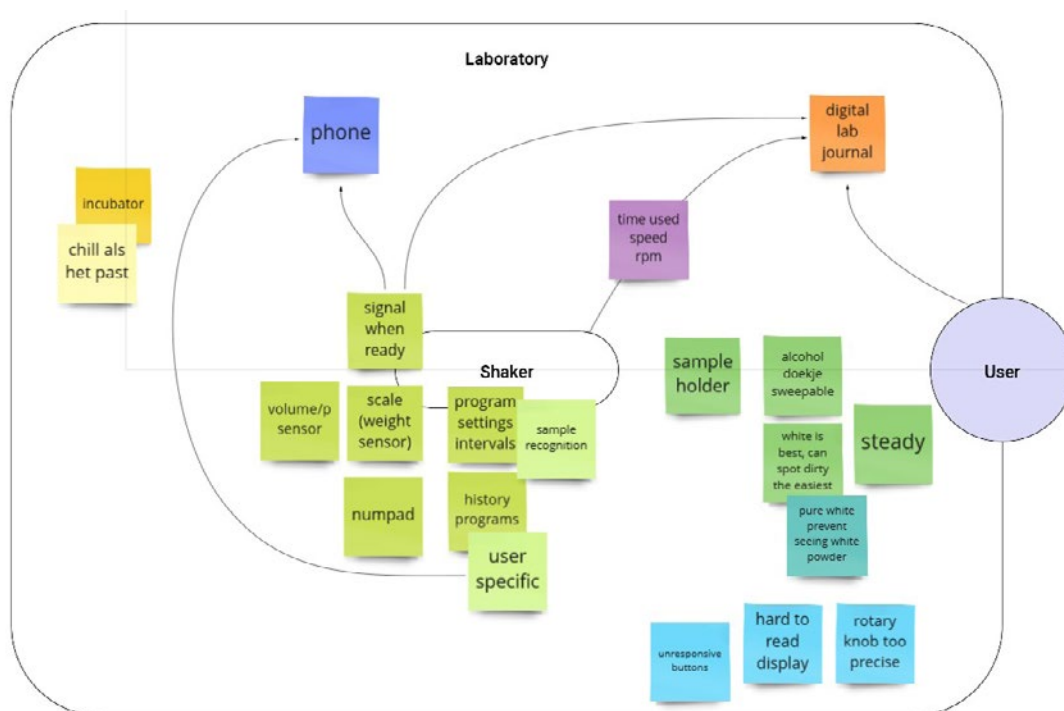


Figure 38: First phase of ACM, Evocation of Ideas for the first participant

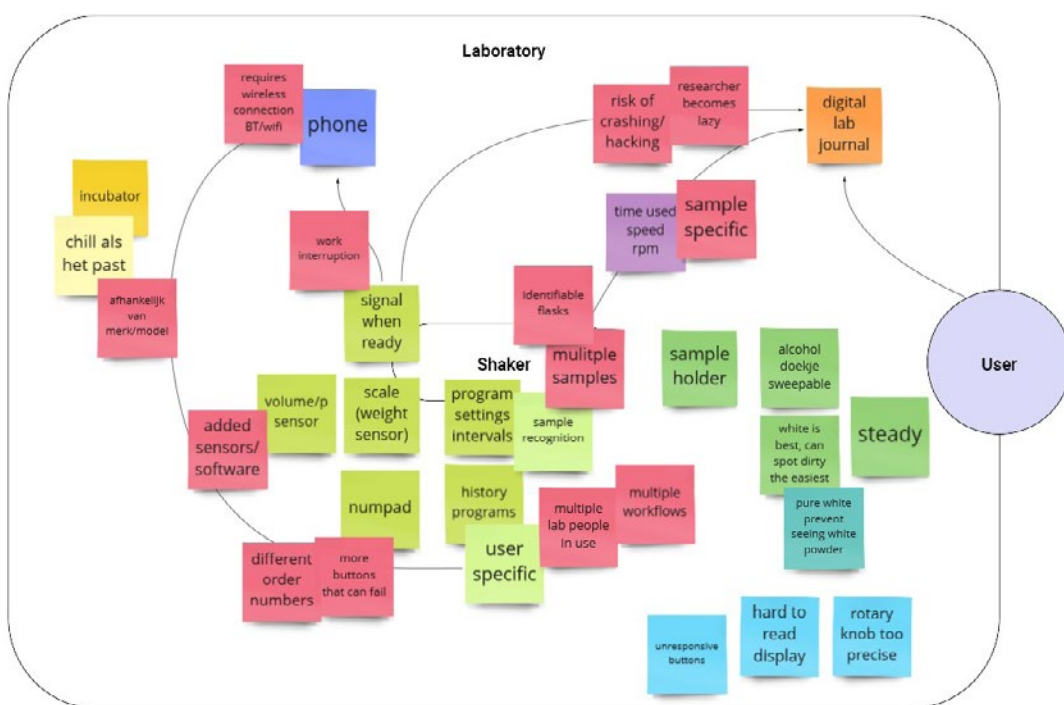


Figure 39: Second phase of ACM, Evocation of Constraints for the first participant

E2 Second participant

Fleur van Oosterom, Infection and Immunity, Master Student University of Utrecht

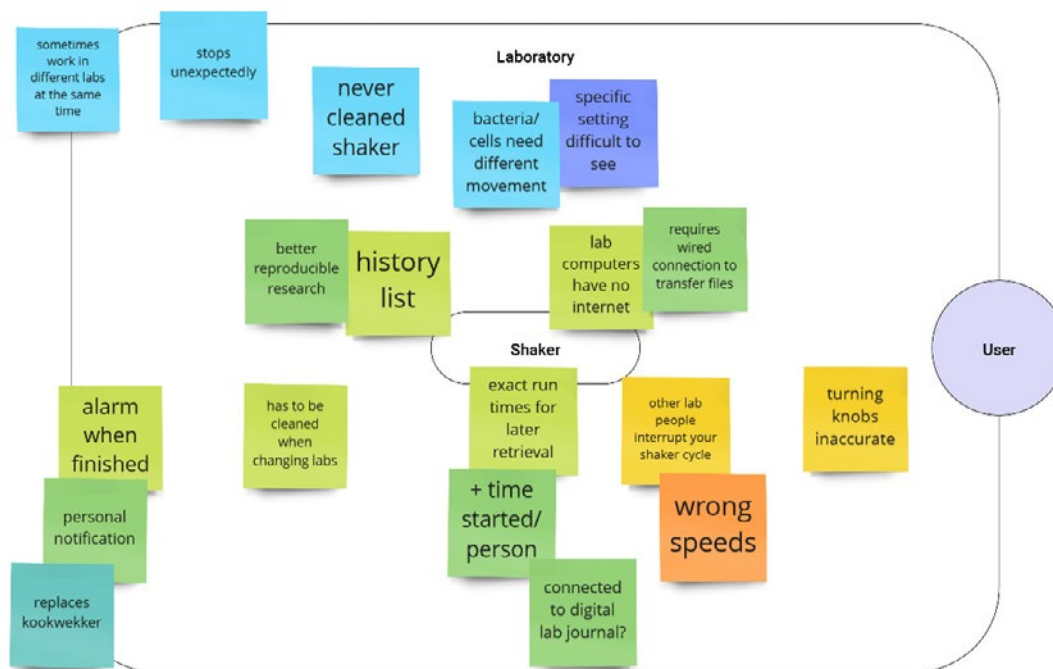


Figure 40: First phase of ACM, Evocation of Ideas for the participant participant

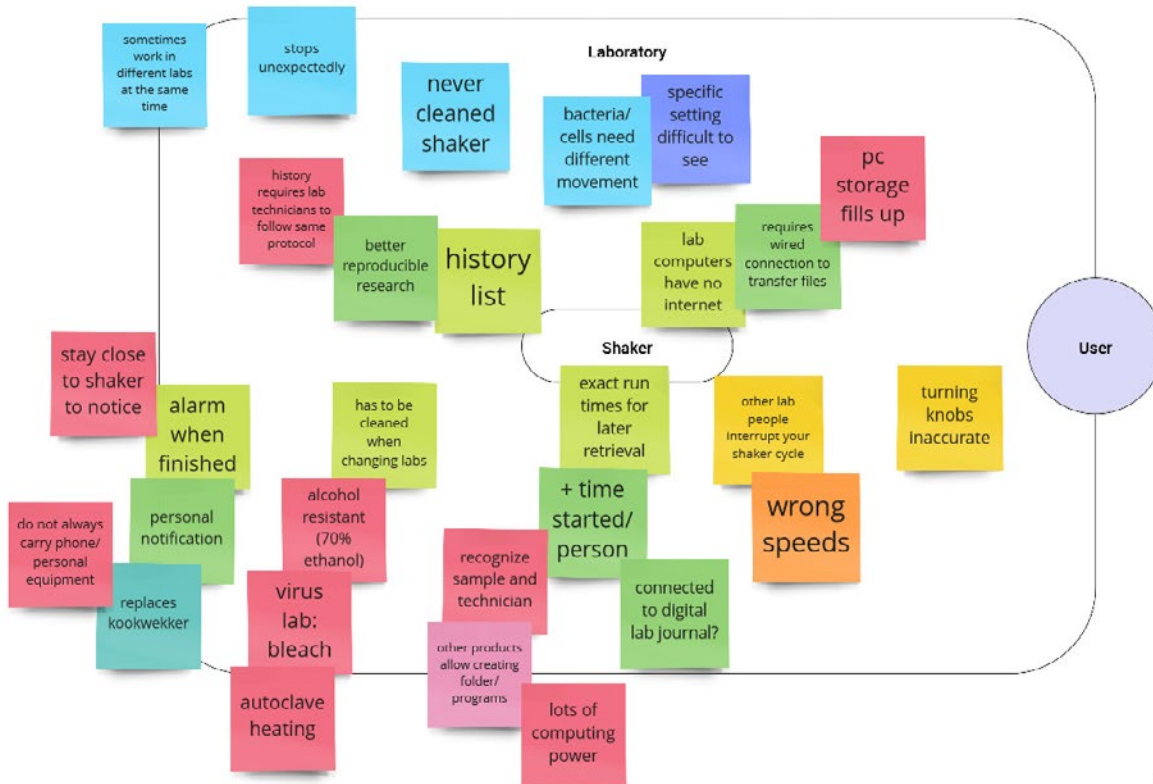


Figure 41: Second phase of ACM, Evocation of Constraints for the second participant

