Designing a naturalistic foraging device for captive ring-tailed lemurs

to stimulate natural behaviour and improve well-being

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-Joshua

Abstract

This report highlights the steps taken to design a foraging device that engages captive ring-tailed lemurs in a natural way. After identifying the stakeholders and their requirement, research into ring-tailed lemurs' natural and captive situation is done with the goal of identifying opportunities for design to enhance the lemurs' welfare in captivity. At the same time, it also aims to improve zoo visitors experience.

As a result, a design is introduced that focuses on purposeful locomotion to increase activity, promoting different foraging interactions, stimulating multiple senses, and giving the animals a choice on when and how to interact. At the same time, it is shaped to look like a fruit these animals would eat in nature, and its placement increases the time lemurs spend close to the visitors.

Multiple rounds of prototyping and tests with the ring-tailed lemurs in Rotterdam Zoo have been done to refine the concept and to assess its effectiveness. These test results seem promising, as lemurs interacted many times with the prototypes. The effectiveness of the final designed system and its long-term efficacy needs to be assessed in the future.

The final design consists of multiple wirelessly (un)lockable pods filled with food and connected to a scent machine. A number of these are unlocked at a time and a scent cue is given, prompting the lemurs to go investigate. Unlocked pods stay attached to their base using magnets, thus lemurs need to interact with both locked and unlocked pods to figure out which can be detached. This feeding system is an addition to the lemurs' normal feeding regiment, as a result they are stimulated and engaged more than before.

Definitions, abbreviations and clarifications

Name	Definition
Allogrooming	Caring actions done by one lemur to another, such as combing their hair using teeth, claws or tongue, often strengthening their social bonds.
Arboreal	Living / moving in trees
Browse	A collection of twigs containing leaves that are given to leaf-eating animals as food
Cathemeral	Awake and active during the day but also (partly) during the night
Foraging	Everything around an animal's search for food: locating, gathering, and eating
Diurnal	Awake and active during the day
Endemic	Plants or animals that are native and exclusive to a certain geographic region
Grooming	Self-caring actions by the lemur, such as combing its hair using teeth, claws or tongue.
Lemur Catta	Ring-tailed lemur
Locomotion	Movement of an animal from one place to another
Naturalistic	Something that is designed to look or mimic natural, but is human-made
Olfactory	Sense of smell
Primates	Order of animals that includes apes (incl. humans), monkeys and prosimians
Species-specific behaviours	The repertoire of behaviours, innate or otherwise, that is shared by virtually all members of a given species.
Stereotypic behaviour	Repetitive behaviour that occur due to stress or too little stimulation (e.g. pacing around, head bobbing,
Subordinate	Of lower rank in the troop
Terrestrial	Living / moving on the ground
Troop	A group of (ring-tailed) lemurs

A note on the term enrichment

The term enrichment can often feel as though it is just an extra for an animal, while most of these "enriching improvements" are essential for the species' physical and mental health. When you only sometimes give an animal an enriching item or experience, that means the rest of the time the animal is cared for subpar. One should always aim for a 10/10, not just on special occasions.

Natural versus naturalistic

Natural refers to things that exist in and are produced by nature. Things like rainforests, mountain ranges.
Naturalistic, on the other hand, describes artificial things that are made to resemble or imitate nature. Things like a nature painting or a beautiful garden – things made artificially by humans to resemble nature.

In the context of zoos, this distinction comes up frequently, as balancing these two can be quite a challenge. While a fully natural enclosure would often be ideal, it is usually not feasible due to cost, climate differences, and various safety or logistical concerns. So, many zoos opt for a combination of natural and naturalistic elements to create natural-looking habitats.

Figure 1 shows a non-naturalistic enrichment device made of old firehoses used in Rotterdam Zoo's polar bear exhibit. While the polar bears are engaged by this, to visitors it might look a little bit weird. In contrast, Figure 2 shows a naturalistic solution used to provide browse feed (leaves and twigs) used in Wuppertal Zoo.

Photo credits

Ring-tailed lemurs are often very photogenic – and sometimes hilariously not – and thus this report is filled with many photographs to keep the reader engaged. All these uncredited photographs were taken by me during the run of this project, and one or two by my lovely girlfriend.

Figure 1 - An enrichment device in Rotterdam Zoo's polar bear exhibit

Figure 2 - A naturalistic device to provide food in Zoo Wuppertal's Aralandia

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Part I. Introduction

This report introduces a novel foraging device for ring-tailed lemurs, which aims to improve their well-being by stimulating and engaging them in ways inspired by their natural behaviours, characteristics, and habitat, all of which will be delved into in the coming chapters.

Firstly, what is foraging, you might ask. It encompasses everything related to food procurement. How animals locate food sources, what actions they take to collect food, and how they eat it.

The upcoming chapter delves into the background and context of this project, leading to the design goal and research questions used in the research part of this project.

1. General introduction

1.1 Nature conservation

Each year, more species of animals and plants become threatened with extinction, with the current number reaching around 47,000 (The IUCN Red List of Threatened Species, n.d.). This is often the result of habitat destruction by human activities. The primary goal of conservation is to limit this damage and restore natural environments wherever possible. Many endangered species are kept in zoos, where they can be protected, participate in breeding programs to increase populations, and be studied. Combined with educating visitors, these factors are used to aid conservation efforts.

1.2 Animal Welfare

1.2.1 History

Animal husbandry started mainly to benefit humans purely, for hunting, enjoyment, and to show off status and power. Later, as scientific research advanced and the cognitive and emotional capacities of non-human animals became better understood, ethical questions kept being raised. As a result, animal welfare became an increasingly important topic and accredited zoos started to become more evolved in conservationism and education, and the strive to keep improving captive zoo animals' quality of life.

1.2.2 The need for good welfare

All kinds of animal species feel negative emotions in captive situations where their needs are not met. This can result in displays of unnatural and sometimes self-harming stereotypic behaviours. A well-known example of this is pacing – in Dutch "ijsberen" – of tigers, lions, and polar bears. Since no animal in a zoo chose to be captured or born into captivity, it is our ethical responsibility to give them a life that is as good as possible. Next to that, a high standard of welfare for zoo animals results in them behaving similar their wild versions, which results in reliable research possibilities.

When the needs of captive animals are well met, they generally show species-specific behaviours at similar levels to wild animals of the same species. Observing the animals (Jones et al., 2022) and comparing these behaviours with wild ones can then help identify a lack of stimulation or assess whether an addition improves their welfare.

1.2.3 Individuality

As every species is different, there is no one-size-fits-all solution to improve their lives. Appropriate environments, nutrition, enrichment, and care must be tailored to each animal to ensure they thrive. Even then, something that works great in one zoo could flop in another, making it important for a designer to keep checking design choices with both animals and zookeepers.

1.3 Context

1.3.1 Rotterdam Zoo

The project takes place in Rotterdam Zoo (Diergaarde Blijdorp) who are focused on improving the welfare of animals in their care and becoming a substantial institution that actively contributes to the conservation of flora and fauna (Diergaarde Blijdorp, 2023).

Here, animals are used as "ambassadors", which tell the story of struggles their species faces in the wild. Capturing visitors' interest and educating them is an important aspect of the zoo, something which is proven to help conservation efforts (Godinez & Fernandez, 2019; McNally et al., 2025).

1.3.2 The ring-tailed lemur (Lemur Catta)

This project focuses on the ring-tailed lemur. Ring-tailed lemurs are native to Madagascar, where they sadly are endangered, mostly due to habitat loss (LaFleur & Gould, 2020). They are curious to new things and safe to test prototypes with (much easier than a lion). Also, planned renovations to their exhibit coincide well with the timeline of this project.

1.3.3 Stakeholder overview

Resulting from meetings with stakeholders such as the zookeepers and animal staff, park development team, nutrition, and technical team, the stakeholder analysis of Figure 3 could be created, wherein their main wants for this project are highlighted.

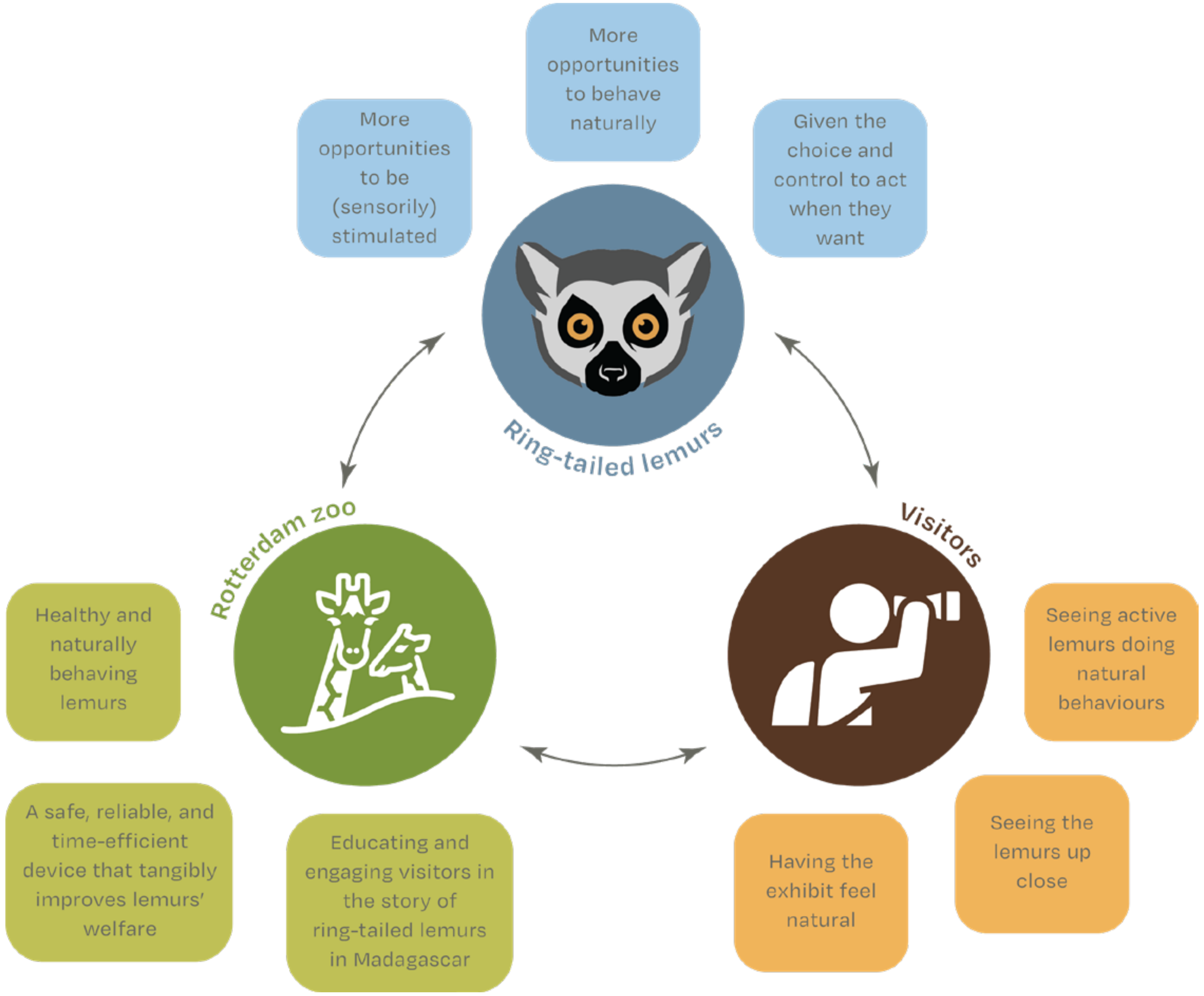


Figure 3 - Stakeholder analysis

1.5 Problem definition

As highlighted earlier, animal welfare is a constant striving to make things better. The ring-tailed lemurs in Rotterdam Zoo are not treated poorly, but it can – and should – always be improved.

The ring-tailed lemurs spend most of their day waiting for feeding time (V. Ketellapper - Zookeeper, personal communication, 1 May 2025); they know food comes from the zookeeper just a few times per day, and because of this, they lack the motivation to explore and move around their enclosure to search for food and explore during the rest of the day.

It is essential that the animals show behaviours very similar to those in the wild, which these huge spikes in attention followed by bouts of boredom are not.

As a result, the following problem definition can be derived:

The ring-tailed lemurs experience a lack of natural stimulation throughout the day and night.

1.5.1 The zoo-experience paradox

To aid conservation of the species, visitors need to be educated about the problems the species faces. This is where a paradox seems to arise: naturally behaving animals often stay hidden and far from observers, while visitors want to see them up close – though still behaving naturally (Godinez et al., 2013; Miller, 2012).
So, this is an important thing to balance during the project. An important aspect to consider in this is the choice and control principle, which emphasises giving animals the choice and power to act within their environment as they wish. Not forcing them to come close to the visitors but supplying them with reasons to do so, after which the animals can decide to or not.

1.6 Design goal

We can then rephrase this into the following design goal, fitting in the scope of this project:

A challenge of this design project is how to improve the animals' welfare under very rigid constraints: the size of their enclosure cannot be increased, and there are significant cost constraints.

This project aims to create a naturalistic addition to Rotterdam Zoo's ring-tailed lemur enclosure that engages them more than they currently are, while keeping the visitors' experience in mind.

1.7 Research Questions

To design something that enhances lemurs' lives, it is important first to get to know these animals well. Then to identify which aspects are suboptimal in captivity and what might be possibilities or directions to delve into. For this, the following four research questions are created:

- What physical characteristics are essential to the ring-tailed lemur?
- What behaviours are essential to the ring-tailed lemur?
- What behaviours of the ring-tailed lemur are missing in captivity?
- What opportunities are there to enrich ring-tailed lemurs' lives?

1.8 Project approach

Figure 4 on the next page gives an overview of the approach of this project. Additionally, a general guideline on what questions to ask and what aspects to investigate when designing something for an animal in a zoo has been created and can be found in Appendix B.

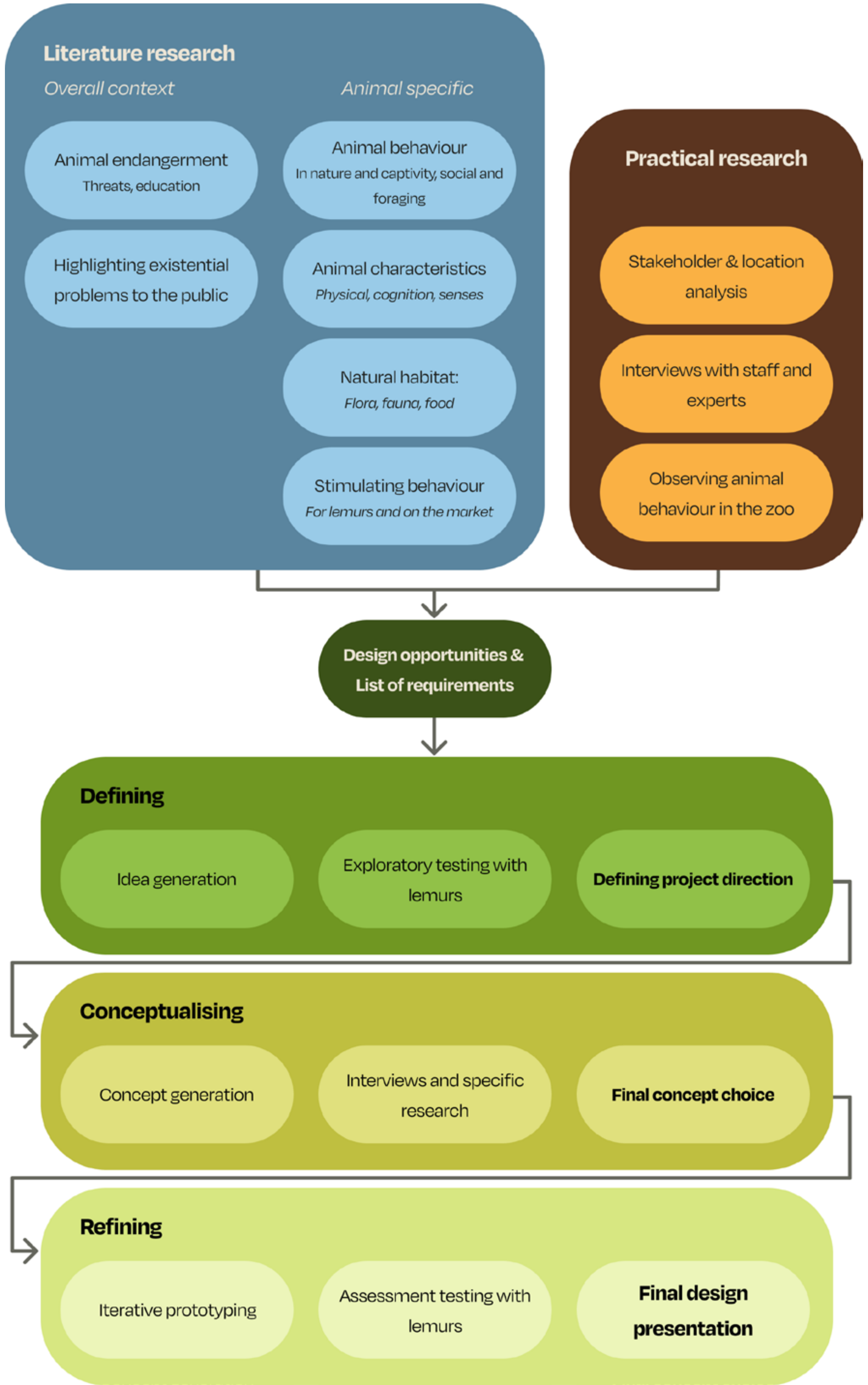


Figure 4 - Project approach

Part II: Research – Deep dive into Lemur Catta

This section of the report examines the ecological context of ring-tailed lemurs, as well as their physical characteristics and behaviours. We also zoom into their lives in captivity and what existing solutions there are to improve their welfare. All with the goal of answering the research questions and identifying opportunities for improving lemur welfare within the scope of this project.

2. Living context and education

Before delving deeply into ring-tailed lemurs, we shall have a look at the context in which they exist, first in the wild, and then in zoos and what these can do to help combat the threats faced by the lemurs.

2.1 Ring-tailed lemurs in Madagascar

Madagascar has a uniquely turbulent and unpredictable environment, characterised by an incredibly diverse range of landscapes (Wright, 1999). It is a hub for flora and fauna that are endemic (native and exclusive to Madagascar) (Antonelli et al., 2022).

2.1.1 Living area

Ring-tailed lemurs are only found in the south (Figure 5), where they live in a wide variety of habitats. From gallery forests (figure 6) to cactus-filled deserts and the rough slopes of the Tsingy mountains (Figure 7) (Jolly, 1966a; Kelley, 2011; Sauther et al., 1999)

Due to these factors, ring-tailed lemurs have evolved to be very adaptable, possessing multiple adaptations to limit energy expenditure and to be able to quickly adapt when food sources suddenly become scarce (Kelley et al., 2016; Simmen et al., 2010), as well as a complex social system consisting of sounds and scents that makes sure all are fully aware of their surroundings.

Ring-tailed lemurs tend to live in an established range, in which they travel around throughout the day, ending up in new trees to sleep in every night.

2.1.2 Threats

98% of lemur species are currently threatened with extinction (Lemur Conservation Network, n.d.-b). This is primarily due to habitat destruction, a major part of which is illegal logging. This

Figure 5 - Ring-tailed lemur geographic range (IUCN, 2020)

creates a smaller and smaller area where lemurs can safely live and forage, which in turn results in them coming in contact with humans more often, making them easier to be hunted for the exotic pet trade or food (Sussman et al., 2003; WWF Wildlife Practice, 2022; Borgerson et al., 2016; Jenkins et al., 2011).