Appendix F: Ideation

F1 Morphological diagram

Function					
Turn on/off	Switch	Button		No feature (just plug)	
				Want on/off option	
Change speed & time	2 push buttons + 1 set button	2 rotating knobs		Integrated in a touchscreen	
Show information to user	x-digit LED display	LCD display	LED screen	Touchscreen	LED lights (for status)
Start/stop shaking cycle	1 push button	Auto start when sample is placed	On voice command	Touchscreen	Automatic (sensor)
Connection of shaker with detachable interface	Wired	Bluetooth		Wi-Fi	
		Requires electronics in shaker		Requires electronics in shaker	
Drive shaking mechanism	Brushless DC motor on 1 axle	Brushless DC motor powering multiple axis	Direct drive brushless DC motor on plate (self designed)		
			Not sure about reliability, so better to take something 3rd party		
Keep top plate stable	External stabilizers	2 extra axles and bearings	1 extra axle and bearing	Force plate to move along path on casing	
			Would be less stable than 2 extra axles when having a heavy top plate	Would create friction, thus reliability risks	
Attach interface to incubator	Magnet	Hook that attaches to incubator design		Suction cup	
		Incubator brand specific			
Support multiple top plates	Clamps	Friction fit on bottom plate (plastic)	Friction fit on bottom plate (smooth rubber)	Screw/bolt clamps	Friction fit top plate around bottom plate
				Too much "work" for user	