While there are some nature aid initiatives and Madagascar has increased its protected areas, it is difficult to create sustained improvement, and especially the enforcement of conservation laws due to Madagascar's high poverty and political instability.

These aspects are elaborated in more detail in Appendix C.

Figure 6 - Brown lemurs in the Tsingy mountains (Bender, 2018)

Figure 7 - A lemur in a tree in Berenty reserve (Sasy Images, n.d.)

2.2 Education in zoos

Education is a fundamental pillar of many modern zoos. Making information on rare and endangered species more accessible and understandable helps to make their problems known. Only with sufficient awareness is it possible to try to turn some of the bad situations around.

2.2.1 Creating awareness

It is essential for lemurs that visitors are aware of the problems Madagascar's nature and animal population faces and what they can do to help. The zoo animals themselves are the main drivers of creating awareness.

2.2.2 Visitor experience

Besides the educational value, the visitors must have a positive experience at the exhibits. This is done by ensuring the animals are visible and the visitors can see the animals showing natural behaviours (as shown in Figure 8) (Miller, 2012; Salas et al., 2021), which fosters a connection and encourages empathy and concern for the animals' well-being (Godinez et al., 2013). This results in people being far more likely to take actions that help the environment, conservation and the zoo itself (Godinez & Fernandez, 2019).

2.2.3 Captivity struggles

Captive lemurs do not face any of the existential threats their wild counterparts face, nor do they need to fear predators or cyclones. Having a veterinarian on standby can help them live much longer than they would in the wild. As was proven recently by a ring-tailed lemur called Stumpy, who became 39 years old – double the maximum age of wild ring-tailed lemurs (Figure 9).

However, zoo exhibits are not the ideal physical environment for lemurs. Due to size and financial constraints, zoo environments tend to be relatively small and not really dynamic. This stimulates lemurs much less than constant travel to new areas. There is also less stimulation as there are no other animals to encounter, and there is little need for the lemurs to keep travelling to find food ripe for the picking.

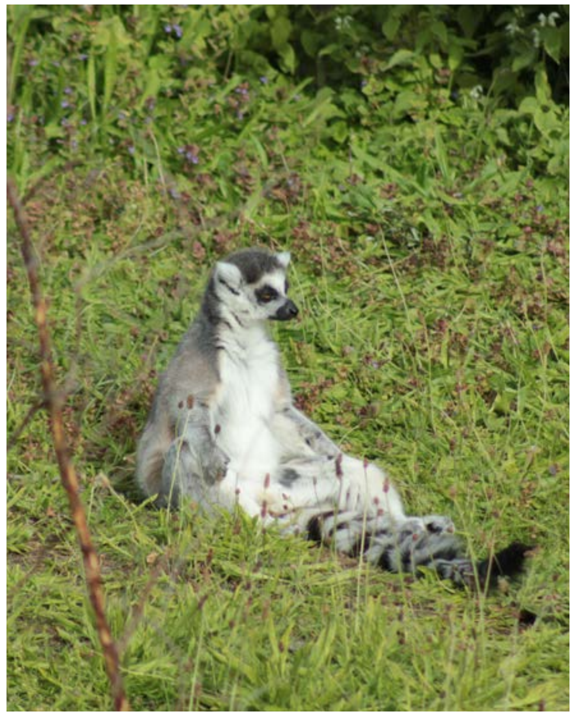


Figure 8 - One of Rotterdam Zoo's ring-tailed lemurs enjoying the summer sun

Figure 9 - Stumpy proudly looking over his Guinness World Record certificate after becoming the oldest living lemur (Millward, 2025)

2.3 Conclusion

This chapter aimed mainly to illustrate the context in which ring-tailed lemurs live, giving a background from which to start and aspects to keep in mind in the design of a welfare-improving device.

2.3.1 Living spaces

Ring-tailed lemurs are very adaptable and can thrive in vastly different landscapes. Their bodies and behaviours are shaped around this, with them travelling and climbing a lot, moving into novel areas to forage, necessitating clear social communication to stay safe.

2.3.2 Zoo and education

Many of these natural aspects are lacking in zoos due to multiple constraints, which highlights the need for welfare improvements. Zoos do play an important role in combating existential threats faced by animals by creating awareness and educating visitors. To successfully do this, visitors need to be positively engaged, which is achieved by ensuring animals are visible and behaving naturally.

3. Lemur Catta - The ring-tailed lemur

The goal is for the design to stimulate the captive ring-tailed lemurs in Rotterdam Zoo to show more natural species-specific behaviours. For an enrichment device to have a clear positive effect on animals, it must be tailored to how they have evolved (Newberry, 1995), allowing the animal to display these exact behaviours. To gain a fundamental understanding of this, one first needs to understand the physical characteristics of the animal as well as their behaviours. To get to the bottom of this, this chapter aims to answer the first three research questions:

What physical characteristics are essential to the ring-tailed lemur?

What behaviours are essential to the ring-tailed lemur?

What behaviours of the ring-tailed lemur are missing in captivity?

3.1. Lemur characteristics

We start by looking at the ring-tailed lemur's physical characteristics, as these are essential to be well aware of when designing a solution that they should physically interact with.

Physical characteristics

of a ring-tailed lemur (Lemur Catta)

Front legs & hands

Ring-tailed lemurs ' paws lack an opposable thumb - which apes such as humans do have. Due to this their hands are not that capable at manipulating items, so they tend to use their hands to hold something stable and then use their mouth to manipulate it.

They tend to grab a twig with their hand and maneuver the leaves or fruit on it towards their mouth, biting it straight from the twig

Mouth

Ring-tailed lemur have sharp teeth in order to shred leaves from trees or break open food sources such as the tamarind fruit, which has a very hard outer shell

Vocalisations / Ears

Ring-tailed lemurs use a wire variety of sounds to communicate. When one lemurs starts the rest of the group often joins in, which ensures everyone in the troop knows what is happening.

Nose & scent glands

Lemur Catta's nose is very important. makes use of its nose to find food sources and to check whether they're ripe.

Using scent glands on their body, lemur catta marks its territory. These marks can be smelled to know what troops are in the area and a ring-tailed lemur even uses scent to know how group members are doing (Palagi 2003).

While they sometimes use smell to identify predators, they mostly rely on their vision and hearing to spot these.

Eyes / vision

Lemur Catta's eyesight is very sensitive to movement but they tend to have trouble noticing non-moving observers.

They're equipped with a tapetum, a layer in the eye that reflects the light back through the retina, resulting in increased nightvision.

Unlike monkeys and apes (including humans) who have trichromatic vision, ring-tailed lemurs are dichromatic.
This results in them lacking a clear distinction between red and green colours, as visualised below.

The black pads at the bottom of their paws give them grip to climb around

Locomotion

Lemur Catta are mostly classified as semi-terrestrial. Travel is mostly done on the ground and when in one place they then mostly found arboreally where they rest, search for food and sleep.

They walk mostly using both their front and hind legs but sometimes move short distances walking or bouncing just by their hind legs.

Hind legs & feet

Lemur Catta's hind legs are very strong and used to jump onto and from trees, landing on just back legs or all fours.

The rear feet have one big toe - that, in contrast to their hands, is opposable - which they use to hold on to twigs and treetrunks

Figure is based on Jolly (1966-a) and Sauther (1999)

Tail

Their tail is the most recognisable feature of the ring-tailed lemur.
It consists of black and white rings and is longer than their body.

It is mainly used for balance when walking on tree branches or jumping between trees. It is also used to help find other members of its troop when spread around an area.

Size and weight

Lemur catta are similar in size to the average house cat, measuring just over 40 centimeters long (excluding the tail), but they are considerably lighter, typically weighing around 2.2 kilograms.

There are very little physical differences between females and males.

3.2 Social dynamics

Understanding why the animal acts the way it does, combined with mapping the differences between natural and captive behaviours, can help identify areas where a design can improve the lives of the lemurs.

3.2.1 Social hierarchy

Ring-tailed lemurs are a very social species, living in groups called "troops" of around 13-18 lemurs. Unlike most other primates, lemur troops are female-dominated, having one alpha-female who determines where they go and what they eat (Sauther et al., 1999).

This social hierarchy is important for ring-tailed lemurs to keep their stress levels low (Sapolsky, 1992) , and they maintain it using different types of vocalisations and some physical aggression, like cuffing with their paw, after which the subordinate lemur will vocalise a submission call. Constant group vocalisations keep the group alert and maintain relationships between the lemurs.

If a dominant lemur wants to have something a subordinate has, it will often take it by force, prompting the subordinate to emit a submission call shown in Figure 10. Most ring-tailed lemur conflicts are of this kind, just between 2 individuals (Ichino & Koyama, 2006).
Ring-tailed lemurs spend quite some time on resting behaviours to conserve their energy and socialise. Their iconic sunbathing with their arms spread wide (Figure 11), or sitting together huddled up in a ball of lemurs are methods they use to warm up. Here, they often groom each other by combing through fur with their claws, teeth, and tongues – called allogrooming (Figure 12). Here, lemurs can often be heard to purr in enjoyment – similar to a cat.

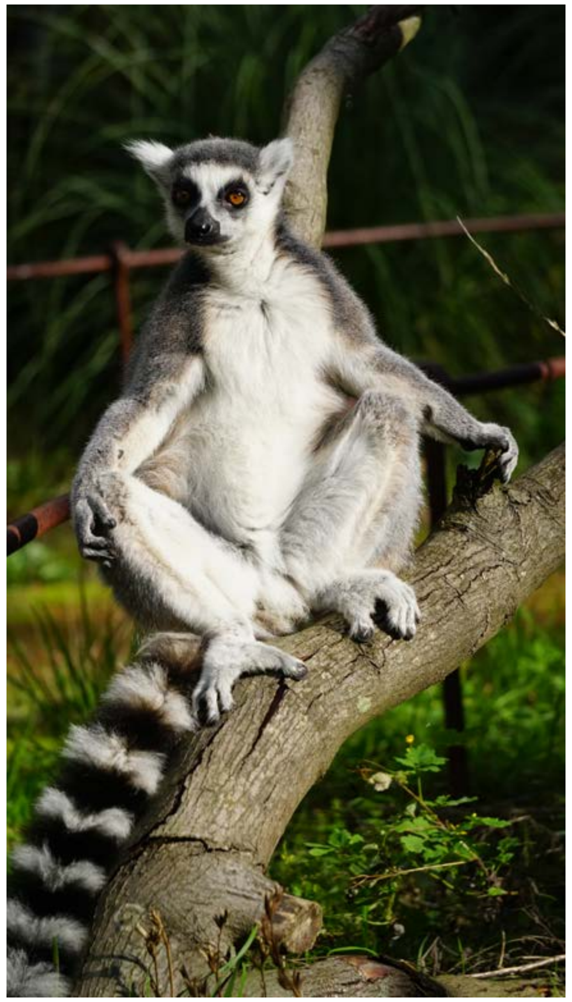


Figure 11 - Lemur sunbathing in the autumn sun

Dominant approaches casually | Dominant shows that she wants the food item | Dominant takes the item from the subordinates hand | Subordinate jumps away, vocalising submissively

Figure 10 - An observed interaction in which food is snatched by a dominant lemur

Allogrooming plays an important role in strengthening social bonds between lemurs. Next to that, it helps spread knowledge and skills through social learning as lemurs that frequently groom each other pay more attention to one another during daily activities, meaning they are more likely to observe and adopt new behaviours from them (Fichtel, 2022).

3.2.2 In captivity

The lemurs can often be observed showing these behaviours in the zoo environment.

Figure 12 - Huddled up ring-tailed lemurs sleeping and allogrooming

Figure 13 - A ring-tailed lemur grooming itself

3.3 Cognition

Given the complexity of their social system, one might wonder how smart ring-tailed lemurs are and how they use their cognitive skills.

3.3.1 Experiments

Ring-tailed lemurs excel in the social domain, but are not that adept in the physical domain (Fichtel et al., 2020). This seems logical, given that they rely heavily on social learning (Jolly, 1966b; Kendal et al., 2010), , and it may account for their difficulties with certain physical problems, such as puzzle boxes (Figure 14) (Jolly, 1964).

Ring-tailed lemurs, including those at Rotterdam Zoo, seem to be very curious and eager to interact with novel objects (Hall et al., 2018; zookeepers, personal communication, 1 May 2025). Interestingly, while wild ring-tailed lemurs rarely engage with inedible novel objects, those in captivity are much more likely to do so (Jolly, 1964). This might suggest there is often too little stimulation for the lemurs in captivity.

Figure 14 - A ring-tailed lemur with a puzzle box

3.3.2 Olfaction

In the wild, Lemur Catta tend to rely on a combination of senses. Their sense of smell is primarily used for interactions within the same species, ranging from territorial marking to intragroup (within the group) communication about aspects such as reproductive status. Ring-tailed lemurs also tend to use their noses to find food (Cunningham et al., 2021; Jolly, 1964) and assess its ripeness (Nevo et al., 2018).

3.3.3 Auditory

Ring-tailed lemurs then also rely on auditory senses. They use a wide range of vocalisations to maintain contact within the troop, alert others to upcoming activities, draw attention to points of interest, and warn about approaching predators (Figure 15). They are highly responsive to unfamiliar sounds – the slightest unexpected sound sends them running into the trees to hide (Gould & Sauther, 2007).

3.3.4 Visual

Lemur Catta's eyesight is very sensitive to movement and is – just like its reactions to unexpected sounds – an adaptation to survive predators. They do not have full-colour vision (Jacobs & Deegan II, 1993, 2003), but despite this tend to rely on their eyes to forage for food that is farther away.

3.3.5 Missing opportunities in captivity

In most zoos, some aspects of the lemurs' olfactory experiences are missing – no territorial smells of other lemur troops. Also, no smells of other species. They can – and do – use their sense of smell to communicate with each other and to inspect food items. And they might get a waft of different human smells and perfumes when the wind direction allows for that.

Figure 15 - A ring-tailed lemur vocalising

In captivity, there are no predators and as such, there is less need for lemurs to do these anti-predatory behaviours. The lemurs are exposed to many unnatural sounds, as helicopters, planes, trucks, and other machines. They do react as they would to a predator to loud sounds and unexpected movements by visitors or others in the troop.

3.4 Foraging

Ring-tailed lemurs are not picky eaters; often called opportunistic frugivores. They eat a wide variety of foods: from mainly fruits, flowers, and leaves to – in rarer instances – insects, dirt, and small vertebrates like birds or reptiles (Jolly, 1966a; Sauther et al., 1999; Simmen et al., 2006; Soma, 2006).

They forage both in trees and on the ground. (Jolly, 1966a; Sauther et al., 1999) They forage for this food mainly using their sense of smell combined with their eyesight – depending on the situation. (Cunningham et al., 2021; Rushmore et al., 2012). Ring-tailed lemurs lick rain and dew from leaves as well as put their paws into tree hollows, licking the water from their hands.

When given the opportunity, ring-tailed lemurs prefer to eat fruits. For most fruits, they check whether it is ripe using its smell (Jolly, 1966a; Nevo et al., 2018) as well as the fruit's weight and softness (Valenta et al., 2016). One of the main staples in a wild lemur's diet is the Tamarind tree. Its leaves stay green – thus edible – all year round, and it produces brown fruits consisting of a soft inside and a hard outer shell that the lemurs need to break open (Figure 16).

Figure 16 - Tamarind pods, one of the ring-tailed lemur's favourite fruits, hanging in a tree

3.4.1 Food in captivity

Thousands of kilometres north, in the Netherlands, the climate is drastically different and there is no abundance of tamarind trees. In Rotterdam Zoo, the animals are fed mostly green vegetables one would find in a Dutch supermarket (e.g. broccoli, lettuce, kale, and sometimes potatoes and paprika). These are nutritionally healthy for the animals, and they seem to like them, but they are far from the flowers, tamarind, and other Malagasy fruits eaten in the wild. (W. Verwer - Nutritionist, personal communication, 8 May 2025).

In the wild, ring-tailed lemurs often forage high up in the trees – often by pulling on a twig to move the fruit that it is bearing to their mouth – and in the middle of the night, both are currently not enabled by the zoo.

3.5 Daily activity in Madagascar

The sketched travel route on the next page below shows an overview and explanation of a wild ring-tailed lemur troop's day. Figure 17 then condenses this into an activity cycle, showing how much time the lemurs spend on different types of behaviours. Synthesising multiple studies, a wild ring-tailed lemur spends around 50% of their active day resting and doing passive social activities, 30% on foraging and 15% on travelling to new places (Gabriel, 2013; Jolly, 1966a; Keith-Lucas et al., 1999; Kelley, 2011; Pinkus et al., 2006; Rasamimanana et al., 2006). While in the dry season lemurs might spend a bit more time foraging, their activity cycle stays relatively similar throughout the entire year as the days are similarly long.

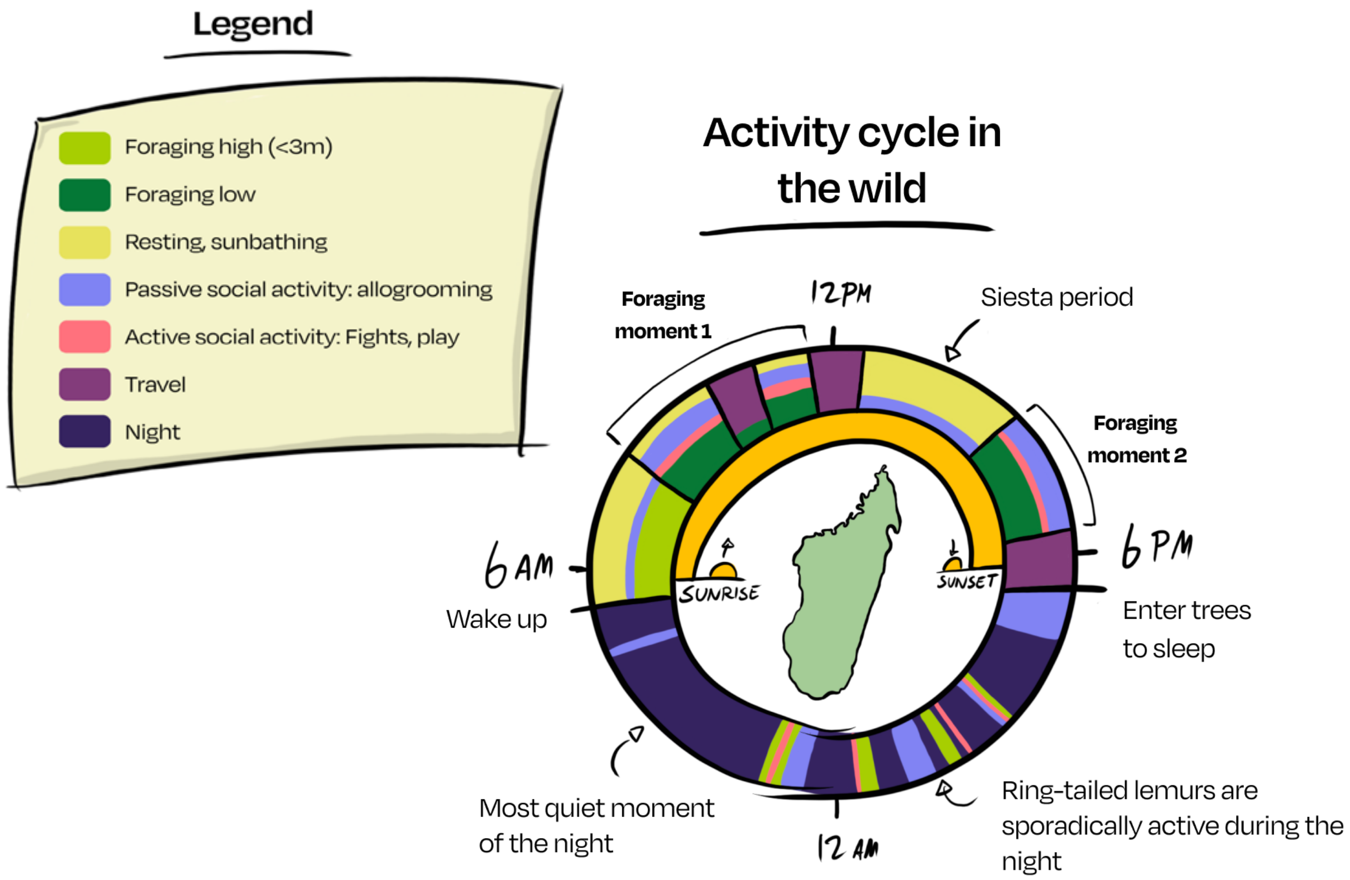
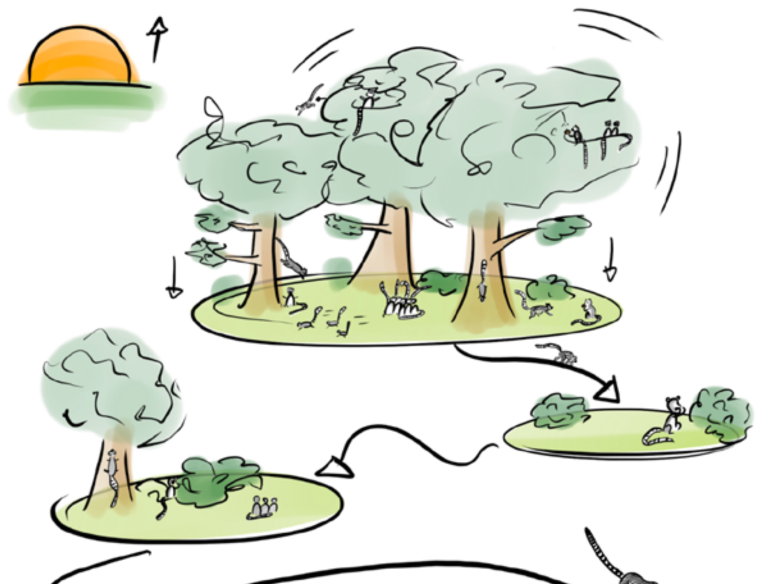


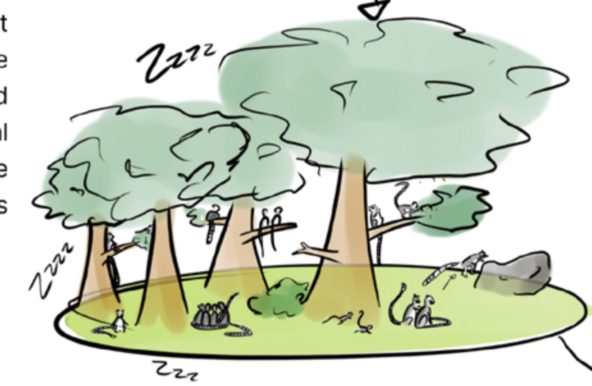
Figure 17 - Activity cycle of a ring-tailed lemur living free in Madagascar



Before dawn, the ring-tailed lemurs wake up, moving about in the trees where they slept. Then, in the early morning, they start feeding and sunbathing mainly in the trees where they slept.

In the latter half of the morning, between around 8 and 1o, the troop descends to the ground to feed some more and to socialise. The lemurs spread around a wider area where they continue foraging and engage in social grooming, while the pups can play with each other. This cycle of feeding and socialising goes on until noon, with the troop sometimes travelling to new feeding sites when needed.

Around noon, the lemurs start travelling to a siesta site where they mainly relax and nap with the occasional grooming in the shade of the trees. When it is hot, siestas can last up to four hours.



In the late afternoon, the troop moves around again in the same area to forage, groom each other, and play.

Around sunset, there is a final long travel where the troop searches for a new set of trees where they will spend their night.

During the night, ring-tailed lemurs sleep as well as feed, jump around and have small fights with each other. While they are not a nocturnal species, they still stay relatively active during the night, especially when there is more light from a full moon (Bray et al., 2017; Curtis & Rasmussen, 2002; Donati et al., 2013).

Based on Jolly (1966a) and Sauther et al., (1999)

3.6 Daily activity in captivity

Figure 18 provides a visual overview of what an average day for a captive ring-tailed lemur in Rotterdam Zoo might look like, based on a combination of personal observations, conversations with animal staff, and literature on similar zoo environments. Due to the big difference between summer and wintertime, two different cycles have been made.

In a zoo environment, animals' living areas are limited. As a result, captive ring-tailed lemurs tend to show quite some resting behaviour (Laméris et al., 2021; Pertoldi et al., 2024) – although this is not always the case, as Goodenough et al. (2019) points out.

At Rotterdam Zoo, the lemurs are fed three times: in the morning, at noon, and in the afternoon. Because all the food is available at once and each lemur wants to grab as much as possible, activity spikes, and the food is rapidly eaten. As such, there is little time for socialising at these moments.

3.6.1 In contrast to the wild

This is a vast contrast to their wild behaviour where there are only 2 clear feeding moments, both of which are spread over a much bigger time window, where the lemurs eat, relax, groom, eat some more, and so on. An important time for socialising, which seems less available in captivity. There is also more nocturnal activity in the wild, where lemurs also have the availability to eat leaves and fruits in the trees in which they sleep, something much less available in captivity

3.7 Other differences between wild and captive lemurs

By supplementing vitamin D, the lemurs stay healthy (Killick et al., 2015), but their behaviours differ from those in Madagascar. The Dutch winters, which are 20°C colder, lead the lemurs to prefer staying huddled up inside, sitting under their heated elements, which often leads to more quarrels. All this while in Madagascar, this would be the dry season – meaning the lemurs would need to travel a lot to find food.

Due to size and monetary constraints, zoo environments offer fewer opportunities for movement and struggle to present animals with novel situations. Installing ropes and placing trees does provide some challenges, but over time, the animals become familiar with these unlike a fast and everchanging natural environment.

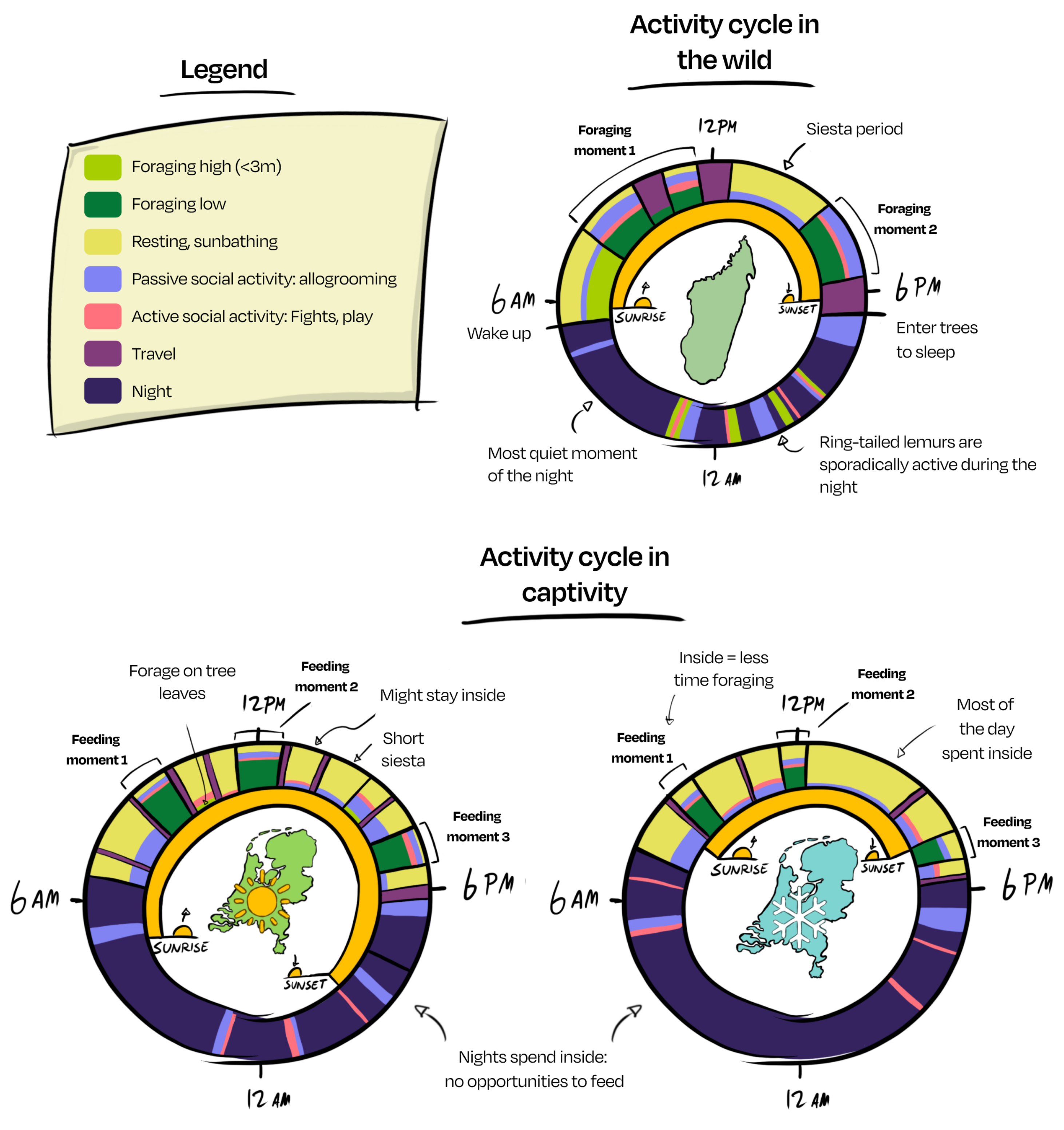


Figure 18 - Daily activity cycles of a captive ring-tailed lemur in Rotterdam Zoo in summer (left) and in winter (right). For reference, the daily activity in Madagascar can be viewed (top)

3.8 Conclusion

After learning much about this species of lemur, we are now able to briefly answer the first three research questions:

What physical characteristics are essential to the ring-tailed lemur?

Ring-tailed lemurs rely heavily on their limbs to climb, groom, and grab food. They use their mouths in combination with their hands to perform more delicate tasks but are not the greatest at manipulating items – often resulting in it falling out of their paws. Their sharp teeth help to break open hard surfaces, mainly tamarind fruits.

Lemur Catta relies heavily on its olfactory senses for communication, to find food, and to identify whether it is good to eat, as well as its eyesight. This is not as sharp as that of humans, but it is well adapted for detecting movement and provides a degree of night vision.

What behaviours are essential to the ring-tailed lemur?

Ring-tailed lemurs are a highly social species; as such, they rely on learning socially. Lemurs need to be kept in a troop in which they can show their species-specific behaviours in socialising, grooming, and fighting to maintain their hierarchical structure. In this group, they can then also make use of their complex set of vocalisations.

Their feeding periods span a few hours and are interspersed with social and resting activity. It is an important time in which relations are maintained by grooming and hierarchical displays (like stealing food).

Ring-tailed lemurs spend significant time resting (and sunbathing in the mornings), in which they also socially bond a lot by huddling and grooming.

What behaviours of the ring-tailed lemur are missing in captivity?

In captivity, there is less time spent socialising while foraging due to competition for the food. There are also fewer opportunities to forage at tree heights.

In the zoo, there are no new areas to explore as everything needs to be fenced in and food is provided where they are. As such, captive lemurs do not need to travel far to find food. And when it is cold outside, they tend to move even less – staying in their inner enclosure as much as possible.

A complete comparison between nature and captivity is provided in Appendix D, as a result of which a list of areas where significant strides can be made in improving lemur welfare was created, listed in Figure 19.

Areas for welfare improvement

- The lemurs lack travel to different foraging sites
- There is a lack of dynamics and change in the ring-tailed lemurs' housing
- There is a lack of olfactory stimulation
- The captive lemurs tend to be hyper-focused on feeding moments and show much less of their relaxed and social eating habits
- There is a lack of feeding at heights
- There is a lack of possibility to feed throughout the night, resulting in more human-like night rhythms
- Some challenges from eating Malagasy fauna are underrepresented in captivity, such as breaking open hard tamarind pods
- Due to the cold Dutch weather, lemurs tend to stay inside a lot in winter

Figure 19 - Areas for welfare improvement

4. Stimulating natural behaviour

Zoos, research centres, and rescue centres are constantly working to improve the lives of their animals. The main way to do this is to implement something that engages the animals and allows them to utilise their species-specific traits and behaviours within the constraints of an animal enclosure.

This chapter will examine the literature on what has been investigated to stimulate ring-tailed lemurs and related species to identify in what ways the design could improve animal well-being.

As such, it aims to answer the fourth research question:

What opportunities are there to enrich ring-tailed lemurs' lives?

4.1 An overview of enrichment devices

4.1.1 Effect of enrichment products

As lemurs mostly tend to either rest, forage, or travel (there is very little play or similar actions for entertainment), most existing enrichment focuses on their foraging behaviour. As mentioned earlier, that is one thing lacking clearly in captivity. Laméris et al. (2021) recently found that enrichment items have a positive effect on captive ring-tailed lemurs, especially those who do not have access to outdoor exhibits. Lemurs that could go outside freely behaved much more similarly to their wild counterparts.
Markowitz & Aday (1998) found that giving captive primates control over their environment, like touching something to get food or to hear music, or silence, enhanced their wellbeing and stress recovery. This principle of giving animals choices and control over their lives is increasingly used in modern zoos, including in Rotterdam.

4.1.2 Existing solutions

Figure 20 shows a collage of available enrichment solutions. As there are not that many lemurs in the world, zoos often opt for either items designed for other animals – like dog toys - or generic primate items, or build something custom, often at relatively low cost.

Nearly all these foraging enrichments focus on increasing the time it takes the animal to get the food out of the thing it is placed inside. All of these rely on the zookeeper giving them out – something that is often not done at the time lemurs would naturally forage –, after which the lemurs can work on getting the food out directly. Then, after the food is removed, lemurs would stop interacting with it until the next time zookeepers refill it.

Besides, many require much zookeeper interaction time to prepare and to remove for cleaning. There seem to be no automated solutions that target lemurs' natural rhythms, keep them re-engaged, and are relatively hands-off for zookeepers.

Figure 20 - An overview of some available enrichment items for (ring-tailed) lemurs

4.2 Foraging enrichment

As highlighted, most existing solutions to improve lemurs' welfare focus on foraging, since this is a significant part of their natural activity. Spreading food out over the exhibit and increasing the amount of manipulation needed to be able to eat their food is an effective way to improve captive ring-tailed lemurs' foraging experience (Dishman et al., 2009). Giving lemurs access to varied options helps to keep them engaged (Fernandez & Timberlake, 2019).

There are many ways this has been achieved, ranging from store-bought dog-chewing toys to DIY projects made with old plastic bottles. While most of them probably work well, few look naturalistic enough to fit into a lemur exhibit without capturing a lot of attention (like Figure 21). Also, a lot of them are only meant to make getting food take more time, not help the lemur interact with the world more naturally (a wild lemur would never find a glass puzzle box in Madagascar).

Figure 21 - Naturalistic looking foraging device

4.3 Sensory enrichment

Devices that stimulate different senses can also help animals behave more naturally. For lemurs, it is quite interesting to look at scent enrichment, as olfactory communication is an important aspect of their behaviour. Animal welfare can often best be improved by focusing on a species' dominant sense (Wells, 2009), or by combining multiple senses (Wang et al., 2025).

4.3.1 Olfactory enrichment

According to experiments by Baker et al. (2018), adding novel scents to a ring-tailed lemur exhibit enhanced their natural resting behaviour as well as locomotion. Recent studies suggest that biologically relevant scents (such as those of other lemurs) can have a small effect in encouraging more natural, species-specific behaviours in lemurs (Costantini et al., 2024; Fontani et al., 2025). Scrubbing trees clean where the lemurs have applied their scent nudges them to show more scent-marking behaviours by reapplying it (Sorraia, 2018) and giving lemurs browse that smells like other species causes them to investigate it together, improving social ties and increasing territorial behaviour (Browning & Moro, 2006).

4.3.2 Auditory and visual enrichment

The consensus on the impact of auditory enrichment seems mixed. On the one hand Caselli et al. (2022) found that using audio of primate species unknown to lemurs reduced their stress, while on the other, Browning & Moro (2006) found that playing lemur sounds caused stress and intragroup aggression.

As for visual enrichment, little research has been done on the effect on lemurs. A study on chimpanzees showed that watching screens for visual enrichment did not alter their behaviour much, except taking up a large chunk of their day and looking unnatural (Bloomsmith & Lambeth, 2000).

4.3.3 Personal addendum

When I was visiting Apenheul, I spent quite some time observing their troop of ring-tailed lemurs. At the time when the feeding moment is about to start, a music fragment is played to remind visitors. The lemurs, apparently, have also learnt exactly what this means. After hearing this auditory cue – meaning to them: "we're going to get food" – they promptly woke up from their nap, stood up, and walked in a line to the location where the zookeeper talk was happening (Figure 22).

Figure 22 - Lemurs in Apenheul walking to feeding moment

4.4 Interactions with other animals

Ring-tailed lemurs in nature are very tolerant of other species. They can often be found near other lemur species that are more arboreal with little problem, and Jolly (1966a) even observed a moment where a snake slithered through a troop of ring-tailed lemurs, with them not showing a care in the world. As a result, many zoos are housing Lemur Catta together with other animals, often lemur species – such as for example in Apenheul. Having different species together in an enclosure yields a lot of (multisensory) entertainment for the animals, which is great for improving welfare.

Adding another species does, however, bring many management issues, and there are many logistical reasons as to why Rotterdam Zoo also is not planning on implementing this solution for the ring-tailed lemurs.

4.5 Predator simulation

Predator avoidance and the evolved alarm call system are important aspects of wild lemur life; something captive lemurs have little experience with, although calls are sometimes given when a large bird or helicopter flies past (figure 23).

Short moments of stress due to predator simulations seem beneficial for Marmosets and Tamarins – types of monkeys that also use complex alarm calls (Chamove & Moodie, 1990; Sánchez-Barroso Cano, 2019). It helped them reduce overall stress and improve group dynamics, awareness and daily energy budget management.

There are no studies on this with lemur species, but there might be an opportunity for them to use these predator avoidance behaviours more in captivity.

Figure 23 - A ring-tailed lemur vocalising, showing anti-predatory behaviour

There are many ways this has been achieved, ranging from store-bought dog-chewing toys to DIY projects made with old plastic bottles. While most of them probably work well, few look naturalistic enough to fit into a lemur exhibit without capturing a lot of attention (like Figure 21). Also, a lot of them are only meant to make getting food take more time, not help the lemur interact with the world more naturally (a wild lemur would never find a glass puzzle box in Madagascar).

Figure 24 - SensorySafari in use: A child watches the lemurs trigger a stimulus (left) while a different child plays a guessing game on what the lemurs like the most (right) (Wang et al., 2025)

4.6 Visitor engagement

One aspect of nearly every zoo animal's life is all the visitors who stand, look, and walk by. For ring-tailed lemurs, more active visitors often resulted in the lemurs moving around more and being more alert (Goodenough et al., 2019; Pertoldi et al., 2024), while Collins et al. (2017) found that visitors had little effect on the lemurs.