F2 Moodboard

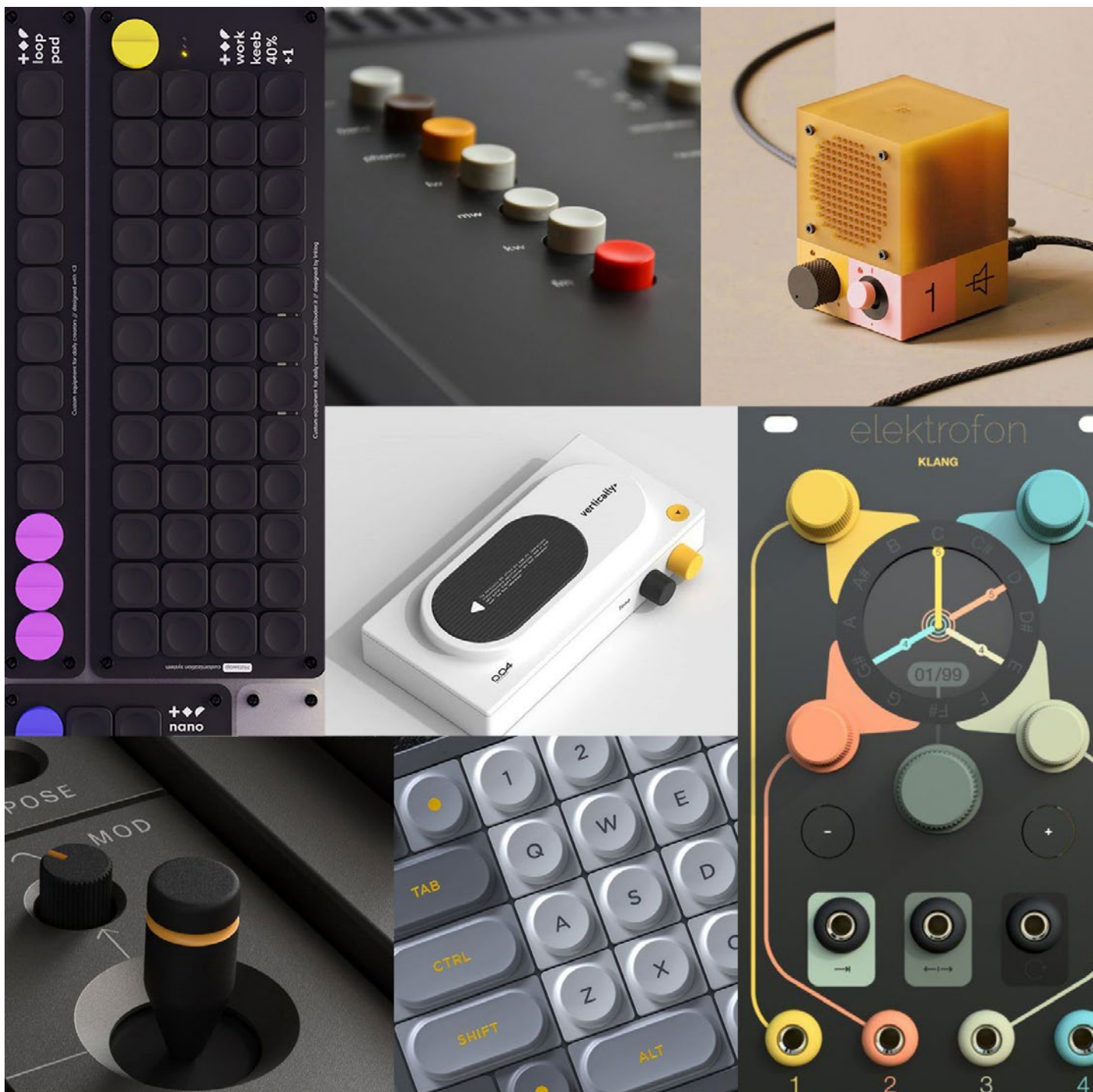
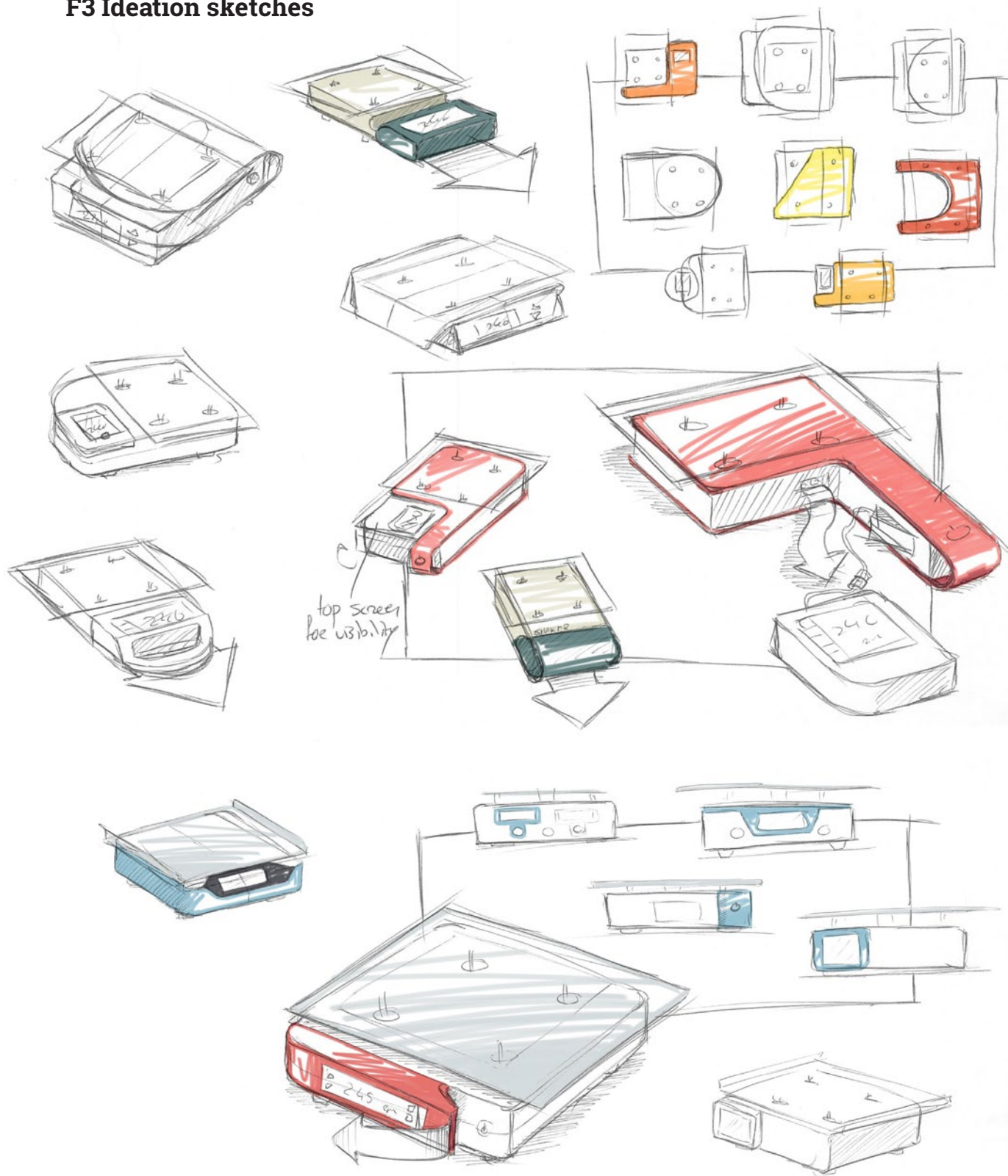
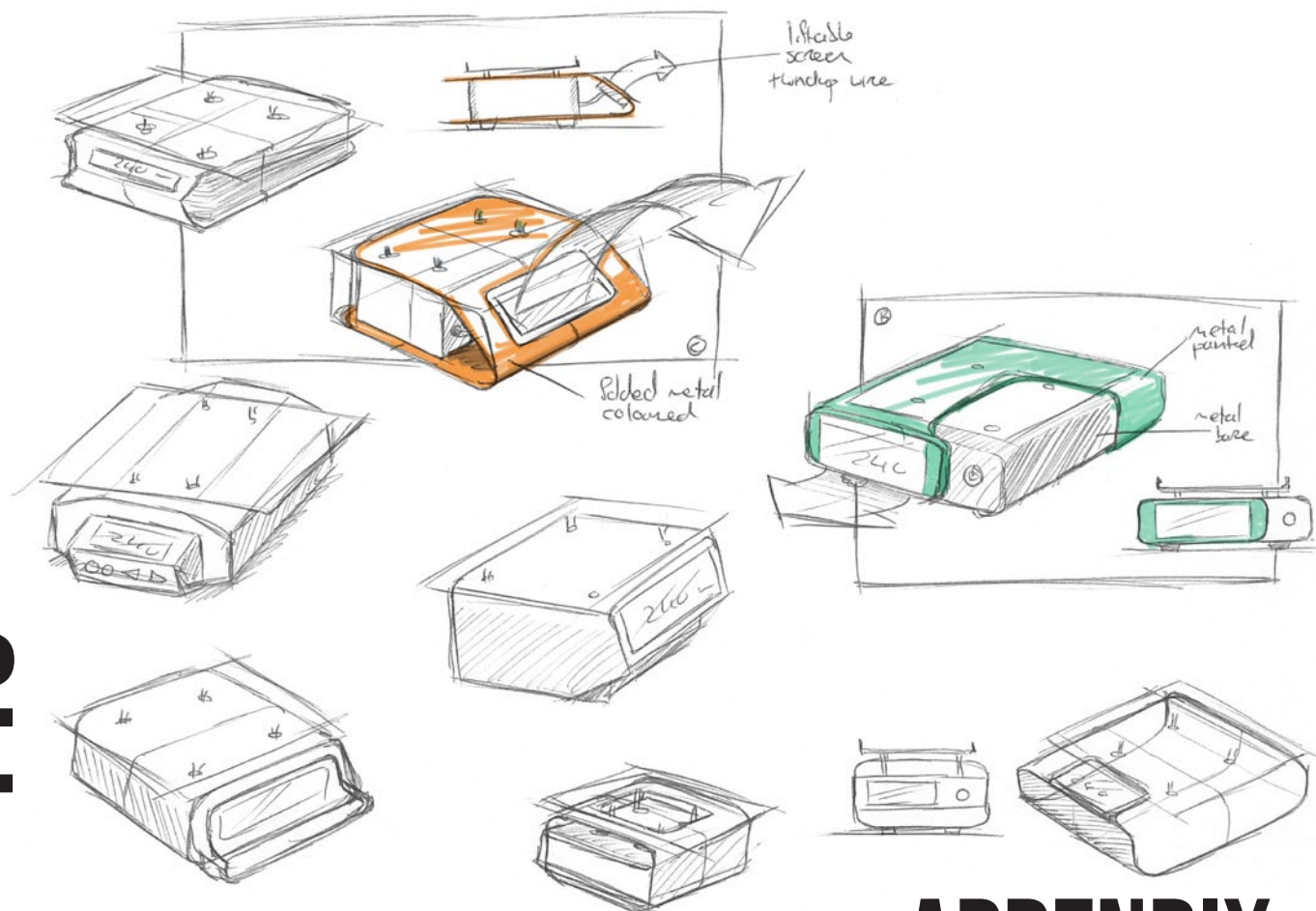
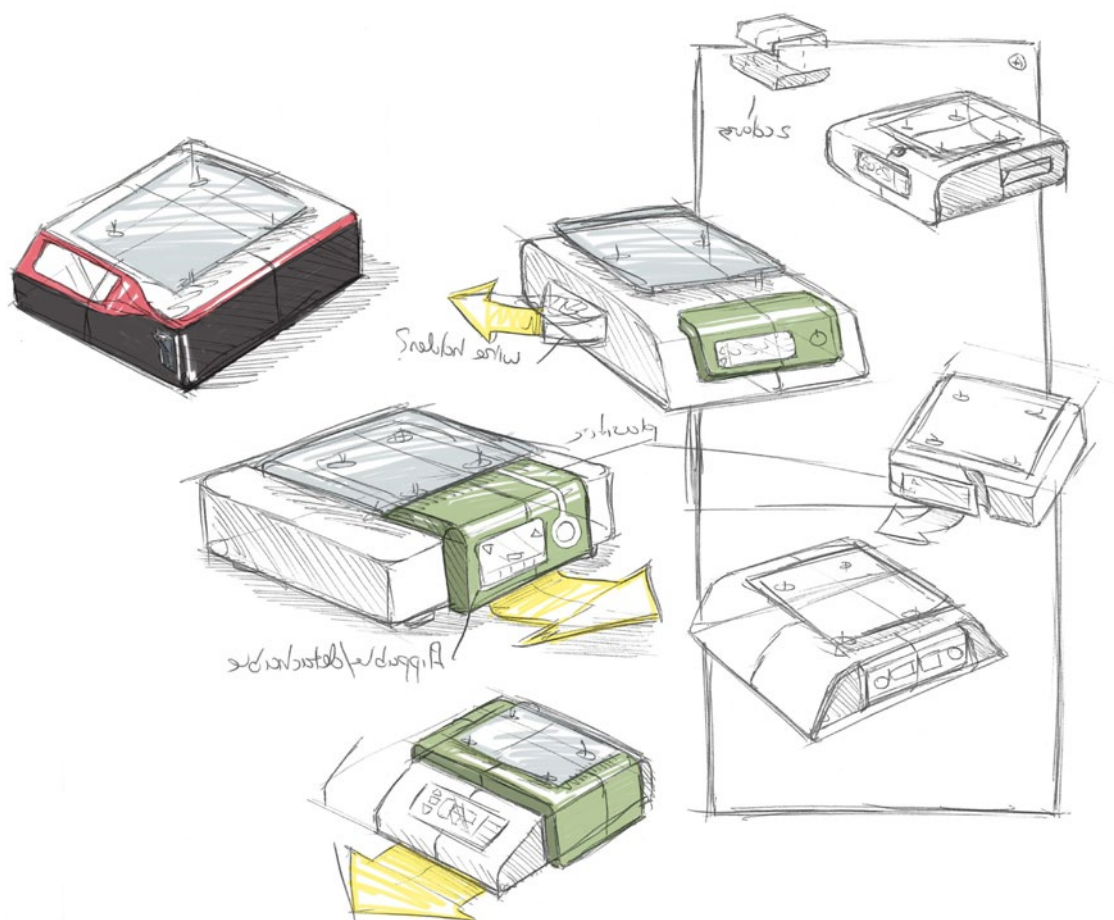


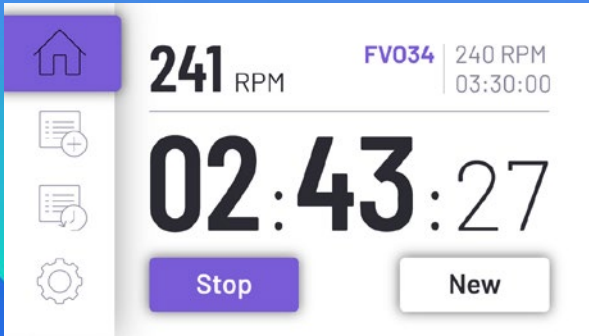
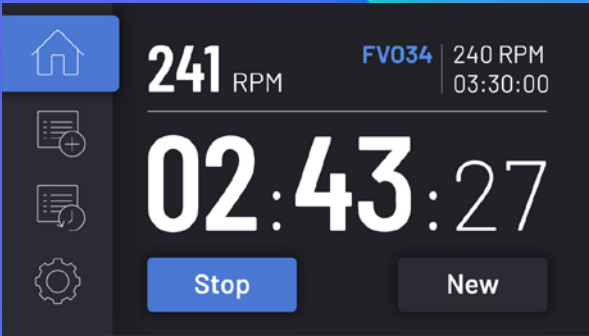
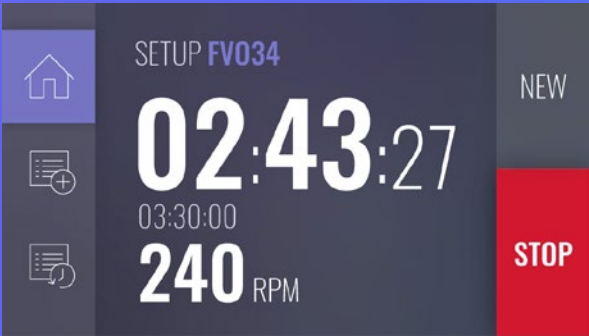
Figure 42: Moodboard for the shaker design