Some form of visitor engagement could also be achieved by adding a form of interactivity, like creating a walkthrough enclosure – which increases lemur activity (Goodenough et al., 2019; Pertoldi et al., 2024) – or a device like Wang et al.'s (2025) SensorySafari, in which lemurs can trigger auditory, visual, or olfactory stimuli which the visitors can then experience at the same time as the lemurs (Figure 24).

4.7 What is missing?

For Lemur Catta, there is a high focus on simple foraging devices where they must use their hands to get small pieces of food out of an object and at the same time, there is little focus on foraging behaviour high up in trees and during the night.

Most items are filled with food and then placed in the exhibit; there are very few systems that allow the animals to choose when they receive something enriching on their own, and none that are automated to work at the perfect time in lemurs' natural schedule. There is also a clear lack of multisensory devices, devices that focus on presenting browse, and devices that focus on other unique lemur behaviours, such as sunbathing.

4.8 Conclusion

4.8.1 Design opportunities

Based on conclusions about what lemurs miss in captivity – focusing on their behaviours and differences in captivity – and on what kind of enrichment devices are missing from the market, a list of design opportunities can be made to answer the research question:

What opportunities are there to enrich ring-tailed lemurs' lives?

These opportunities – listed in Figure 25 – serve as inspiration for ideation by giving clear things for which to think of solutions.

4.9.2 Visitor experience

It is important to balance these opportunities with the enhancements to the visitor experience, for which lemur activity close by should be encouraged.

4.9.3 Requirements

Based on the results of this and the previous chapters, as well as brief interviews with stakeholders throughout, a list of requirements for the design can be created. The main requirements resulting from these chapters are shown in Figure 26 and the list can be found in Appendix E.

Design opportunities

- To design something that results in an environment for the ring-tailed lemurs that feels more dynamic and changing
- To design something to enable the lemurs to choose when they want to interact with it, thus offering them a similar degree of control to that in nature over their foraging habits
- To design something to allow foraging at higher heights.
- To design something that mimics the challenges lemurs face when eating native Malagasy food
- To design something that nudges the lemurs to be more active inside or something that nudges them to come outside (safely) in colder weather.
- To design something that stimulates the lemurs' olfactory senses, or

Figure 25 - Design opportunities

Main Requirements

- The device should not become predictable after a few uses
- The device gives lemurs a reason to travel more
- The device should be multisensory, preferably using smell
- It should take the lemurs much longer to use than it takes staff to set it up
- It should be easy and efficient to use and maintain by the staff
- It should be possible for the lemurs to choose when to interact

Figure 26 - Main requirements for the design

"one important component of naturalistic enrichment is that it interacts with species-typical behavioral repertoires, which is particularly true for foraging behavior."

-Quote from Fernandez 2019

Part III: Creating the Final Design

This part of the report shows the process towards the final design. The schematic below shows how this part of the report is built up, showing the steps of converging into many ideas or concepts and where and diverging into clear results.

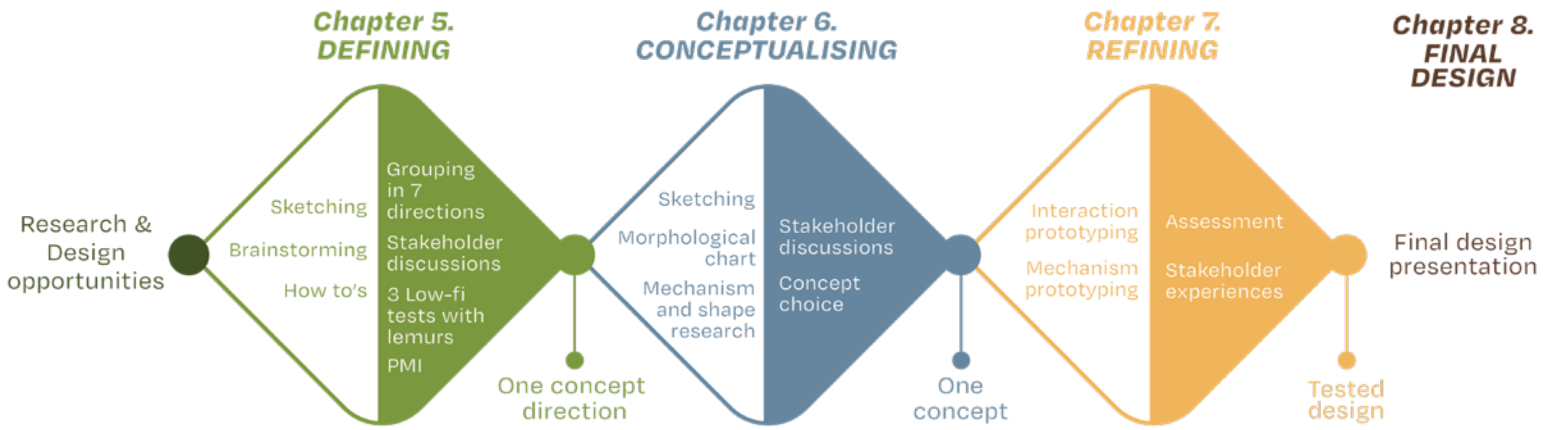


Figure 27 - Process towards final design

5. Defining

This chapter begins by generating ideas, which result in multiple directions that are assessed through stakeholder meetings and prototype testing. Finally, one concept direction is chosen.

5.1 Ideation goals

The design opportunities and requirements formulated at the end of the previous chapter were reformulated into clear goals for the ideation phase of the project categorised per main stakeholder in Figure 28.

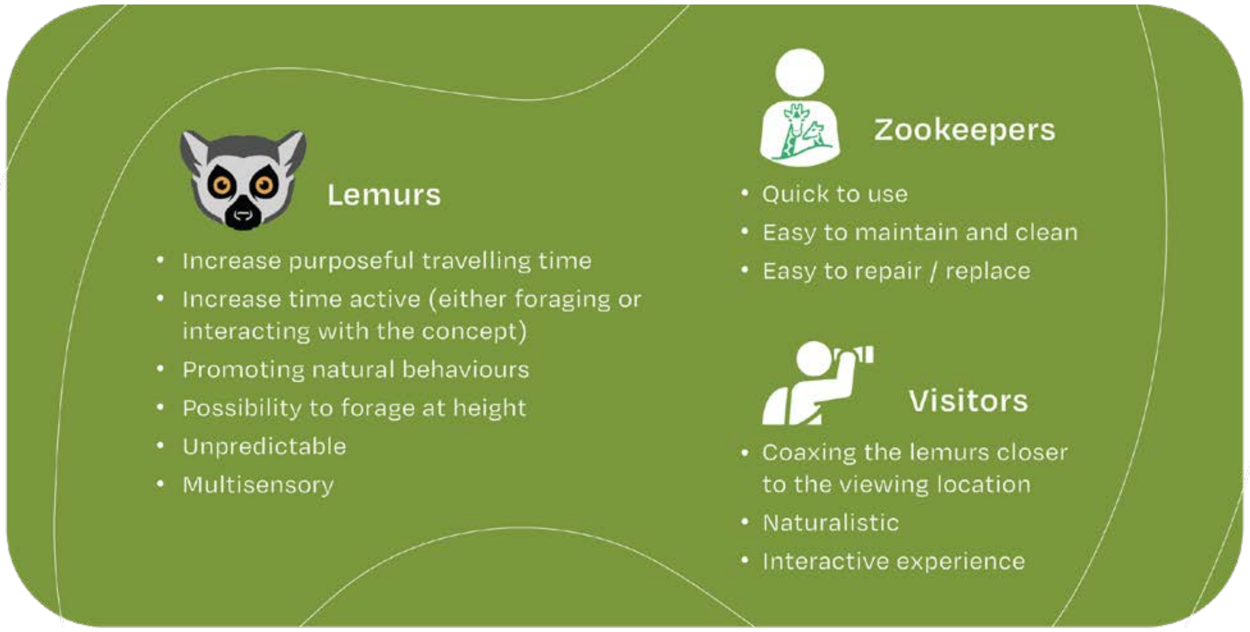


Figure 28 - Reformulated goals per stakeholder

5.2 Early Ideation

In this round of idea generation, the focus lay on how to engage the lemurs in different ways, which were in line with the desk research, personal observations of how the ring-tailed lemurs behave, and conversations with zookeepers. This research was used as inspiration for different idea generation methods, like brainstorming, how-tos and discussions with designers and non-designers. From here, a variety of ideas were generated some of which are shown in Figure 29 (all can be found in Appendix F).

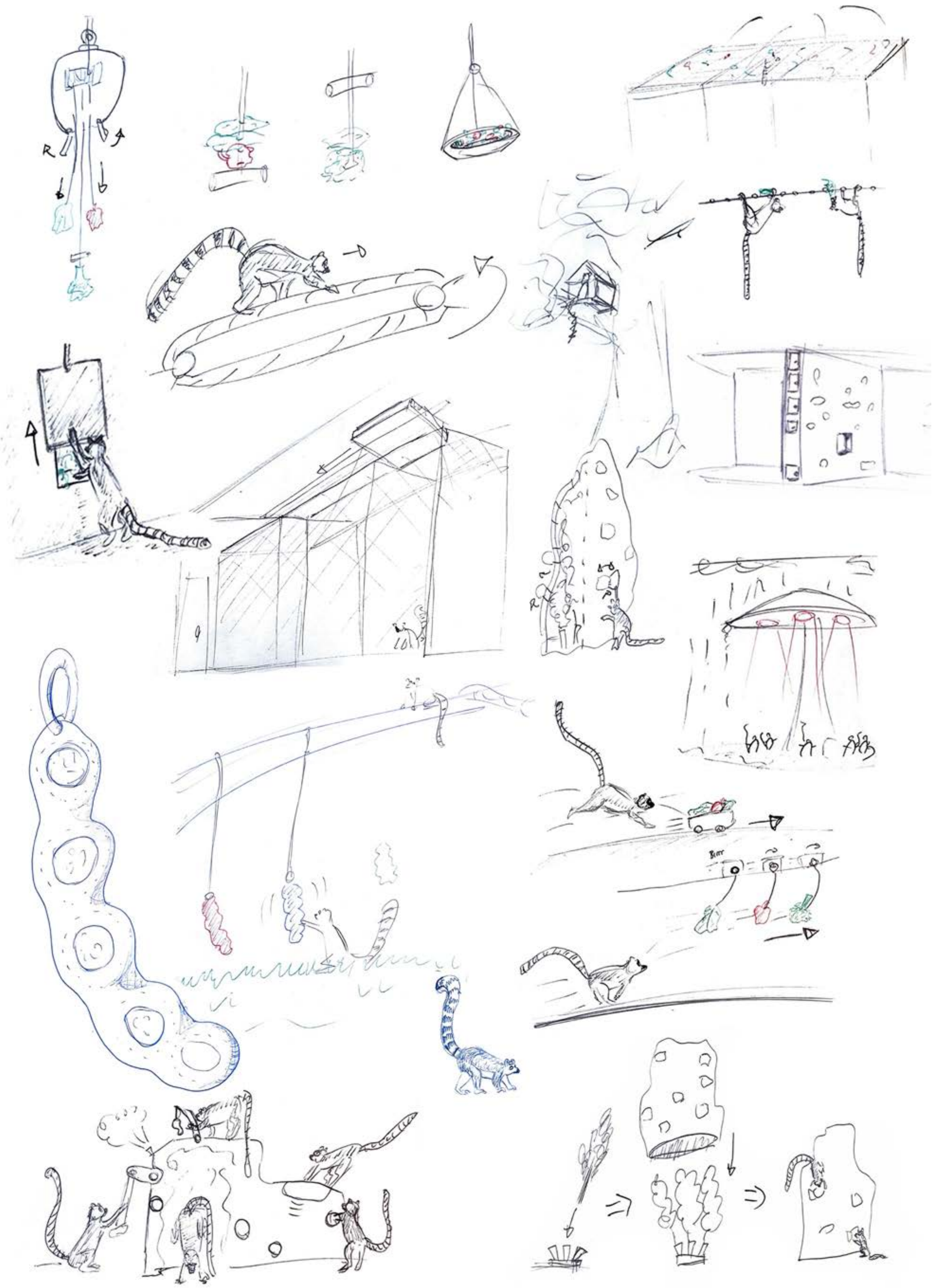


Figure 29 - Impression of generated ideas

5.3 Seven Idea Directions

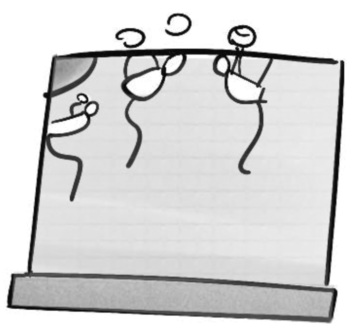
Using Post-its to go over the sketches critically, the ideas that seemed possible and potentially interesting to the lemurs were highlighted. Those deemed impossible due to budget and location constraints were shot down, while the interesting aspects of those were kept in mind. Similar ideas were grouped and combined into a total of 7 idea directions, briefly summarised here.

(1) Tamarind fruit opening system

In the wild, lemurs get access into the hard tamarind fruits by breaking them open; this idea aims to simulate those behaviours by giving them an object in which fruit is hidden. The lemurs need to open it up to get the food.

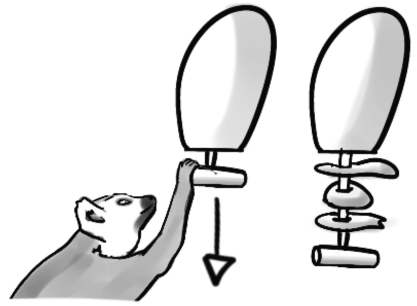
(2) Scatter feeder in trees

Placing a scatter feeder high up in the trees, food is flung around landing on plates in the trees, on branches, or on the ground; resulting in a varied area to forage and feed, encouraging the lemurs to move and climb more.



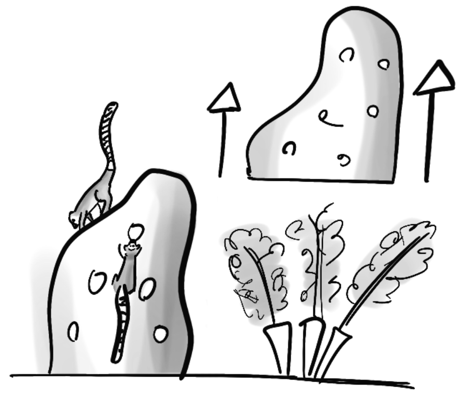
(3) Feed spreader/box at the top of the inside enclosure

Something to make it more difficult for the lemurs to gather food while they are in their inside enclosure. The zookeepers can easily throw the food in one place, after which it gets distributed to the lemurs by the system.



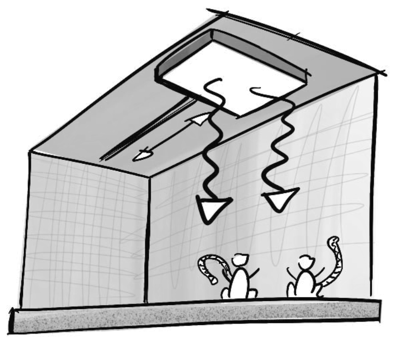
(4) Pulling food system

Lemurs tend to pull twigs towards them to get to the fruits or leaves, so this idea aims to simulate that by making the food only accessible if the lemurs pull far enough on the device.



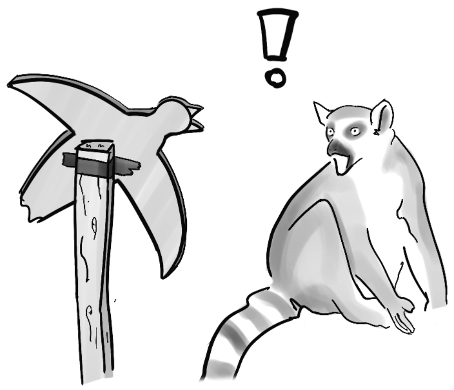
(5) Interactive browse system

Browse (leaves on twigs) is hidden under a fake rock / tree with holes in them, making it more time-consuming for the lemurs to get the leaves, but easy for zookeepers to exchange the empty twigs for new, fresh ones.



(6) heat & sun systems

This idea tries to enhance natural sunning behaviours by adding a moving artificial sunlight into the inner enclosure or adding heat elements, prompting the animals to keep moving during the day to where the "sun" is the nicest.



(7) Predator simulation

Here, the animals are scared by artificial predators, eliciting alarm calls and predatory avoidant behaviour – like jumping away or into trees – and potentially improving group cohesion.

5.4 Narrowing Down Directions

In discussions with multiple stakeholders – consisting of animal staff and project management, three idea directions were found to have the most potential:

(1) The tamarind fruit opening system
(3) Feed spreader/box at the top of the inside enclosure
(4) Pulling food system

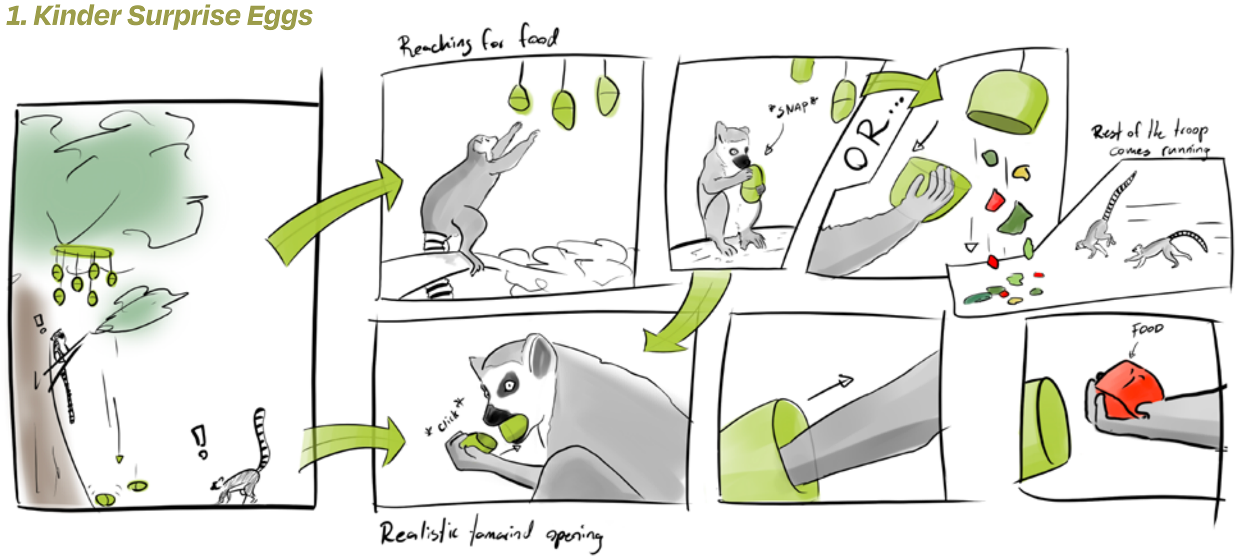
The others were either not interesting enough for the lemurs, already extant or to be (partly) implemented in the overhaul of the enclosure or had too many difficulties to overcome (to be feasible). A brief explanation of the exclusion for each of these directions can be found in Appendix G.

These three directions focus mostly on foraging behaviour. This is an area where the most improvement can be gained, as they naturally spend around 40% of their time on this. Rotterdam Zoo's ring-tailed lemur population tends to spend less time foraging – they eat all their food quickly – and spend more time being inactive compared to wild populations. Encouraging the lemurs to be more active by needing to forage for food helps increase their daily movement and activity.

5.5 Three Idea Directions

Based on the stakeholder feedback, the three chosen idea directions were further detailed. For all three, the way it works will be explained, what their goal is, and what the areas of interest are.

1. Kinder Surprise Eggs

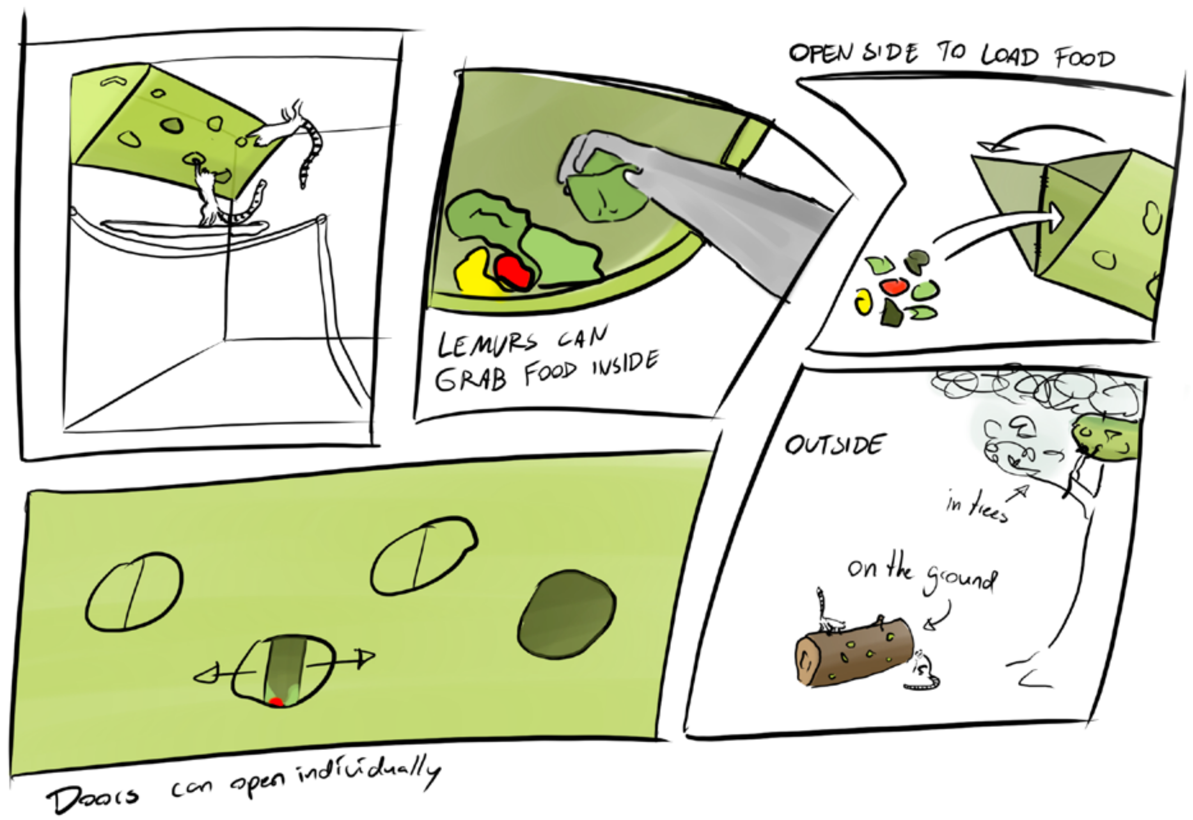


Here, the main idea was to stimulate the lemurs more by making getting access to the food a similar challenge as they would encounter in the wild when eating tamarind fruits. These have a very hard outer shell, so the lemurs need to break and rip them open; something which this idea tries to emulate.

It also encourages the animals to move around and explore more, using their olfactory senses to find leftovers in the thrown-around shells. The time at which the lemurs are able to open the pods can be automated, allowing zookeepers to fill them at an earlier time only for the lemurs to have access at a later (more natural) time.

Many Kinder eggs are needed, as too little availability will result in quarrels and lower-ranked lemurs being left empty-handed each time. How much time it takes to gather, clean, and fill the eggs is also a consideration on the side of the usability for the zookeepers.

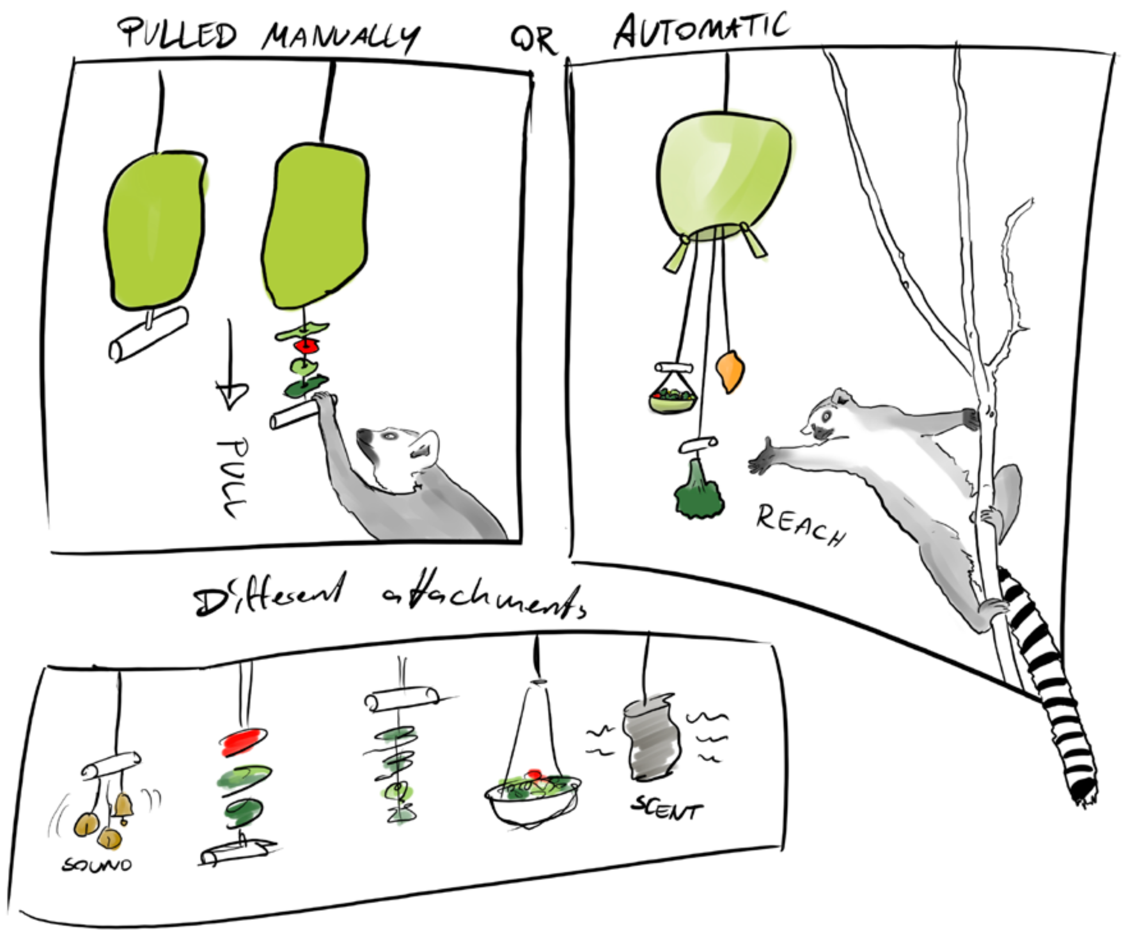
2. Blind box (grabbelton)



This idea mainly focuses on the ease of use and efficiency for zookeepers. They can just throw all food in at once and are done with it for some time. Cleaning it out is then simply done by hosing the inside. The animals will be busier with getting food as they need to put their arms or muzzle into the device and manoeuvre them around to find the food. This is not exactly natural behaviour, but it does engage their motor skills and keep them busy.

Automation is easy to implement by opening some door automatically at different intervals. There is a need for multiple Blind boxes around the enclosure that are open at the same time. Just one would result in the lower ranked lemurs being shooed away by lemurs guarding the entire box, thus getting not enough food. These boxes are relatively big and bulky, so they cannot easily be placed anywhere, and this also makes removal for repair and maintenance a bit more difficult.

3. Pulldown system



This third idea is mainly inspired by a simple hook on which vegetables were skewered in Auckland Zoo (shown in Figure 30) (Auckland Zoo, 2017; a similar device has also been used in Browning & Moro, 2006))

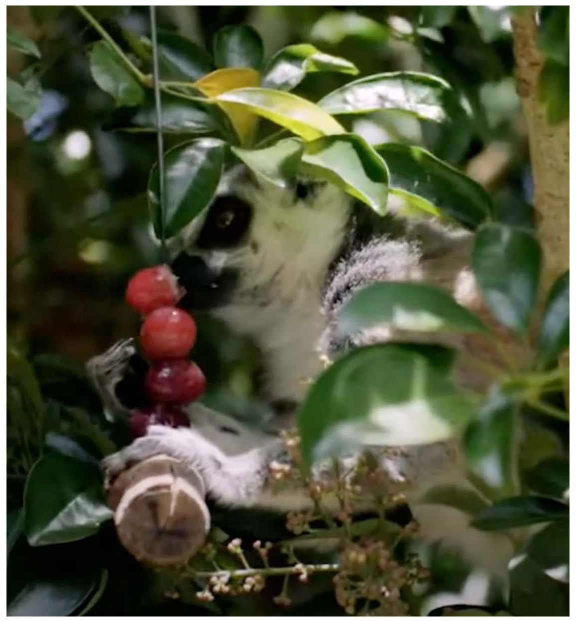


Figure 30 - Sketch and picture of the skewer used in Auckland Zoo

It aims to increase the number of times the lemurs display reach and pulling motions, one of the main ways in which they tend to collect food in the wild (Figure 31). Placing the pulldown system slightly out of reach can create a nice challenge to get food. It also places the choice to act and forage entirely on the animals, as they are free to either interact or not interact with the device at any point.

The main drawbacks are that the presentation of food would take a long time – something of which zookeepers do not have a lot spare – and would be quite messy with squishy items like tomatoes. The caregivers also voiced concern about the safety of the animals; the danger of a limb or an entire animal getting stuck in the system.

Figure 31 - Ring-tailed lemur reaching for food

5.6 Prototype Testing

To substantiate the choice of one final design direction, three simple prototypes – further called Low Fidelity (LoFi) prototypes – are created to simulate the main principle of each idea.

The goal for all three of these prototypes was to:

- Assess the interest of the lemurs in this type of feeding (how much do they interact with it compared to the normal feed, and for how long?)
- Observe how the lemurs interact with the object
- Observe how it influences the lemurs' behaviours and social interactions

All prototypes were used during normal feeding times when there were also vegetables freely available to the ring-tailed lemur group. In total, 5 observation sessions were held, the first three focused on prototype 1, and the final two looked at prototypes 2 and 3.

5.6.1 Direction 1 – Kinder Surprise Eggs

Dog toys of the brand KONG were used, which could be filled with the normal feed or peeled tamarind fruits (Figure 32). They are placed/thrown at varied places near the normal feed. It tests whether the lemurs would be engaged by small egg-like objects.

5.6.2 Direction 2 - blind box (grabbelton)

A box with holes drilled in it of varying sizes (26mm-33mm) bigger than a lemur's hand (we do not want a lemur getting stuck) in which food items can be placed. It is hung next to a couple of climbable logs, allowing the lemurs to reach for the holes and move it around (Figure 33). It tests if a blind(-ish) box would improve and increase the time spent foraging and how the lemurs try to gain access to the food.

5.6.3 Idea 3 – pulldown system

A box where the bottom is connected to the top using elastic bands. The lemurs need to pull the bottom down, using a similar motion as the idea suggests. It is hung next to or under a log, allowing the lemurs to reach and to try and open the box (Figure 34).

Note: The pink colour of the box is not expected to have much of an effect to garner the lemur's attention. While to our human eyes the box's pink colour is very bold and vivid, for the lemurs it appears much less so, as they perceive it as a white colour.

Figure 32 - Kong toys filled with kibble (top left) and peeled tamarind (top right), at the bottom a lemur can be seen interacting with the Kong toy

Figure 33 - Blindbox prototype in the lemur enclosure

Figure 34 - Pulldown box prototype in the lemur enclosure

5.6.3 Addendum: Personal anecdote

During one of my observations, I stood in the enclosure for an hour, with the lemurs not caring much. At the end, I dropped my pen and all of a sudden 4 lemurs stood in front and next to me, looking fascinated at the object in my hand. The same object I had used for an hour while observing; but after the sudden movement and sound of falling it had become the most interesting thing in the world to them.

This anecdote illustrates how quick their reflexes are whenever they see some form of quick movement.

Figure 35 - A curioous young ring-tailed lemur looking at the camera

5.6.4 Types of interactions observed

The following collages (Figure 36 and 37) shows the different ways the ring-tailed lemurs engaged with the low-fidelity prototypes.

Figure 36 - Observations Kongs test

Figure 37 - Observations pull down and blind box test

5.7 Results

Table 1 shows the summarised findings of these low-fidelity tests. The observations of each individual test and the in-depth conclusions of the prototypes can be found in Appendix H.

Table 1 - Conclusions LoFi prototype tests

Conclusions LoFi (summarised)

1. Kong	**Increased locomotion** • to gather food • to protect food Kongs were spread around the entire enclosure. *(One is still lost at the time of publishing)*	A lot of time is spent manipulating the kongs to get food out Lemurs would periodically walk towards, check, and sniff kongs left behind by others or themselves.	Kongs are used next to food readily available on the ground Interest in the kongs depends on the type of food available freely	After closing time, the lemurs had interacted with the kongs *(natural behaviour & choice)*
2. Blind box	Used after (the majority) of available food & food in (3) pulldown box is eaten	Lemurs spend a lot of time interacting, more than (3).	The lemurs use their arms to pull the food towards the exits and their mouth to manouvre it out	Locomotion is very little. Lemurs sit around the box and below it, where the food drops
3. Pulldown box	Some lemurs sat inside, showing terretorial antagonistic behaviours	Access to the food takes little effort and is eaten quickly	Locomotion is very little. Lemurs sit in and around the box and below it, where the food drops	

5.8 Conclusions

5.8.1 Kong

Overall, the lemurs interacted with each prototype, often preferring the ones from which gathering food was easier first. The smaller dog toys resulted in a lot of extra movement, while for the boxes, the lemurs mainly stayed around that area. The Kong toys also gave lower-ranked lemurs the chance to defend their portion by running away, while the boxes (mainly the easier to gather from #3) were quickly claimed by higher-ranked ones.

5.8.2 Blind box

The motivation to use the Blind Box prototype (#2) differed greatly per lemur. Some gave up quickly, while a few others stayed for much longer, trying to wrangle food out of the holes (with increasing success!).

5.8.3 Pull-down box

Both times, the pull-down box did not keep the lemurs engaged for long. The first time, they managed to tilt it, so all the food slid to one side and was eaten quickly. The second time, a few lemurs would sit in the box, enjoying the all-you-can-eat buffet and shooing away others.

5.8.4 Discussion: Change in group dynamics

Between the Kong and box prototype tests, the group of Rotterdam Zoo's lemurs, which consisted of males and females, was reduced by more than half to 7, all females. This change in dynamics might be why there seems to be less activity in the box tests. Fewer lemurs means less competition for food. Besides, there are no more males (which have the lowest rank) and are easily scurried away by the females, resulting in fewer spats and less need to run away with their loot.

While these prototype observations did not result in hard, scientific results, they still make some of the lemurs' preferences quite clear and can give a much clearer idea of how and why they react to the different aspects of the designs.

5.9 Final direction

5.9.1 Choice of concept direction

It was decided to continue developing the first concept direction – the automatic pods tested with the Kong toys – because it best met the goals and requirements. All three directions were compared and scored using a PMI method; the conclusion of which is summarised in Table 2. The complete comparison between the three prototypes and three concepts can be found in Appendix I.

5.9.2 Main reasons

This concept encourages the lemurs to show natural behaviours – breaking open the pod and moving up to a safe place to eat. The unpredictability of its use gives anticipating lemurs different ways to get an edge over others. It also increases locomotion the most and encourages various types of social behaviours, while it can fit well into their natural feeding times. For visitors, this results in the most interesting and different activity by the lemurs.

5.9.3 Zookeepers opinion

Next, to the lemurs' opinion on these tests, zookeepers also reacted most positively to the Kong tests. They noticed a positive effect on the lemurs' activity, whilst it did not have much of an impact on the time they had to spend at the lemur enclosure. Preparing food was done quickly, and retrieving the Kongs can be done at the same time as cleaning the exhibit.

Table 2 - Concept direction choice conclusion

Concept direction choice

Scoring

2 points

1 point

0 points

Kong: 25
Concept 1: 21

Grabbelton: 15
Concept 2: 15

Pulldown: 13
Concept 3: 15

Concept 1 - Automated system to grab and drop food pods.

Main reasons

Lemurs:
- Increased locomotion - *purposeful travel*
- Increases activity inside
- Unpredictability for the lemurs
- Facilitates many different social interactions
- Simulates natural behaviours that are missing in captivity
- Foraging behaviour / interaction at night

Zookeepers:
- Good to maintain & clean and quite ratproof
- Quite simple to use though it can add some time

Zoo:
- Many possibilities for visitor interactions
- Can coax the animals closer to the viewers, while still giving them the freedom to choose where to eat

6. Conceptualising

In this chapter, continuing in the direction chosen, multiple preliminary concepts are generated and developed into a single final concept.

6.1 Refined design goals

Following a now improved understanding of what is needed to design a welfare enhancing item for the ring-tailed lemurs and their surroundings. As such, the initial design goals set in chapter 5 are rephrased into new ones, which are given in Figure 38.

6.2 First preliminary concepts

Using these new goals and my observations of lemur behaviour, gathered during the rounds of testing, the chosen direction can be turned into tangible concepts. Figure 39 shows more specific questions that were then generated to serve as prompts for idea generation.

Using these questions with the morphological chart method, four initial concepts are generated, which are shown in Figure 40 (more details on these concepts are found in Appendix J1 and J2).

Questions for concept generation

- How would it stay in place?
- How would it stay closed?
- How exactly should the lemurs interact with it?
- How is it powered?
- What are possibilities for user interaction?
- How can the ease of use for the zookeepers be improved
- How can it look natural?