F3 Ideation sketches





Appendix G: Design
G1 Interface design concepts



G2 Concept morphological diagram

Function					
Turn on/off	Switch	Button	No feature (just plug)		
Change speed & time	2 push buttons + 1 set button	2 turning switches	Integrated in a touchscreen		
Show information to user	x-digit LED display	LCD display	LED screen	Touchscreen	LED lights (for status)
Start/stop shaking cycle	1 push button	Auto start when sample is placed	On voice command	Touchscreen	When door incubator closes (IR sensor)
Connection of shaker with detachable interface	Wired	Bluetooth	Wi-Fi		
Drive shaking mechanism	Brushless DC motor on 1 axle	Brushless DC motor powering multiple axis	Direct drive brushless DC motor on plate (self designed)		
Keep top plate stable	External stabilizers	2 extra axles and bearings	1 extra axle and bearing	Force plate to move along path on casing	
Attach interface to incubator	Magnets	Hook that attaches to incubator design	Suction cup		
Support multiple top plates	Clamps	Friction fit on bottom plate (plastic)	Friction fit on bottom plate (smooth rubber)	Screw/bolt clamps	Friction fit top plate around bottom plate

G3 Quantitative assesment - Concepts

A B C

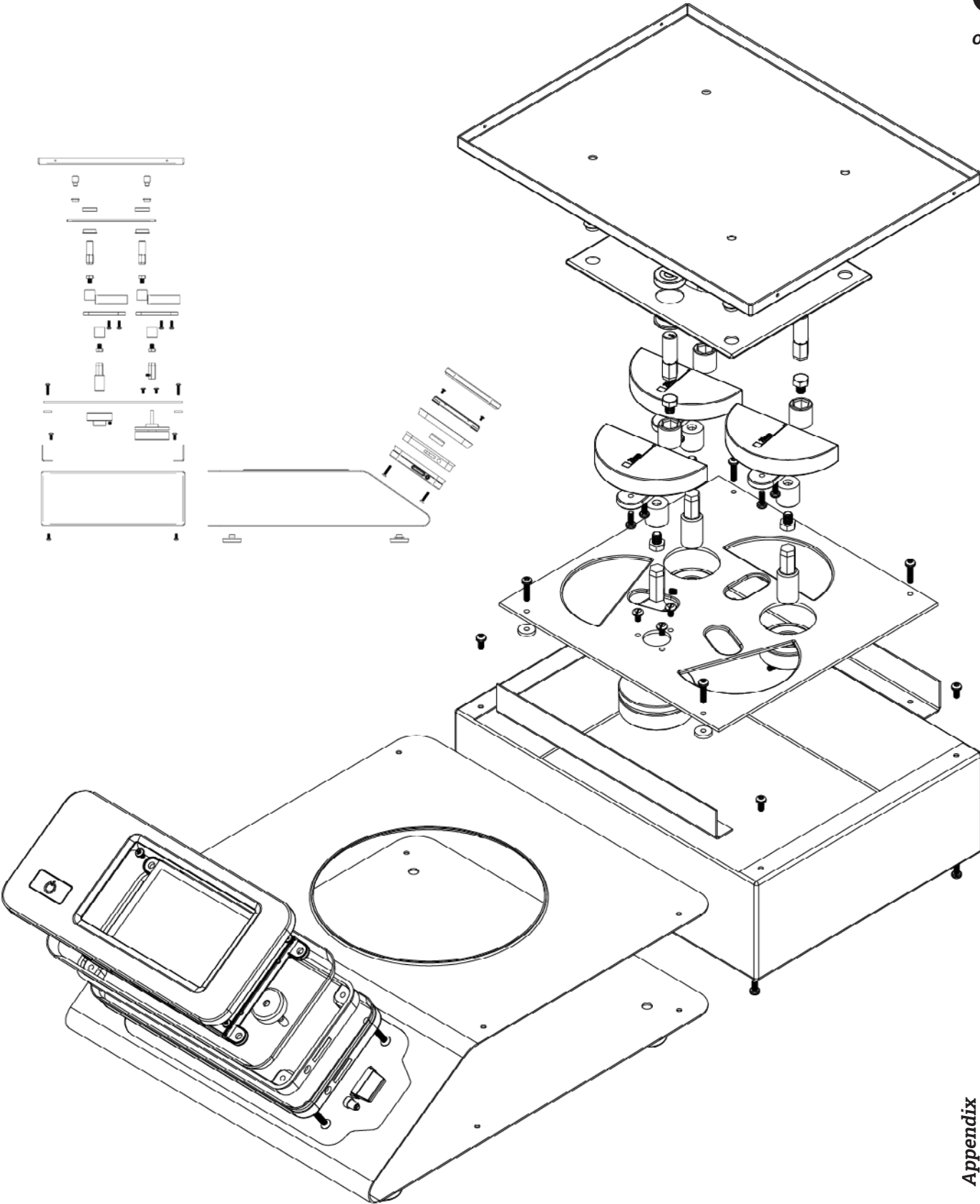
No.	Criteria	(1-5) Weight	(1-10) Score	Total	(1-10) Score	Total	(1-10) Score	Total
1	Design							
1.1	Overall looks	3	6	18	7	21	8	24
1.2	User friendliness	4	6	24	9	36	7	28
1.4	Stand out from competitors	3	7	21	9	27	5	15
		Total		63		67		84
2	Performance							
2.1	Predicted reliability	5	3	15	9	45	8	40
2.2	Predicted vibration/stability	5	4	20	9	45	7	35
		Total		36		90		75
3	Cleaning							
3.1	Easy to clean	4	7	28	6	24	10	40
3.2	Cleaning "prevention" (not look dirty too quickly)	1	5	5	5	5	6	6
3.3	Liquid/leaking resistance	2	8	16	6	12	9	18
3.4	Heatability in autoclave	5	10	50	10	50	10	50
		Total		99		91		114
4	Flexibility of use							
4.1	User changeable orbit	5	10	50	7	35	8	40
4.2	Incubator use	4	7	28	8	32	9	36
4.3	Tabletop use	3	5	15	8	24	7	21
		Total		91		91		97
5	Manufacturing							
5.1	Predicted costs	2	4	8	7	14	9	18
5.2	Predicted difficulty/stability of quality	3	6	18	8	24	7	21
		Total		26		38		39
6	Weight							
6.1	Within 9 kg	1	6	6	6	6	7	7
		Total		6		6		7
	Max score = 500	Total		322		400		399

G5 Quantitative assesment - Weighting table

Criteria		Weight (1-5) User 1	Weight (1-5) User 2	Weight (1-5) Self	New average	Difference
1	Design					
1.1	Overall looks	2	2	3	2.3	-0.7
1.2	User friendliness	1	5	4	3.3	-0.7
1.3	Stand out from competitors	1	4	3	2.7	-0.3
2	Performance					
2.1	Predicted reliability	5	5	5	5.0	0.0
2.2	Predicted vibration/stability	5	5	5	5.0	0.0
3	Cleaning					
3.1	Easy to clean	4	3	4	3.7	-0.3
3.2	Cleaning "prevention" (not look dirty too quickly)	4	3	1	2.7	1.7
3.3	Liquid/leaking resistance	4	5	2	3.7	1.7
3.4	Heatability in autoclave	4	2	5	3.7	-1.3
4	Flexibility of use					
4.1	User changeable orbit	5	3	5	4.3	-0.7
4.2	Incubator use	4	4	4	4.0	0.0
4.3	Tabletop use	5	5	3	4.3	1.3
5	Manufacturing					
5.1	Predicted costs	1	4	2	2.3	0.3
5.2	Predicted difficulty/stability of quality	1	4	3	2.7	-0.3
6	Weight					
6.1	Within 9 kg	3	2	1	2.0	1.0