Figure 39 - Questions for concept generation

Lemurs

Stimulate ring-tailed lemurs' natural behaviour by:

- Giving them more reason to travel and engage in foraging behaviours
- Creating something unpredictable to the lemurs
- Creating something multisensory Enabling foraging at height
- Giving lemurs control over when and how to act

Zookeepers

Create a solution that is easy and quick to use

Visitors

Engage with lemur behaviour and naturalistic looks to create opportunities for education

Figure 38 - Redefined design goals per stakeholder

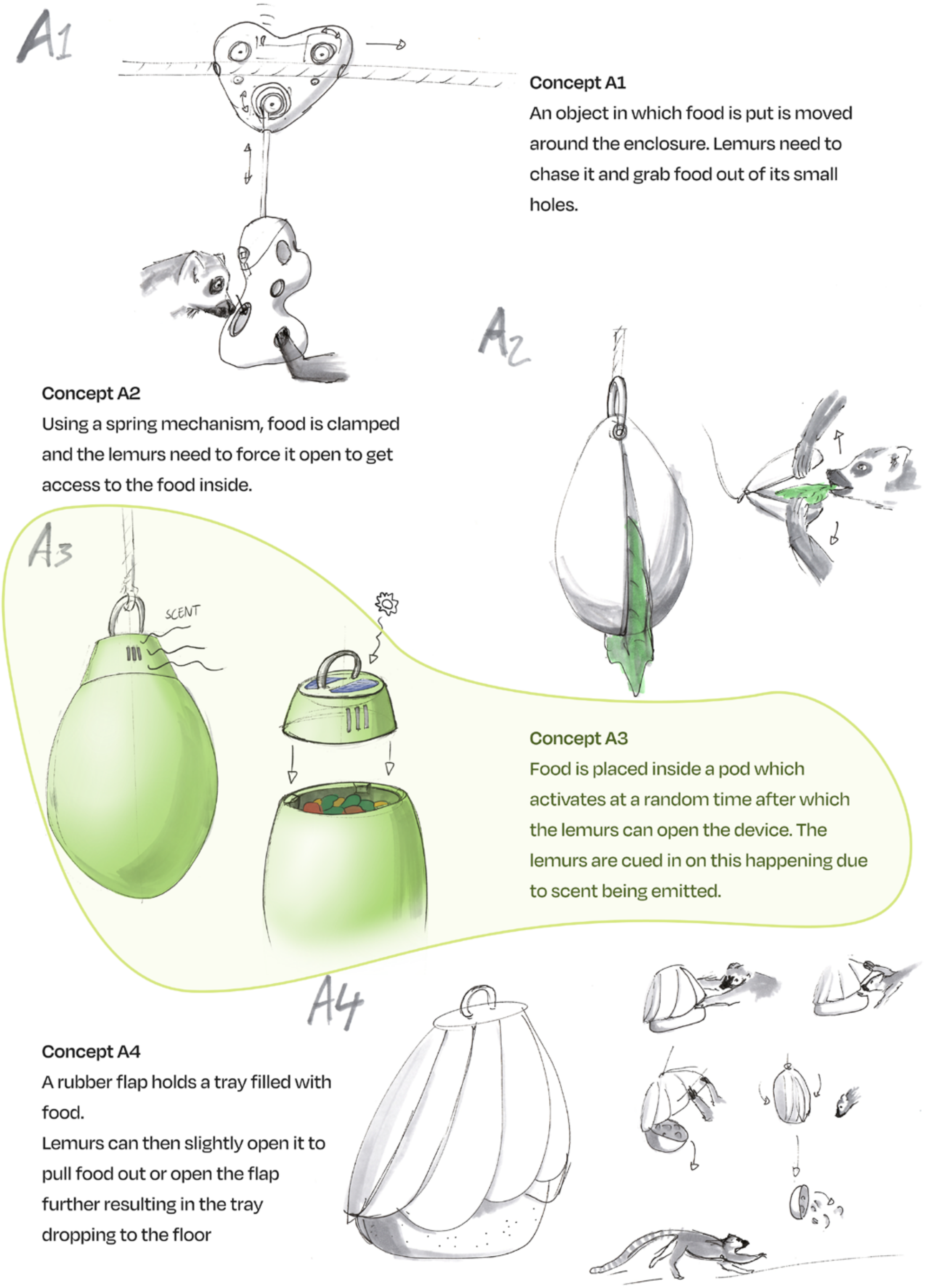


Figure 40 - Four concepts as a result of morphological chart exploration

6.3 Choice of preliminary concept one

6.3.1 Chosen concept

Concept A3 was chosen to continue with mostly due to its being the most feasible. Interest and engagement of lemurs for such a pod-like shape has already been established by the earlier prototype tests and its ability to lock so the lemurs cannot eat everything up straightaway followed by its ability to unlock combined with a scent cue results in the lemurs spending more time foraging and being much more engaged. Being able to move the pods around every few days would force the lemurs to move and explore more around their enclosure. Some aspects of the other concepts were kept in mind, such as small holes in the device to allow lemurs to smell that there is food inside.

6.3.2 Other concepts

Other concepts were either too unnatural, would not increase the foraging time much, or were not feasible for reliable long-term use. Some aspects of these concepts were kept in mind, such as small holes in the device to allow lemurs to smell that there is food inside.

6.4 Additional exploration

In developing these early concepts, it was clear that some more research was needed, specifically in how it could actually work and what it should look like.

6.4.1 Mechanisms

Zookeepers should be able to easily click the lower part of the pod onto the top, after which it should stay locked until activated, and the lemurs are allowed to pull it away. Multiple mechanisms were analysed (Figure 41, more sketches in Appendix J3)

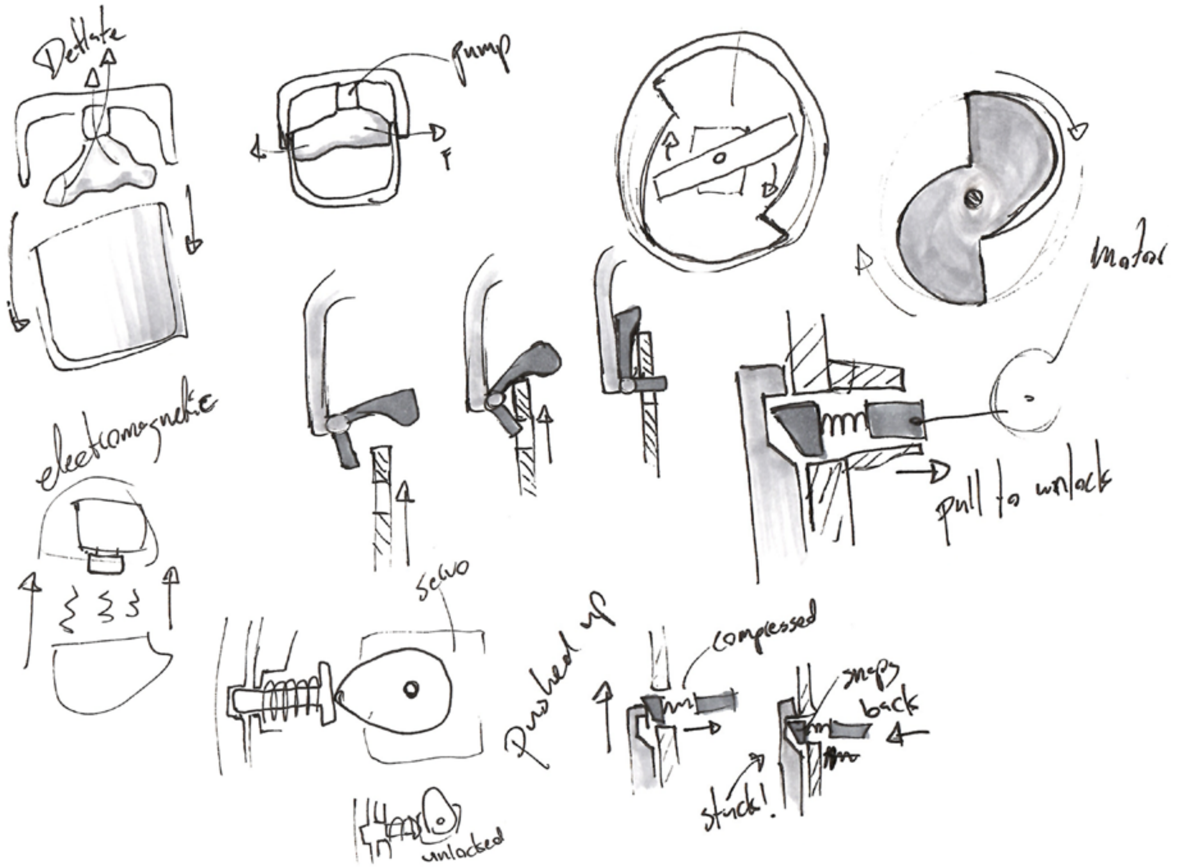


Figure 41 - Mechanism sketches

6.4.2 Form giving

In Madagascar, ring-tailed lemurs' diets can consist of around 60% of fruit (Gabriel, 2013), but in the Netherlands, they are given almost exclusively vegetables due to differences in climate. Shaping the pod into a fruit native to Madagascar can then give zoo visitors a better glimpse into lemurs' natural foraging behaviour. For the lemurs, this all matters very little as they grew up in Rotterdam and do not care for the look of a food container much – they just smell their way to it.

Many fruits that lemurs eat in the wild were analysed, from which the ones deemed most interesting for the concept are shown in Figure 42. A list of all these fruits, as well as an explanation for this shortlist, is shown in Appendix K.

Figure 42 - Possible interesting fruits for the concept

6.5 Second preliminary concept

With a better understanding of these aspects, a second round of ideation was initiated (appendix J4), resulting in the concepts shown in Figure 43 on the next page. All three concepts are controlled and powered from a central point, making them more reliable and easier to manage than many completely independent pods. Concept B3 was then chosen to go further with, mainly due to the possibility of moving it around (to make the solution more dynamic – pushing the lemurs to keep exploring different areas) whilst remaining easy to manage, with one battery powering many food pods. Shaping it in the shape of a tamarind also seems like a good choice due to it being the most staple food of ring-tailed lemurs in Madagascar.

At this point in the project, the main drawback of the other 2 concepts was them being stuck in one place, thus less dynamic.

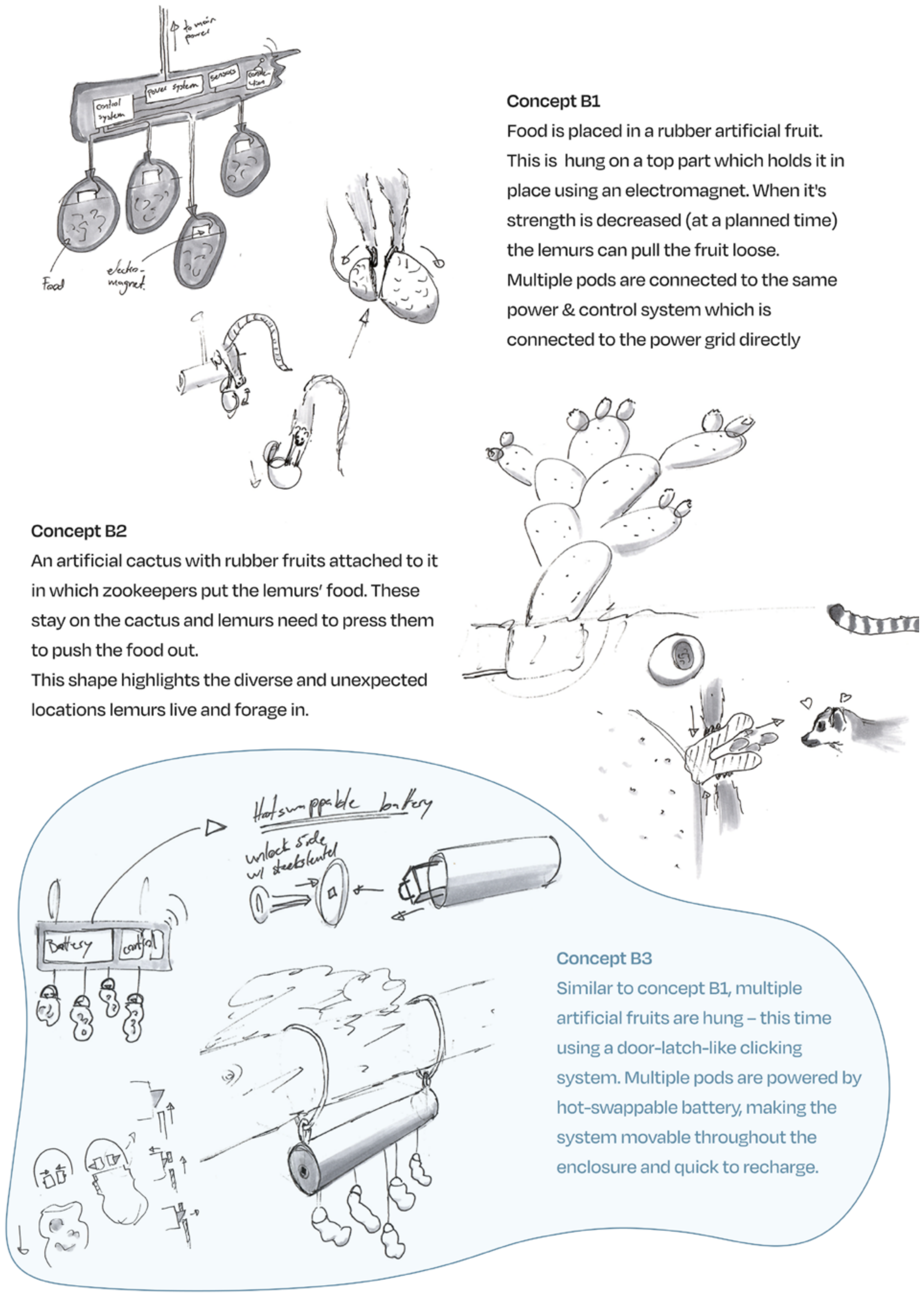


Figure 43 - Three concepts resulting from a second iteration round

6.6 Choosing one concept

Both chosen preliminary concepts (A3 – individual soursop pods, and B3 – grouped tamarind pods) were slightly further developed, as shown in Figure 44, and presented to a panel of animal and technical staff for feedback (presentation posters in appendix J5). The stakeholders' experience in the care of animals and with what seems to work and what does not in the context of a zoo was essential to choosing a final concept.

As a result of this, multiple changes were made to create a final concept, the most important of which was not to use a battery-powered system, but one connected to mains power for reliability. This, and other choices discussed are elaborated on in Appendix L.

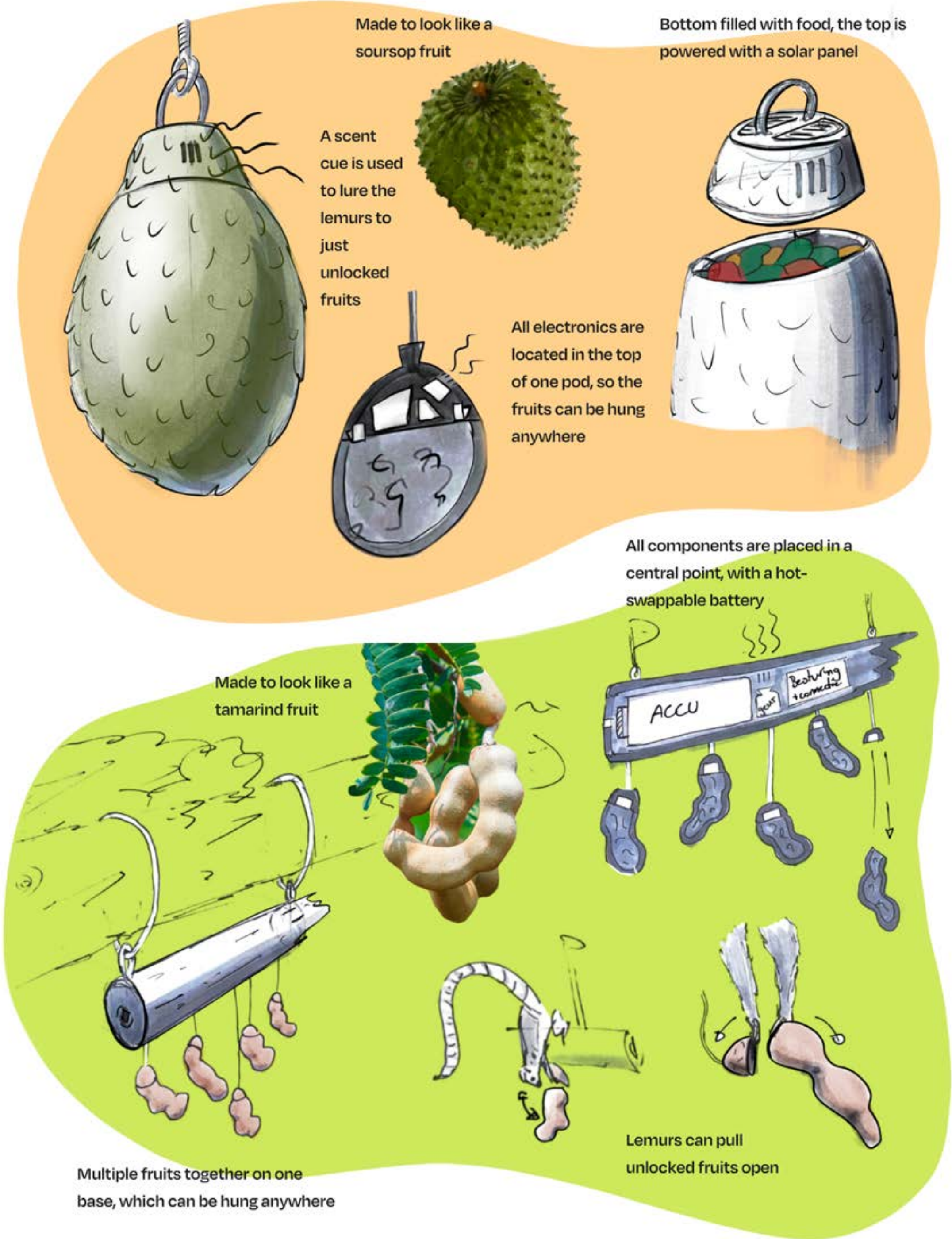


Figure 44 - Two chosen preliminary concepts

6.7 Final concept

As a result, the final concept (Figure 45) is a combination of both preliminary concepts: it uses a larger fruit pod with a door-latch-like mechanism, but multiple pods are connected to a central control area. These are hung and connected through an artificial branch. How this concept works for the lemurs and the zookeepers is shown in Figure 46 and 47.

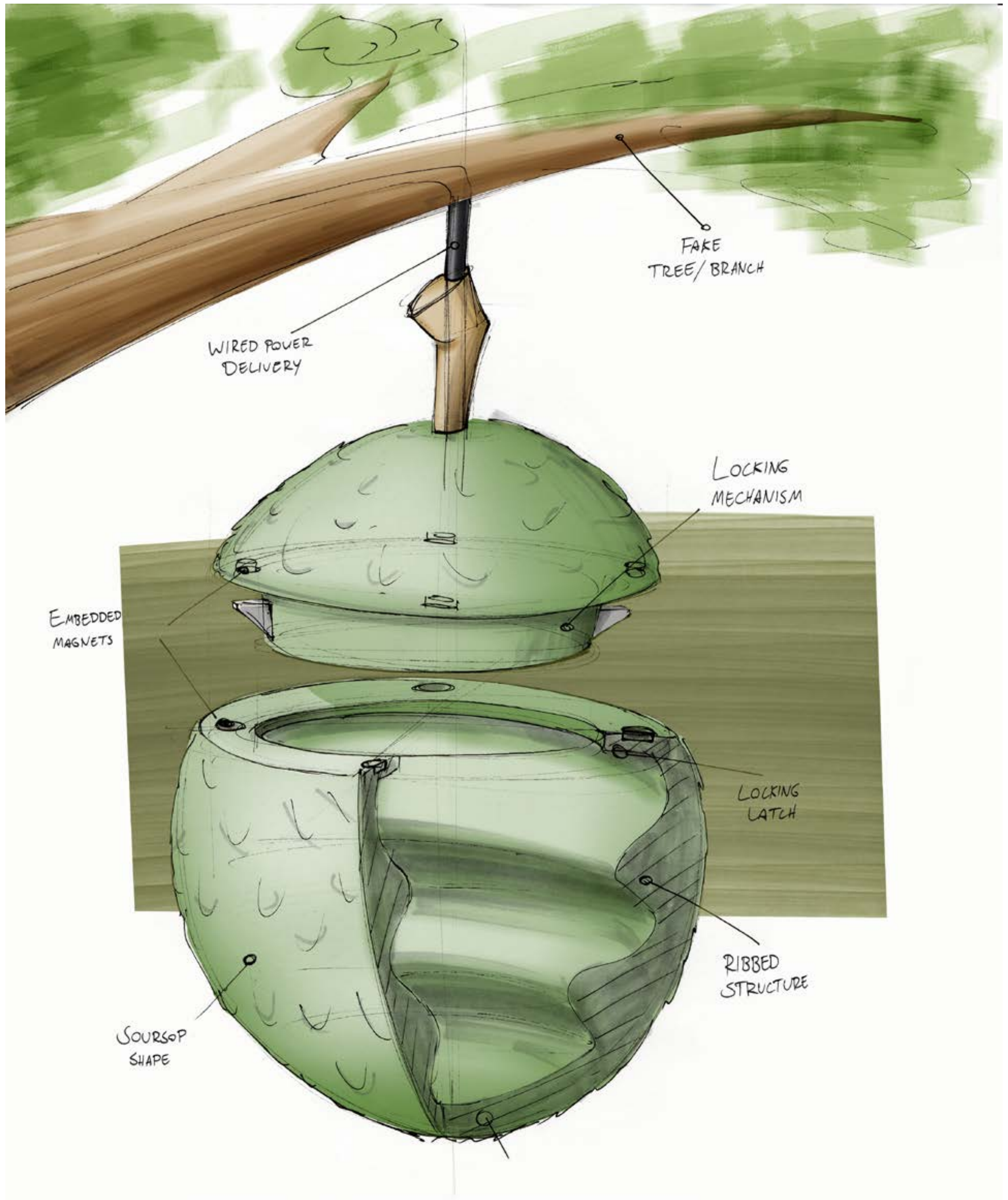


Figure 45 - Visualisation of the concept, highlighting its main aspects

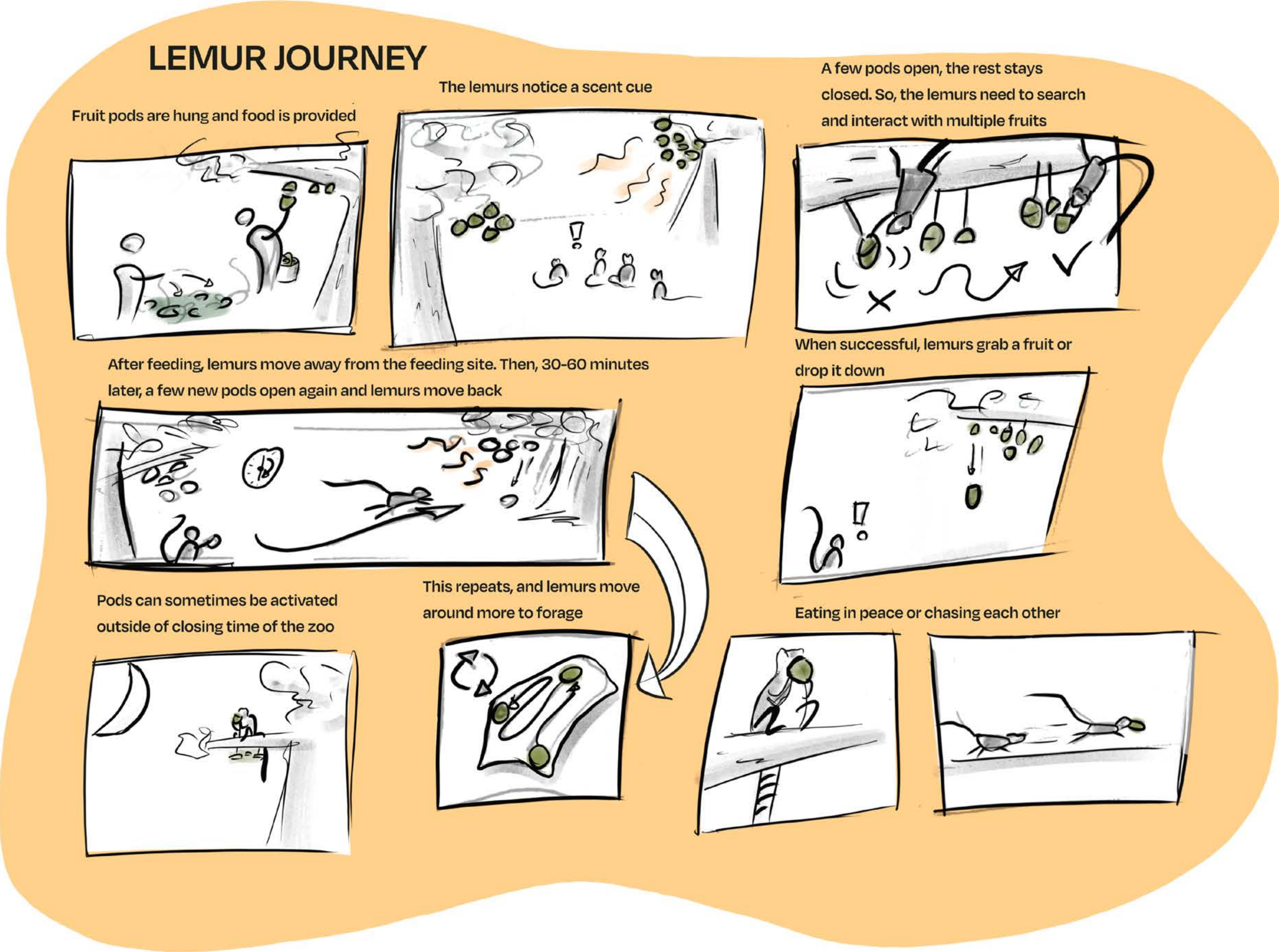


Figure 46 - User scenario point of view lemur

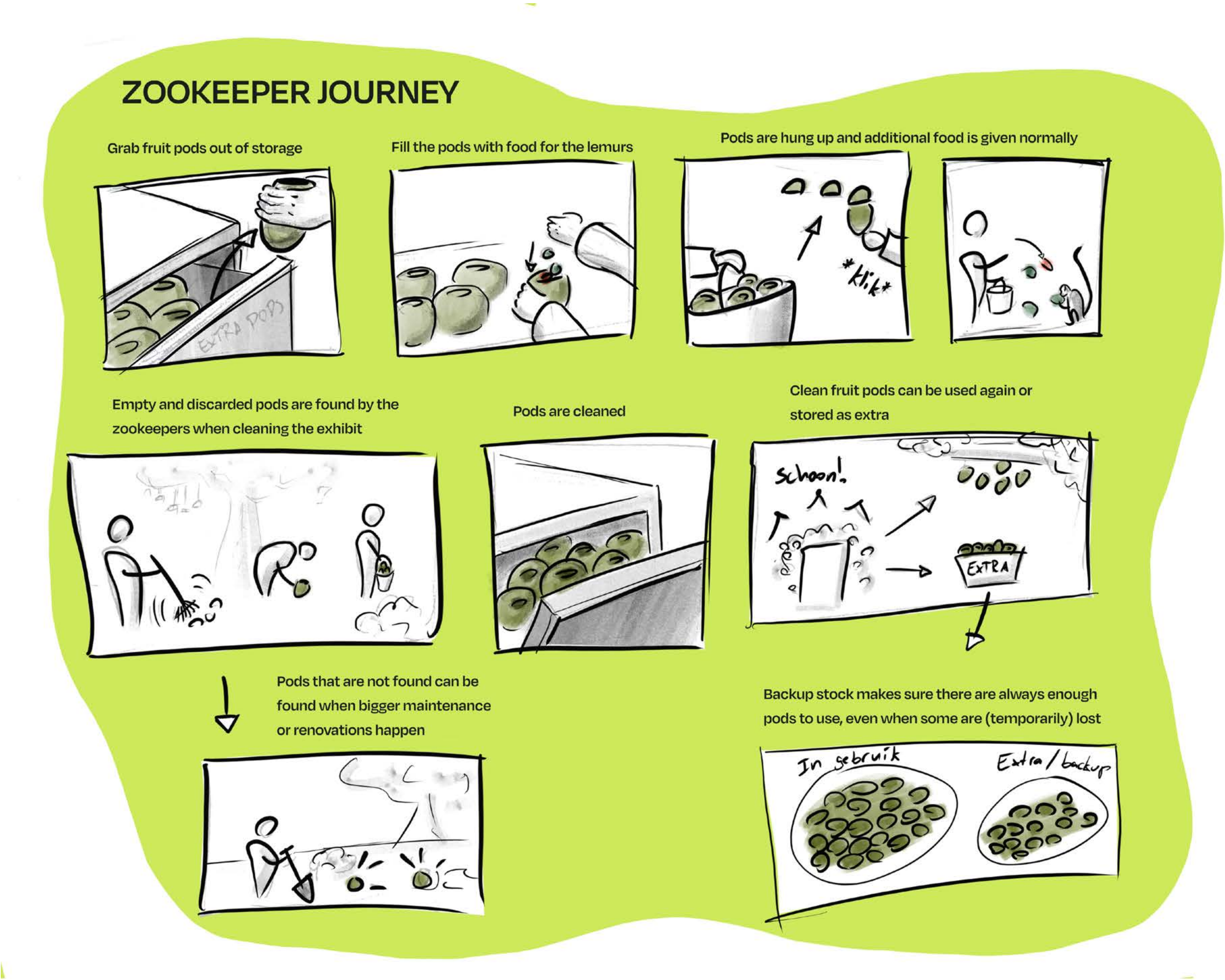


Figure 47 - User scenario point of view zookeeper

6.7.1 Fixed location

For reliability's sake and ease of use for the zookeepers, it is best to hang the fruits in a fixed location connected to the power grid. Locating this close to the viewing area would still result in increased movement for the lemurs, as they would come to gather food, eat it, and then all move away for some privacy, before moving again to the viewing area to get more food from the pods that are now unlocked. What this will look like is visualised in Figure 48.

Figure 48 - Visualisation of the fruit pods hanging from artificial tree branches at the visitor house

6.7.2 Scent

The lemurs know when new fruits are unlocked by a scent cue from a scent machine placed in the dominant wind direction, just outside the enclosure. A cue they are expected to learn, and as such, they are stimulated in a way not currently used much.

6.7.3 Fruit choice

The fruit hanging in the artificial branches is the Soursop (Annona Muricata) (Figure 49 on the next page), the choice of which is elaborated on in Appendix K4. It was chosen over tamarind because it can hold more food in its natural dimensions. Its interesting shape and South American origin can then be used to intrigue visitors and educate them on what happens when new plants are introduced into an ecosystem.

Having these fruits hang from an artificial tree improves the aesthetics of the system greatly, as this looks much better to the visitors than having multiple pods hanging around with ropes and carabiners everywhere. Additionally, it is more naturalistic to have the fruits on a single "tree" rather than scattered around.

Figure 49 - Soursop (Annona Muricata)

6.7.4 Visitors experience

Figure 50 shows how the concept will feel to the visitors. Adding a timer allows them to know when to return or whether to wait a bit to see the lemurs eat. This is possible as pod-unlocking times are programmed into the system each day by the zookeepers, and lemurs will probably react pretty quickly to the scent cue, thus al moving towards the visitor area where the pods are hung to try and be the first to get the best food. As a result, visitors are more engaged at the lemur exhibit.

6.7.5 The final stakeholder

Thus, we have ended up with a final concept that integrates all aspects researched and chosen. However, one stakeholder has not been asked yet – the troop of ring-tailed lemurs! Showing them a sketch and explaining the idea will not yield much of a result, so this naturally leads into the next chapter, which will focus on prototyping and testing the main aspects of the concept.

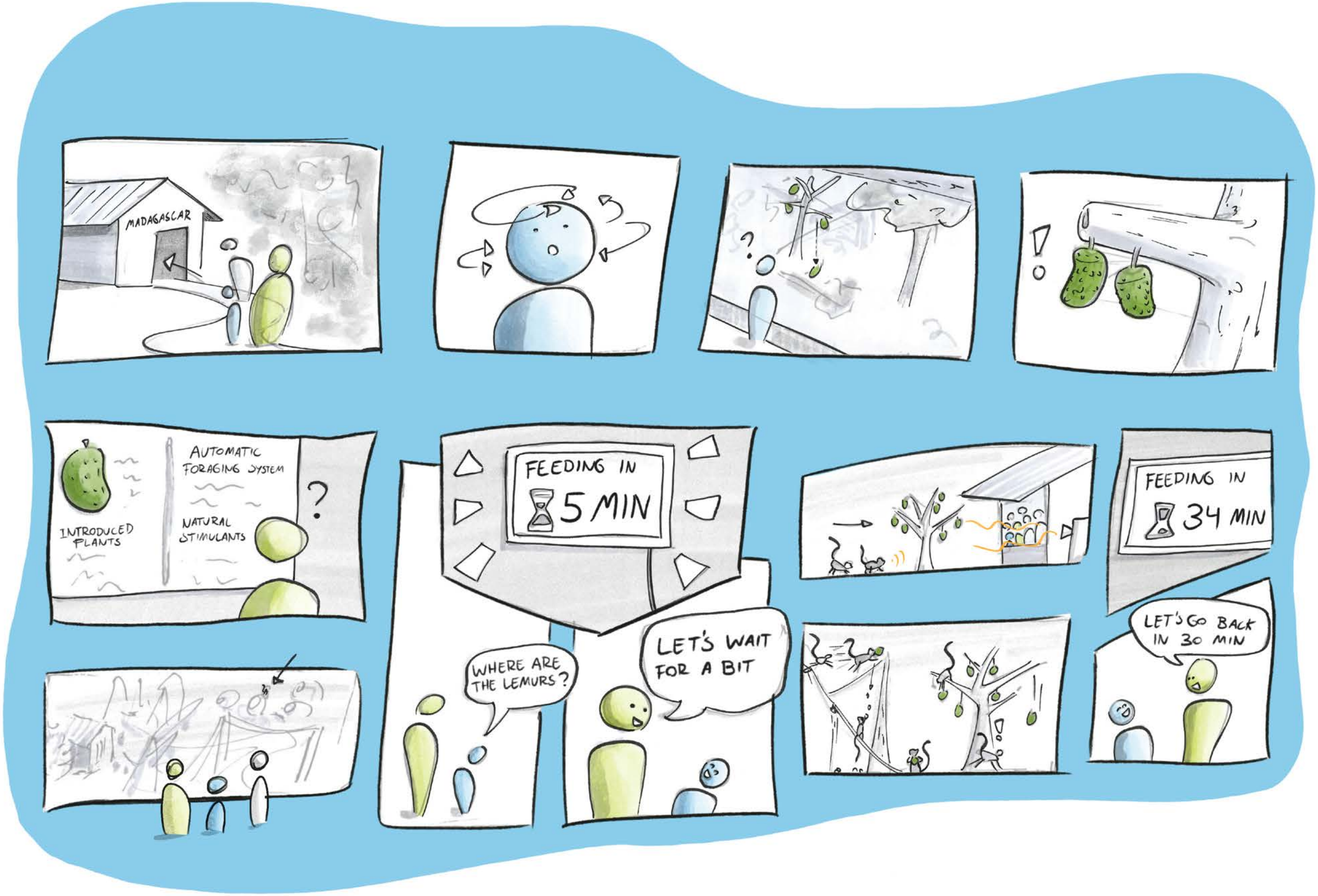


Figure 50 - User scenario point of view visitor

7. Refining

This chapter goes over the prototyping and testing of the part of the concept containing the food and the prototyping and testing of the mechanism to lock and hold the former. As a preview, these prototypes are shown below.

Its goal is to assess the effectiveness of the concept; to figure out if ring-tailed lemurs would make use of it, and if it has a positive effect on their behaviour.

As it is the most innovative part, the choice was made to focus on the working of the pod system purely, leaving how it is hung and the creation of the artificial branch out of scope, as this is something that is preferred to be designed by external parties.

7.1 Food pod interaction – prototype creation

Most of the interaction that the lemurs have with the concept is with the food pod section. To test this, a few different prototypes were created and an overview of their goals are given in Figure 51.

7.1.1 Modelling of the bottom

A Rhino Grasshopper script was created to hollow out a 3D model of the soursop fruit and generate an internal rib structure, shown in Figure 52. This is used to hold the food in when the pod hits the ground, making it more difficult for the lemurs to get the pieces out (process explained in Appendix M).

7.1.2 Creating the prototypes

Both parts are made from food-safe (and thus safe for animal contact) 3D printing plastics. The bottom part is 3D-printed using Thermoplastic Polyurethane (TPU), a rubber-like material (figure 53). The material's flexibility makes it much more durable, able to withstand being dropped from a tree and bitten by lemurs. The top part is printed using PLA, a more conventional 3D-printing material, as this is needed only for these tests to hang the bottom part on. Both parts have magnets embedded, so they snap together.

Goals magnetic prototype tests

- Gauge lemurs' interest and understanding
- Observe lemur-pod interactions
- Test durability of the pod
- Test how well the food stays inside.
- Assess usability zookeepers (filling, gathering, and cleaning)
- Added during testing: Check whether holes to allow the scent to escape improve interest

Figure 51 - Goals interaction prototypes

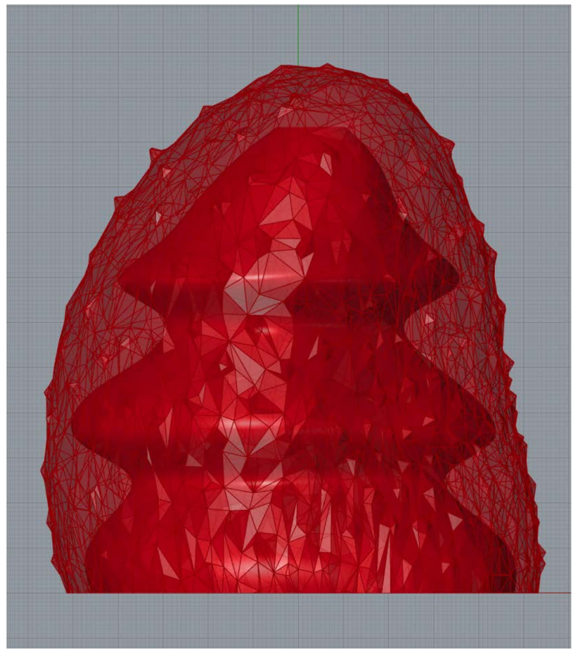


Figure 52 - Outer and inner geometry of the food pod

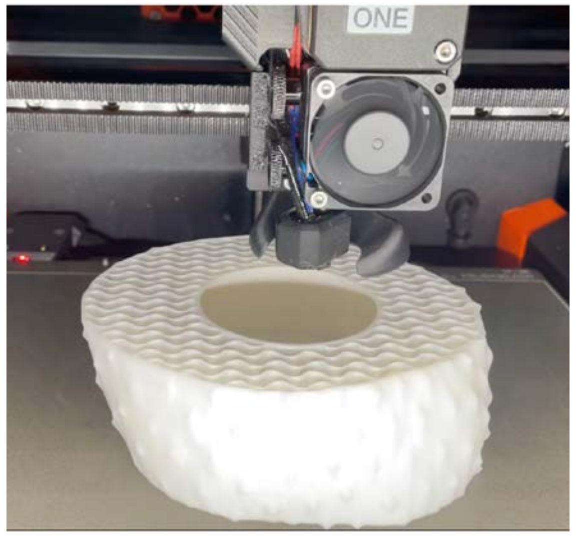


Figure 53 - Bottom part being 3D-printed in TPU

7.2 Food pod interaction - lemur tests

7.2.1 Setup

At first, one, and later two, prototypes were hung in the enclosure at the normal feeding times on the climbing structures, within reach of the lemurs (Figure 54).

The prototypes are filled with the lemurs' ordinary diet, of which some is also distributed around freely – as would be for an ordinary feeding session. During some tests, primate kibble was also added to the pods as a treat.