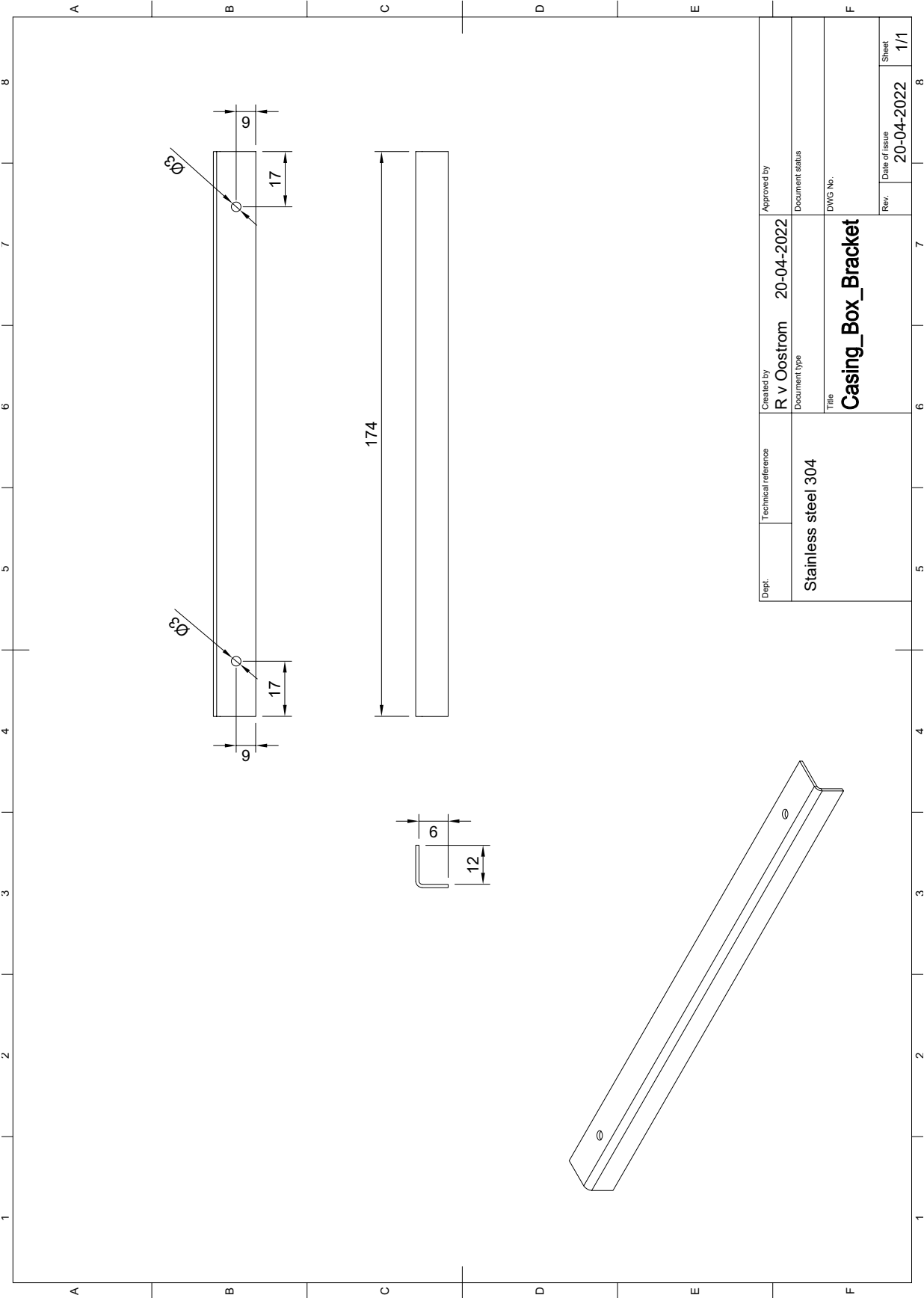
Appendix H: Final design

H1 Final design exploded view

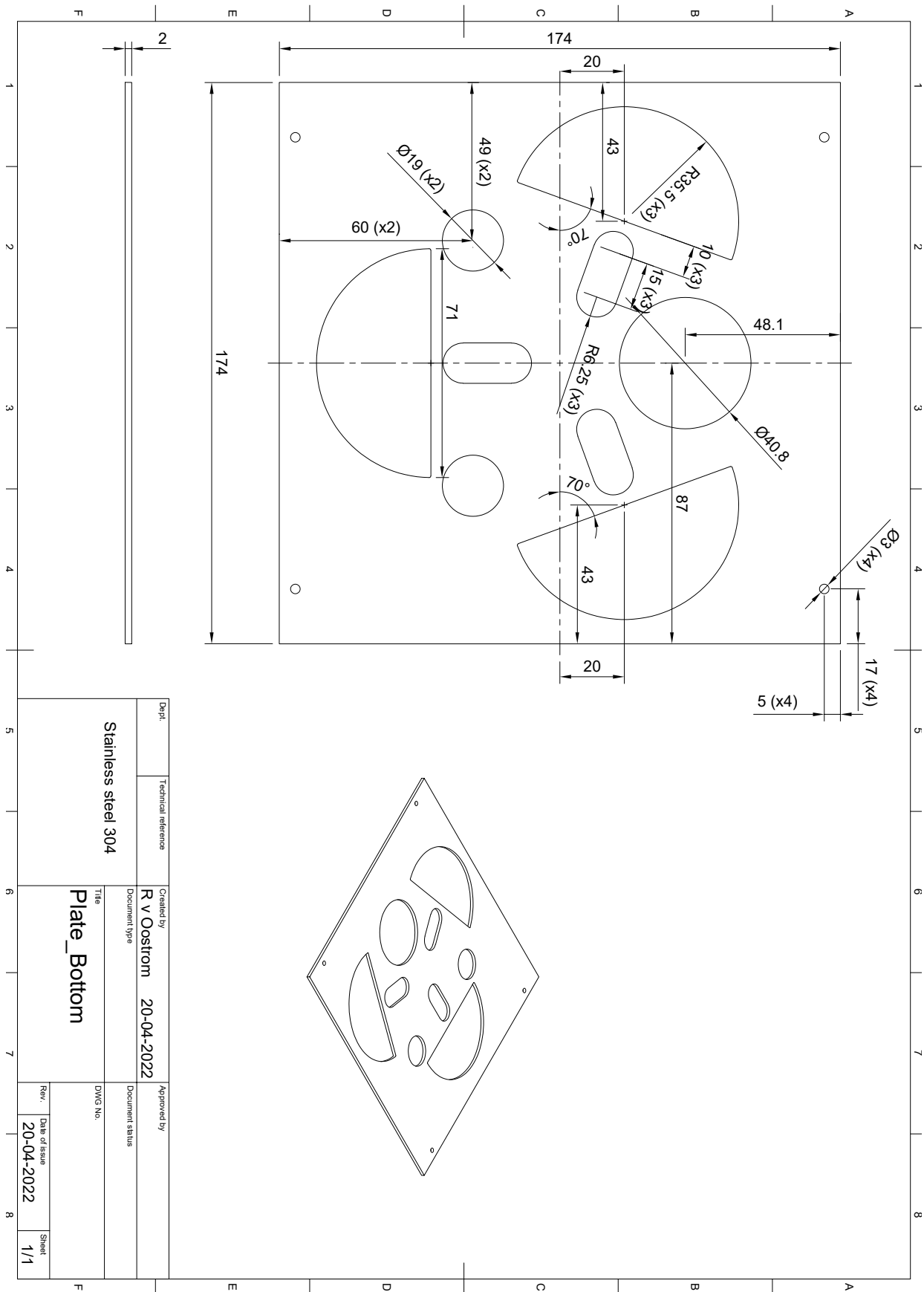


Appendix I: Prototype technical drawings

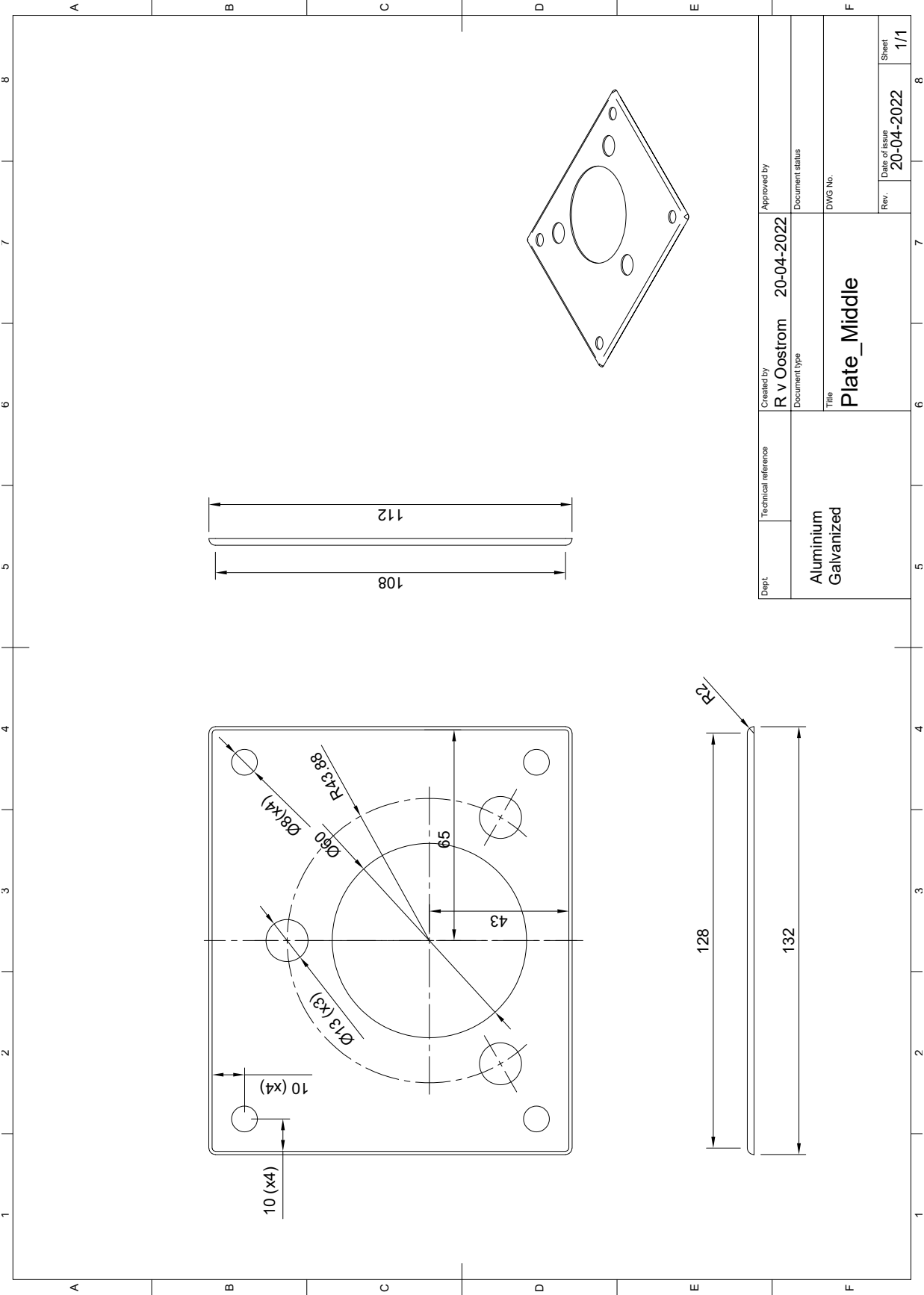
II Casing bracket



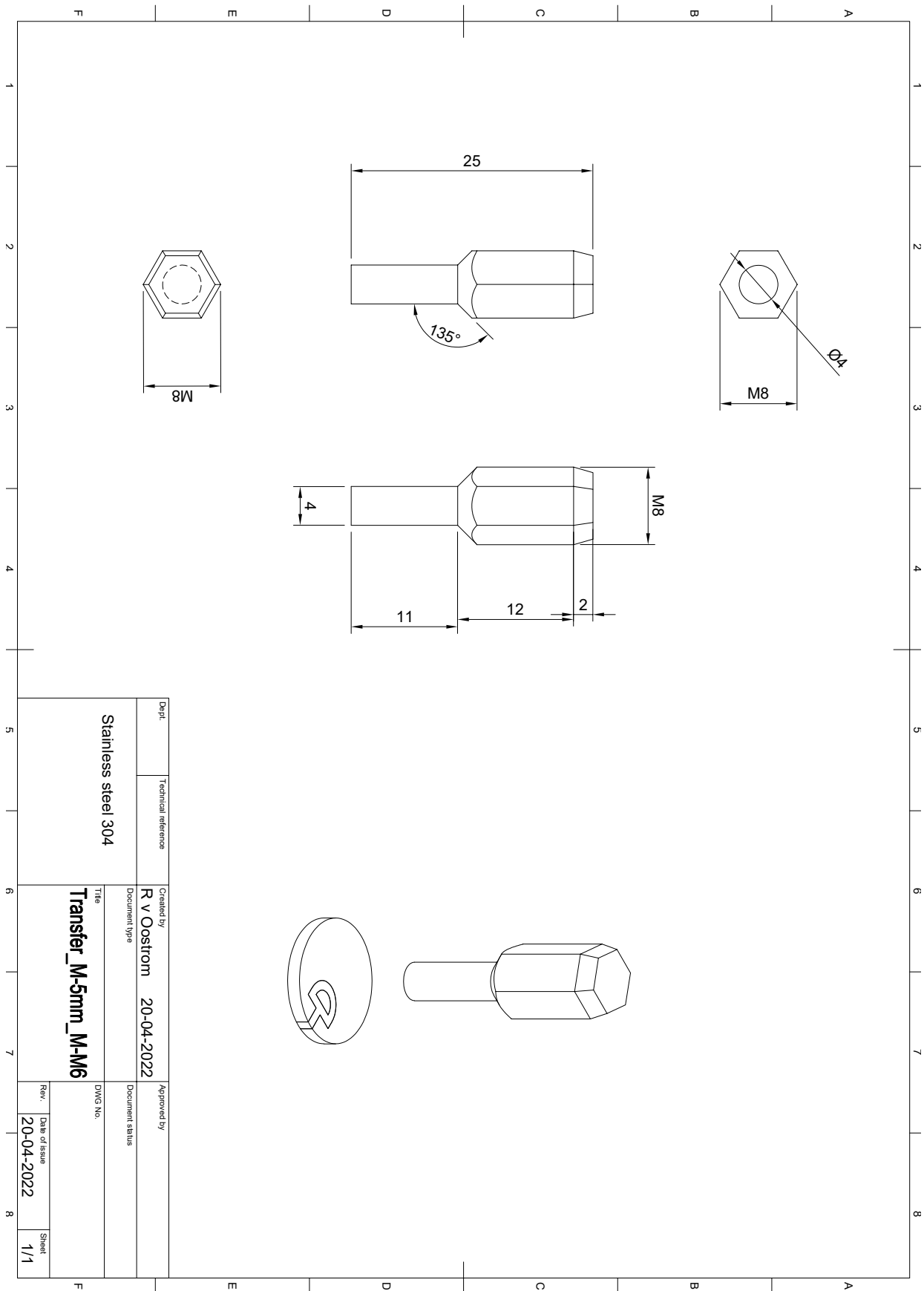
I2 Bottom plate



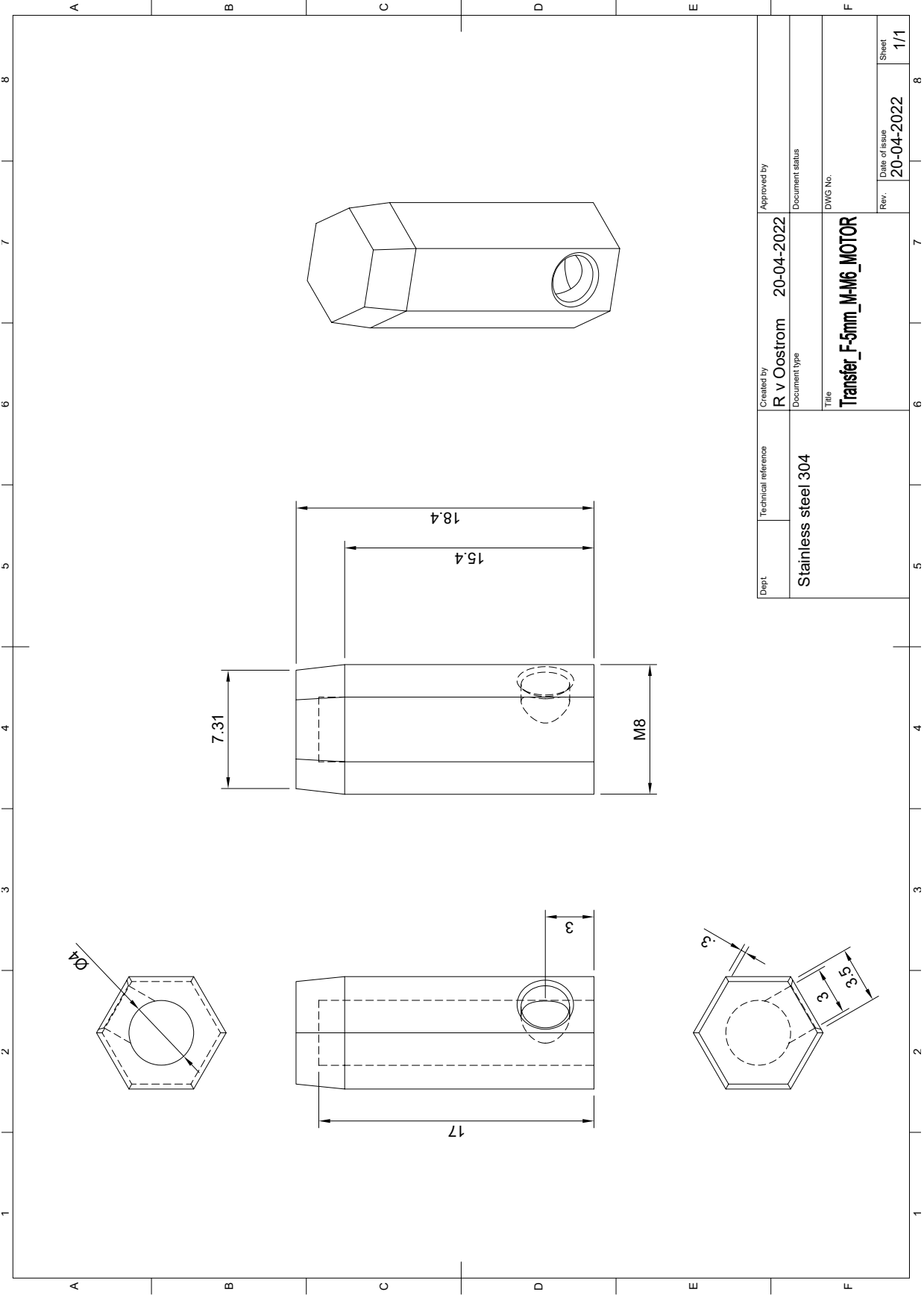
I3 Middle plate



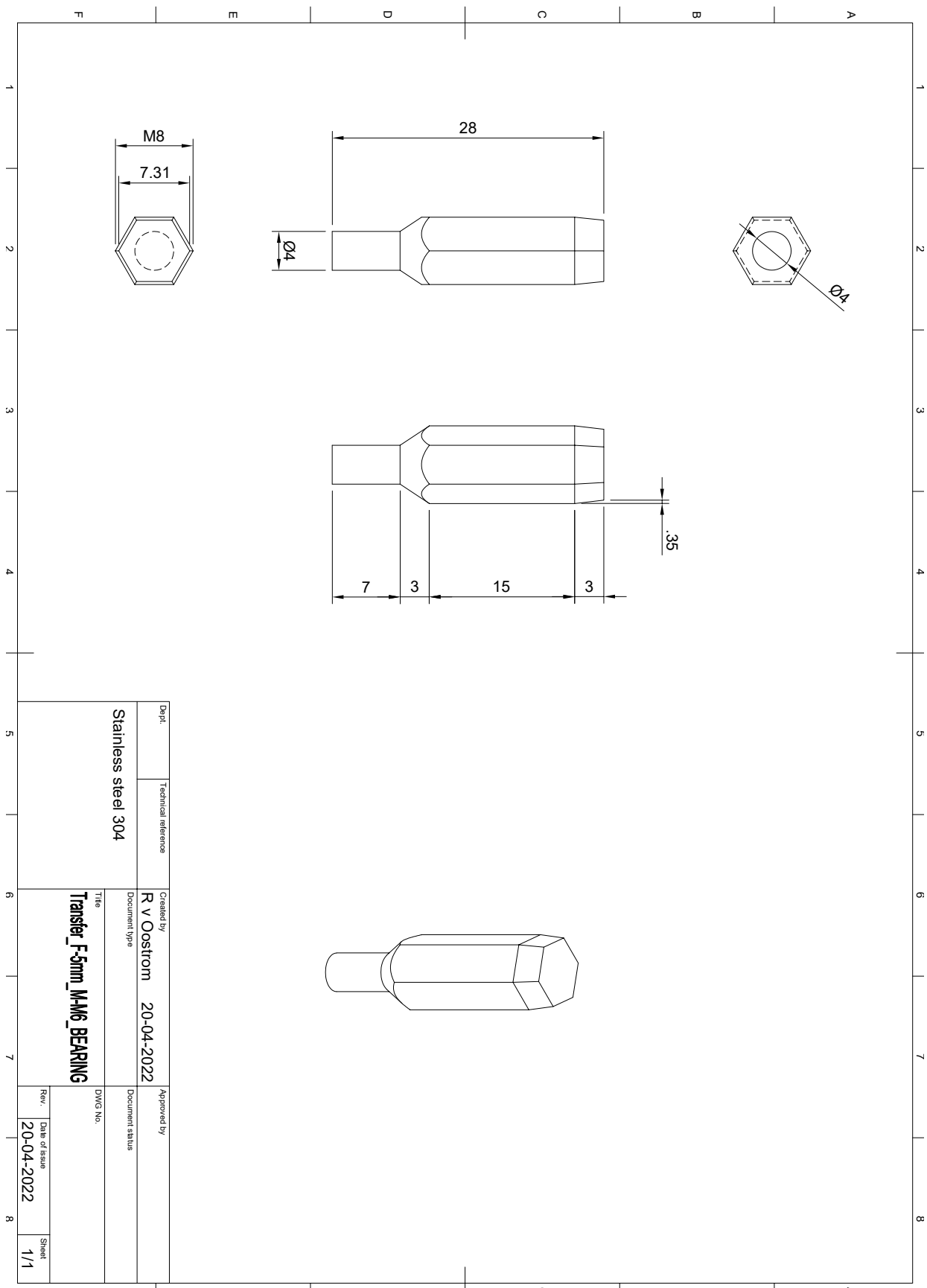
I4 Transfer upper bearing



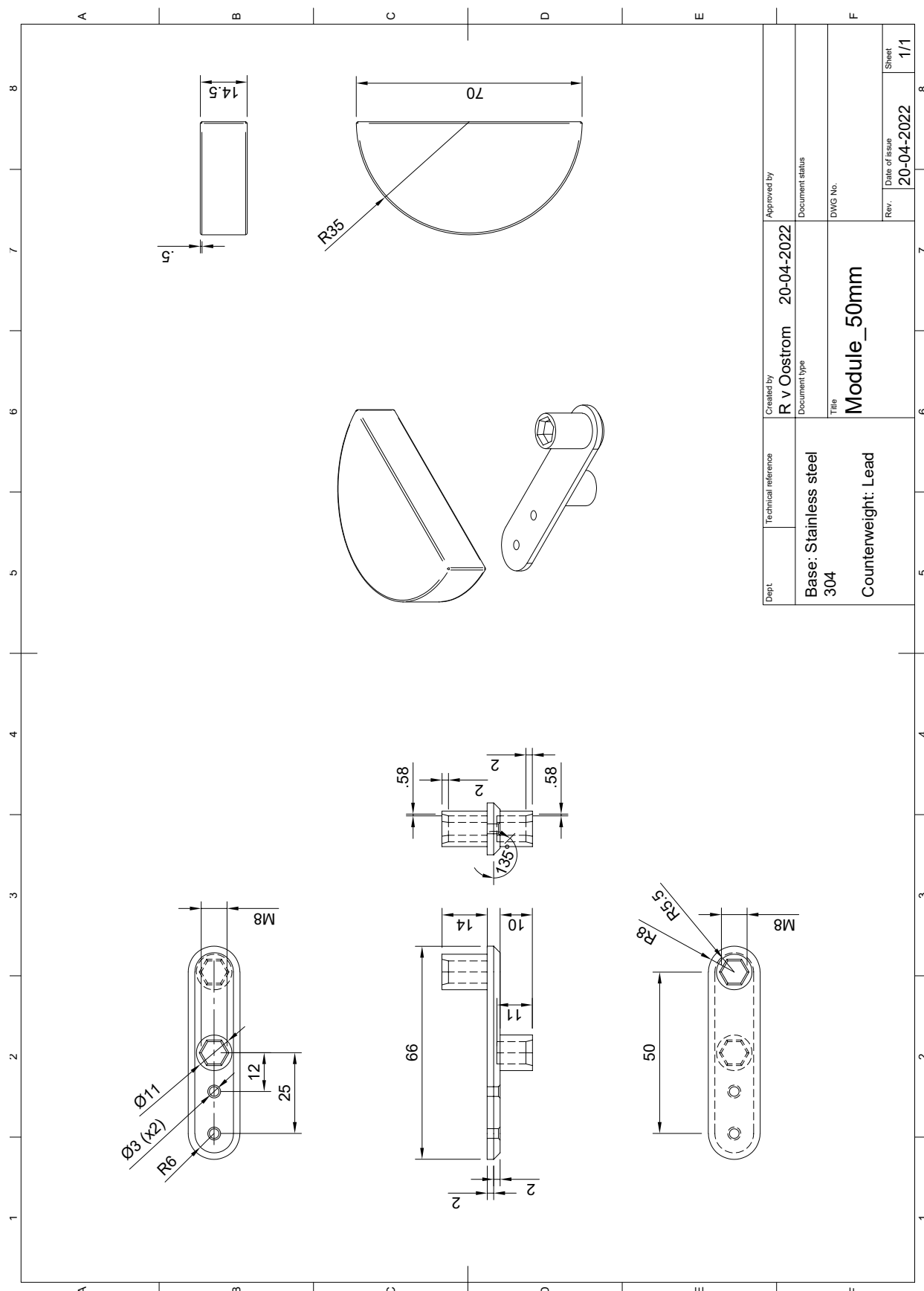
I5 Transfer motor



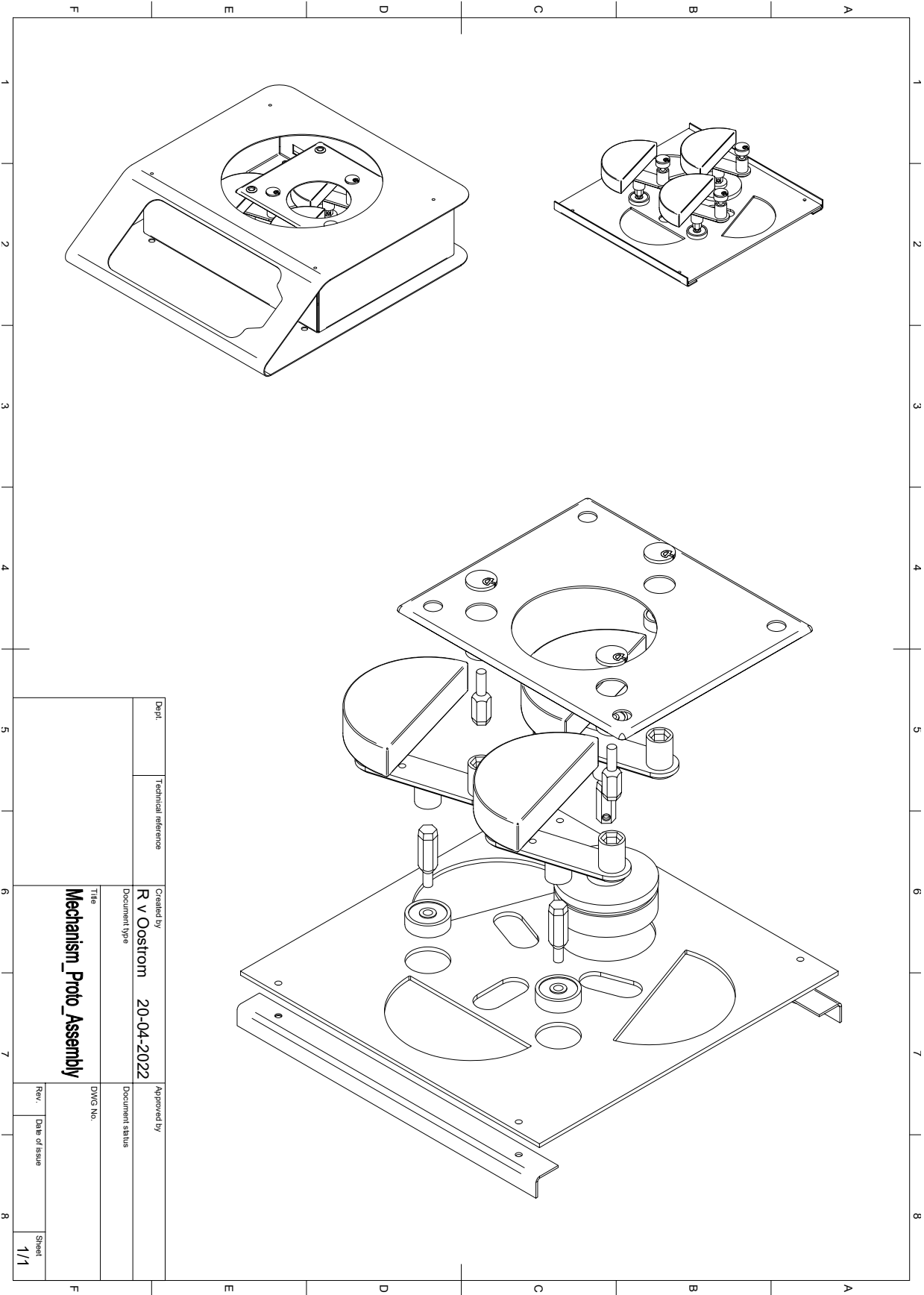
I6 Transfer lower bearing



I7 Module 50mm



I8 Assembly exploded view



Appendix J: Prototyping

J1 Summary of code

```

void setup() {
    //Arduino serial communication to interface startup
    //Arduino pin setup for motor control
    //display startup procedure
}

void loop() {
    //timer update
    //call interface events
    genie.DoEvents();
}

void myGenieEventHandler(void)
{
    //local variables
    //check if interface reports event
    if (Event.reportObject.cmd == GENIE_REPORT_EVENT) {
        //check what type object sends event
        if (Event.reportObject.object == GENIE_OBJ_XX) {
            /* XX: type of object
            * GENIE_OBJ_FORM          = form (page)
            * GENIE_OBJ_WINBUTTON    = buttons (all are winbuttons)
            * GENIE_OBJ_KEYBOARD     = keyboard (for keypresses) */
            //check index of object
            if (Event.reportObject.index == y) {
                /* y: specific index for each object
                * 1, 2, 3, etc */
                //do associated actions
            } } } }

//function for saving setups to EEPROM memory:
void SaveMemory (int index, String saveName)
{
    //match selected index (button) with save location
    if (index == 1) {
        saveLocation = 10; }
    //save content in correct location
    EEPROM.update(saveLocation);
    EEPROM.update(saveName);
}

//function for reading saved setups from EEPROM memory:
String readMemory (int index)
{
    //match index with save location
    if (index == 1) {
        saveLocation = 10; }
    //read content from location
    savedSetup = EEPROM.read(saveLocation);
    return savedSetup;
}

```

```
/*the timer functions works in seconds, but the input is HH:MM:SS,
//so these needs to be converted when updating the timer on screen*/
//convert seconds to HH:MM:SS, when updating display:
String (secondstoHHMMSS(int t)
{
    //calcute correct hours, minutes and seconds
    int s = t % 60;           //seconds calc
    t = (t - s) / 60;
    int m = t % 60;           //minutes calc
    t = (t - m) / 60;
    int h = t;                 //hours calc
    //convert them to double digit format
    if (h <= 9) {               //hours
        String HH = "0" + h;   }
    else {
        String HH = h;         }
    if (m <= 9) {               //minutes
        String MM = "0" + m;   }
    else {
        String MM = m;         }
    if (s <= 9) {               //seconds
        String SS = "0" + s;   }
    else {
        String SS = s;         }
    //add all to one string, clear values and return
    String TT = HH + ":" + MM + ":" + SS;
    HH, MM, SS = '\0';
    return TT;
}

//convert HH:MM:SS to seconds, when reading input:
int HHMMSStoSeconds(String TT)
{
    //get amount of hours, minutes and seconds
    int h = TT.substring(0, 2);
    int m = TT.substring(3, 5);
    int s = TT.substring(6, 8);
    //multiply all to seconds and add them up
    int t = (h * 3600) + (m * 60) + s;
    return t;
}

//the Arduino output to the motor control is a PWM signal where
//0.1V = 0% PWM      = 6250 RPM
//5V    = 100% PWM   = 62 RPM
//so input RPM has to be converted to PWM signal:
int speedCalculation(int speedRPM)
{
    //set any speed lower than required to minimum speed
    if (speedRPM < 62) {
        x = 62;   }
    //calculate necessary voltage, formula from datasheet of motor controller
    float v = (((float)speedRPM - (float)speedMin) / ((float)speedMax - (float)speedMin)) * 4.5 + 0.1;
    //convert voltage to 0-255 input of Arduino digital pins
    int pwm = round((v / 5.0) * 255.0);
    return pwm;
}
```

J2 List of design improvements

Type	Description	Parts
Mechanical	Slots instead of holes	<i>Brackets, bottom plate</i>
	Correct threaded holes	<i>Top box, brackets</i>
	Smaller size hexagonal fittings (M5)	<i>Module</i>
	Smaller diameter top plate inserts	<i>Top plate middle plate</i>
	Tighter fit / more friction hexagonal fittings	<i>Module, bearing axis connections</i>
	Rethink module storage slots	<i>Bottom plate</i>
	Wider brackets	<i>Brackets</i>
	Smaller bottom plate for easier fit	<i>Bottom plate</i>
	Proper fix axle and bearing	<i>Axle, bearings (top and bottom)</i>
	Angled edges to remove sharpness	<i>Top plate</i>
Electrical	Redefined motor configuration	<i>Motor</i>
	Include speed sensor	<i>Motor</i>
	Add speed ramp for acceleration and braking	<i>Motor control</i>
	Wire clips in casing to better hold wires in place	<i>Casing</i>
Digital	Add indefinite option for timer	<i>Setup time</i>
	Remove time formats	<i>Settings</i>

Appendix K: Discussion

K1 Evaluated requirement specification

Index	Requirement	State
1	<i>The shaker should be operable at max 37 °C</i>	Uncertain
2	<i>The shaker should be operable at 95% Relative Humidity (RH)</i>	Uncertain
3	<i>The shaker should allow for a changeable speed of 50 to 350 rpm</i>	Achieved
4	<i>The shaker should allow for setting a timer for operation</i>	Achieved
5	<i>No heat should be generated during operation</i>	Uncertain
6	<i>The shaker cannot create vibration in the placement surface</i>	Failed
7	<i>The weight of the shaker cannot exceed 9 kg</i>	Achieved
8	<i>The width of the shaker cannot exceed 400 mm</i>	Achieved
9	<i>The length(depth) of the shaker cannot exceed 300 mm</i>	Achieved
10	<i>The height of the shaker cannot exceed 100 mm</i>	Achieved
11	<i>The shaking mechanism should, when turned off, withstand heating to 150 °C</i>	Uncertain
12	<i>The electronic components should, when turned off, withstand heating to 150 °C</i>	Uncertain
13	<i>The material casing should, when turned off, withstand heating to 150 °C</i>	Uncertain
14	<i>The orbit of the shaker can be changed to 20 mm by the user</i>	Achieved
15	<i>The orbit of the shaker can be changed to 25 mm by the user</i>	Achieved
16	<i>The orbit of the shaker can be changed to 50 mm by the user</i>	Achieved
17	<i>The shaking parameters can be changed without opening the incubator</i>	Achieved
18	<i>The shaker interface should be understandable without manual</i>	Uncertain
19	<i>The shaker should save operation parameters set by the user</i>	Achieved
20	<i>The saved operation parameters should be accessible by the user</i>	Achieved
21	<i>Any outside surfaces can withstand daily cleaning with alcohol (75%)</i>	Achieved
22	<i>Different types and sizes of flasks can be placed on the top plate</i>	Achieved
23	<i>When exchanging top plates, the user should not need extra tools</i>	Achieved
24	<i>The power cord should be at least 2000 mm long</i>	Achieved
25	<i>The powersupply should be 12V or 24V</i>	Achieved
26	<i>The costprice should be under 2.500,-</i>	Uncertain
27	<i>The costprice should be under 2.000,-</i>	Uncertain
28	<i>The shaker should comply with regulation EN 61010-1:2011</i>	Achieved
29	<i>The shaker should comply with regulation EN 61010-2-051:2015</i>	Achieved
30	<i>The shaker should comply with regulation EN 61326-1:2021 Class A (EMC 2014/30/EU)</i>	Achieved
31	<i>The shaker should follow directive RoHS 2015/863/EU</i>	Achieved
32	<i>The shaker should follow directive WEEE 2012/19/EU</i>	Achieved
33	<i>The shaker should comply with the compliance mark CE</i>	Achieved