Seven tests were done in which the time it takes for the pod to drop and the time it takes for it to be eaten empty were observed, as well as other behaviours such as (positive and antagonistic) group interactions. The first four tests consisted of only pod A (Figure 55, right) after which pod B was added (Figure 55, left) – which is smaller and has some holes in it to check whether this would nudge the lemurs to explore and smell the prototype.

Figure 54 - (Left) Pod A hung under the roof, (Right) pod B hung along a wooden climbing structure

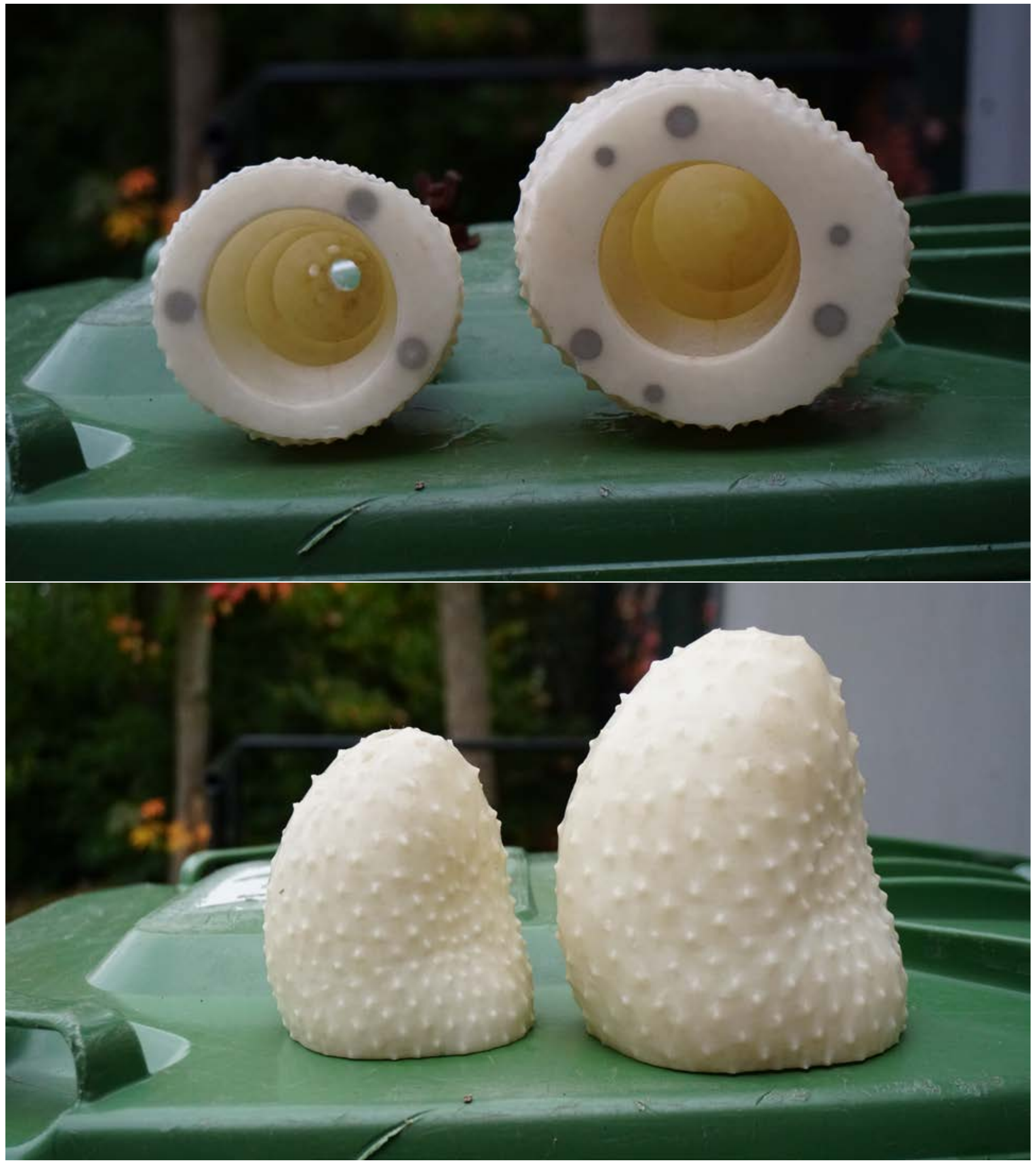


Figure 55 - Size comparison between the two pods (Pod A on the right and Pod B on the left)

7.2.2 Initial results magnetic prototype

Some impressions of the lemurs using the prototype are given in Figure 56, Figure 57, and Figure 58. Overall, the lemurs did interact with pods and the food inside. There was a higher interest in the smaller pod (B) with holes in the bottom as the lemurs got to it quicker. Lemurs could be seen putting their muzzles near the holes and trying to look inside. The smaller size may have also helped to move it around more easily.

A full overview of the results of the 7 observations is given in Appendix N.

Figure 56 - Two lemurs interacting with the first prototype

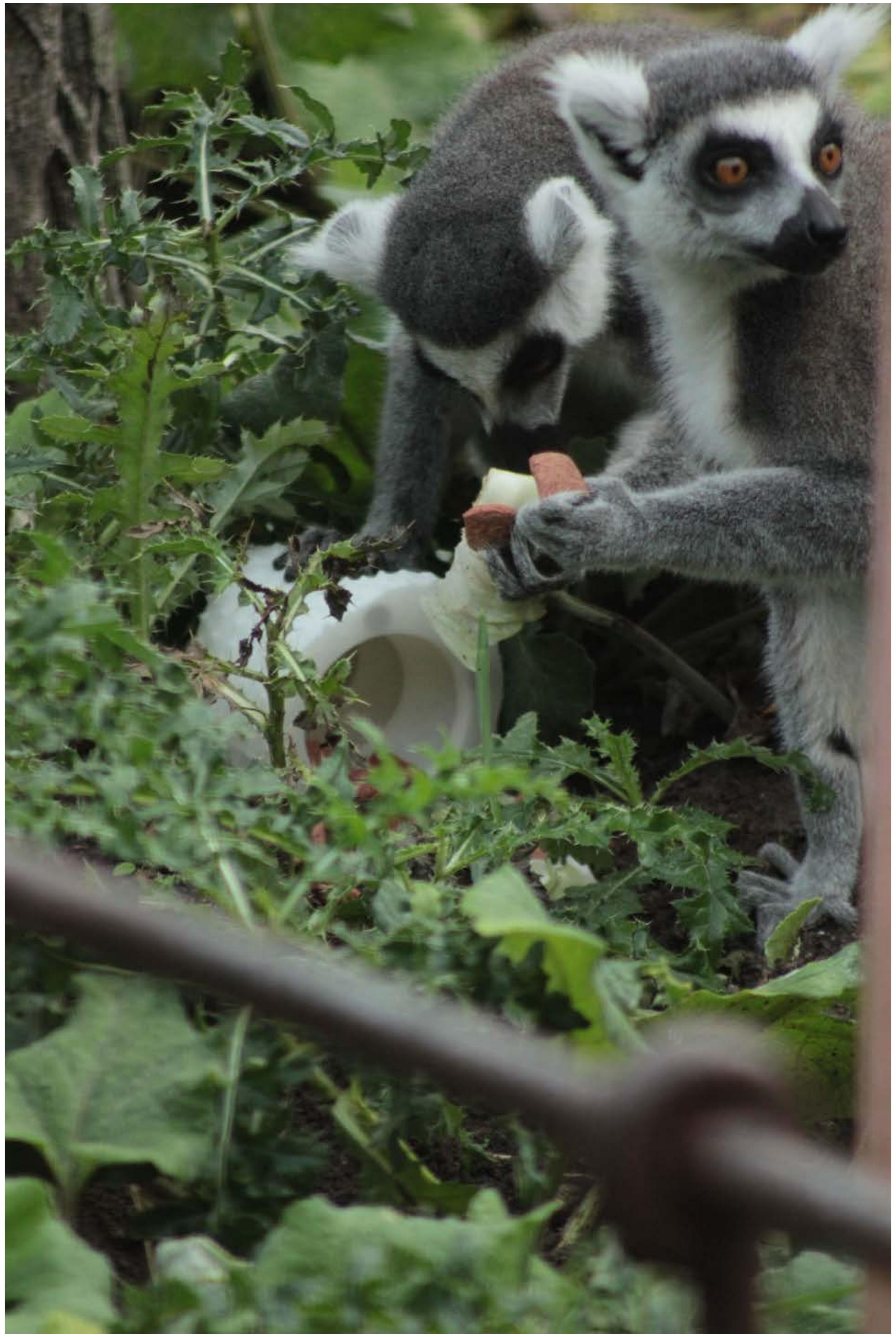


Figure 57 - Two lemurs grabbing food out of the fallen prototype B


Figure 58 - A lemur looking down at prototype B that has just dropped due to its interaction

7.2.3 Discussion: Contrast with Kong tests
In the earlier Kong toy tests of Chapter 6, lemurs moved and manipulated the objects mainly using their mouths in combination with their paws to (re-)orient the Kong. With both these prototypes, the lemurs moved them around a lot less and mostly used their paws to pull the food out. This is probably due to the size difference, with both Soursop pods being bigger than the Kongs, as well as the TPU being quite hard, thus difficult to bite into.

Also, fewer lemurs were running straightaway towards the falling pods. Some did join quickly, but it took a few seconds and resulted in fewer quarrels than dropped Kongs in the earlier tests. However, this is most likely the result of the change in group size and dynamics.

7.2.4 Durability
In each observed dropping, most vegetables stayed in the pods, after which the lemurs spent some time getting the pieces out of the pod. The TPU pod was not damaged by falling or lemurs interacting with it. After all tests, neither pod suffered any visible damage, and after a month of use, both are still intact with no clear damage (see Figure 55, these pods were used multiple times per day for a month).

7.2.5 Zookeeper feedback
It was quite difficult to hang pod A up in the intended correct position (it could be hung in 3 orientations, only one "looking" correct); pod B had a different spacing of the magnets, resulting in it only snapping shut in the correct orientation – an improvement but still easy to miss. A use cue is needed (Figure 59).

In use, the pods stayed quite clean, which made it possible to use them multiple times a day without needing to clean (Figure 60). Rinsing the pods under the faucet was deemed easy and adequate.

Figure 60 - Pod B and A retrieved after use by the lemurs

Figure 59 - Pod wrongly attached

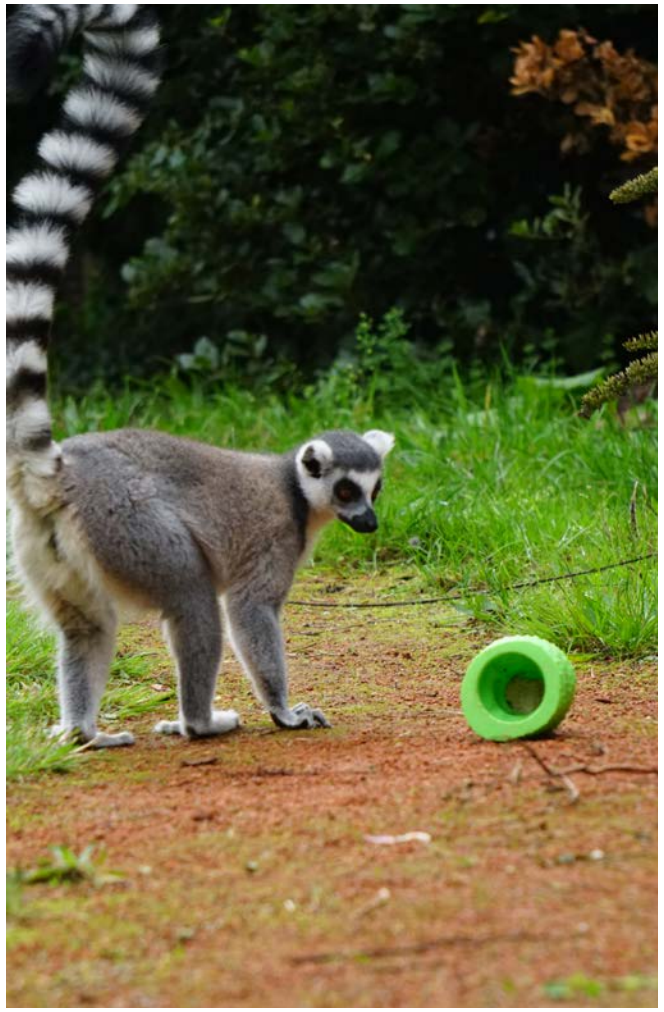


Figure 61 - Piece of corn stuck in the pod

7.2.6 Long-term observations
After my observations, zookeepers kept using both pods for about a month, in which they found that the lemurs tended to use both pods each time, as they got more used to them. Overall, the zookeepers preferred the bigger pod A. Food often got stuck at the bottom of pod B (as seen in Figure 61) and the holes for scent ended up collecting grime and were difficult to clean. Lemurs would also pull down the smaller pod too easily – sometimes directly after it was hung up, meaning stronger magnets are needed to make it more challenging.

7.2.7 Conclusion
The initial results showed a preference for pod B over pod A by the lemurs, as they would always go to that one first. Lemurs would try to get to the food through its holes, manoeuvring the pod a lot and resulting in it falling.

After using the prototypes for a prolonged time, however, zookeepers gave a clear preference for pod A, as pod B was deemed too small and annoying to work with. They perceived little differences in use of both pods by the lemurs.

As a result, it was chosen to make the final prototype's size something in between pod A and pod B.

7.3 Locking mechanism prototype

The other essential part of the design is its locking mechanism, which is developed in this chapter.

After steps of cardboard testing, 3D-printing, burning said 3D-prints, switching the approach, then destroying a servo motor and then calculating how to go about not destroying servo motors (all of which are highlighted in Appendix O), a prototype that reliably works was created (Figure 62 and 63).

7.3.1 Mechanism

The mechanism uses a cam on a servomotor to push two latches to unlock the food pod. When the servo turns back, the springs push the latches outward, allowing the bottom to be clicked into place but prohibiting it from dropping (Figure 64).

7.3.2 Wireless prototype

After some more fine-tuning the first testing prototype was made (Figure 65). It is powered by a sufficiently powerful power bank and controlled wirelessly using an ESP32 microcontroller that is connected over a WIFI hotspot to a mobile app (Appendix P).

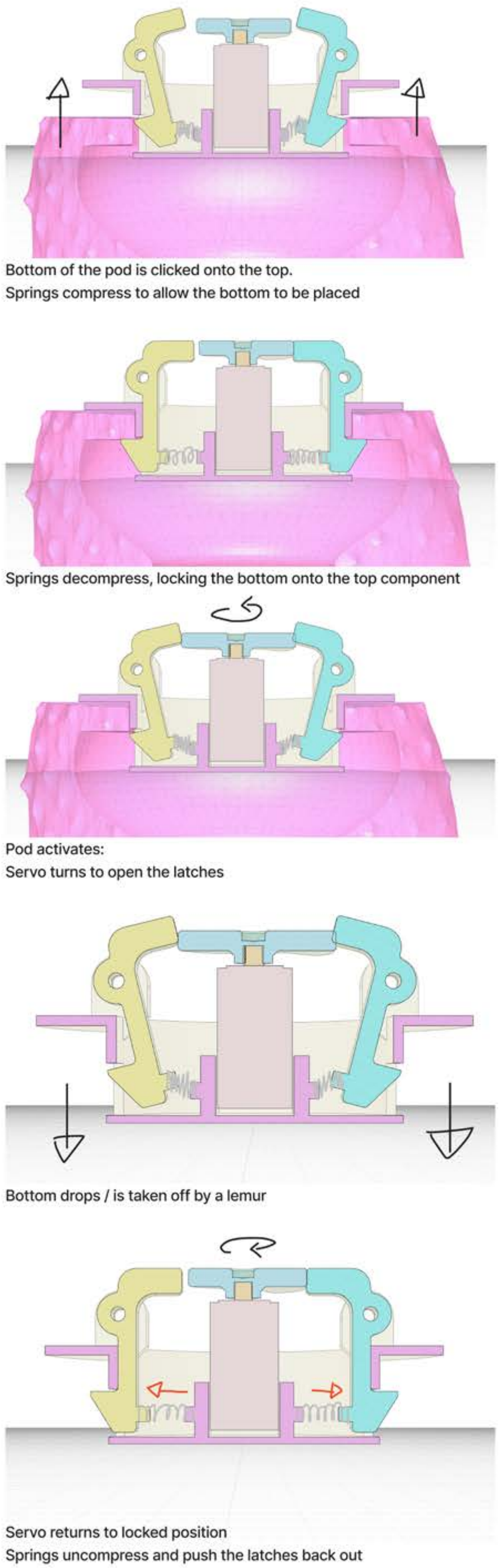


Figure 64 - Visualisation of how the mechanism works

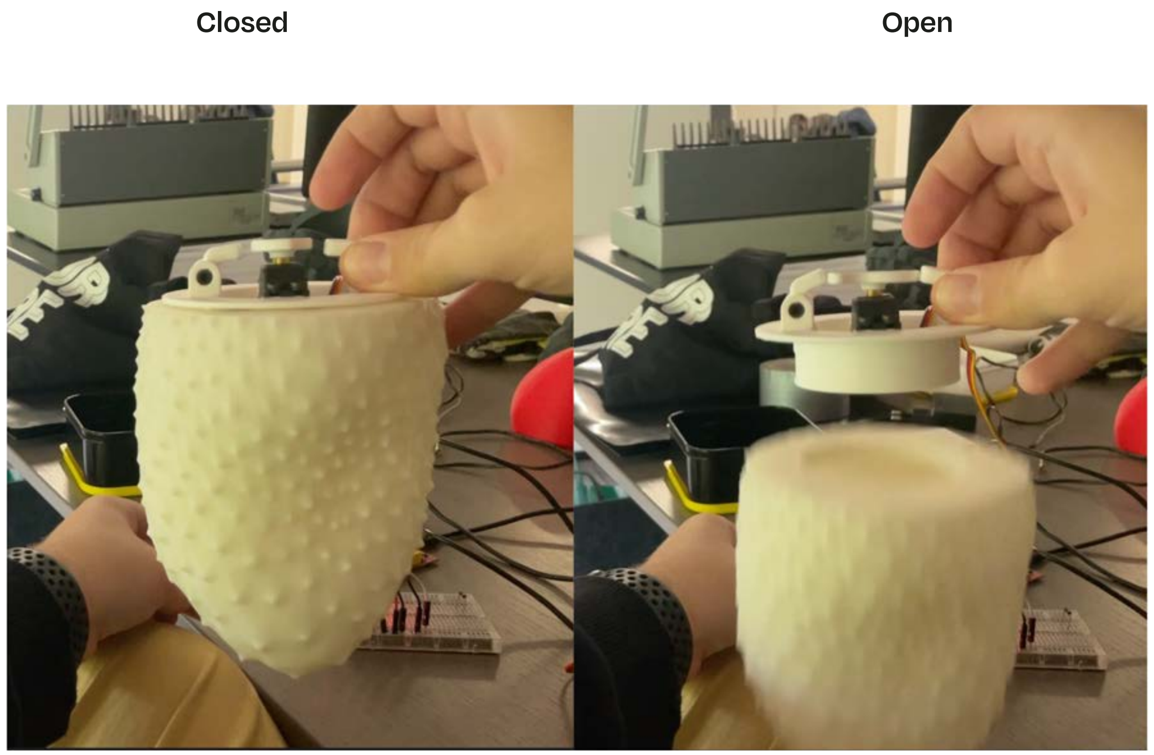


Figure 62 - Photo of an early prototype where the food pod hangs on the locked mechanism (left) and falls after the mechanism is activated (right). This early design sadly killed the servo during a short stresstest

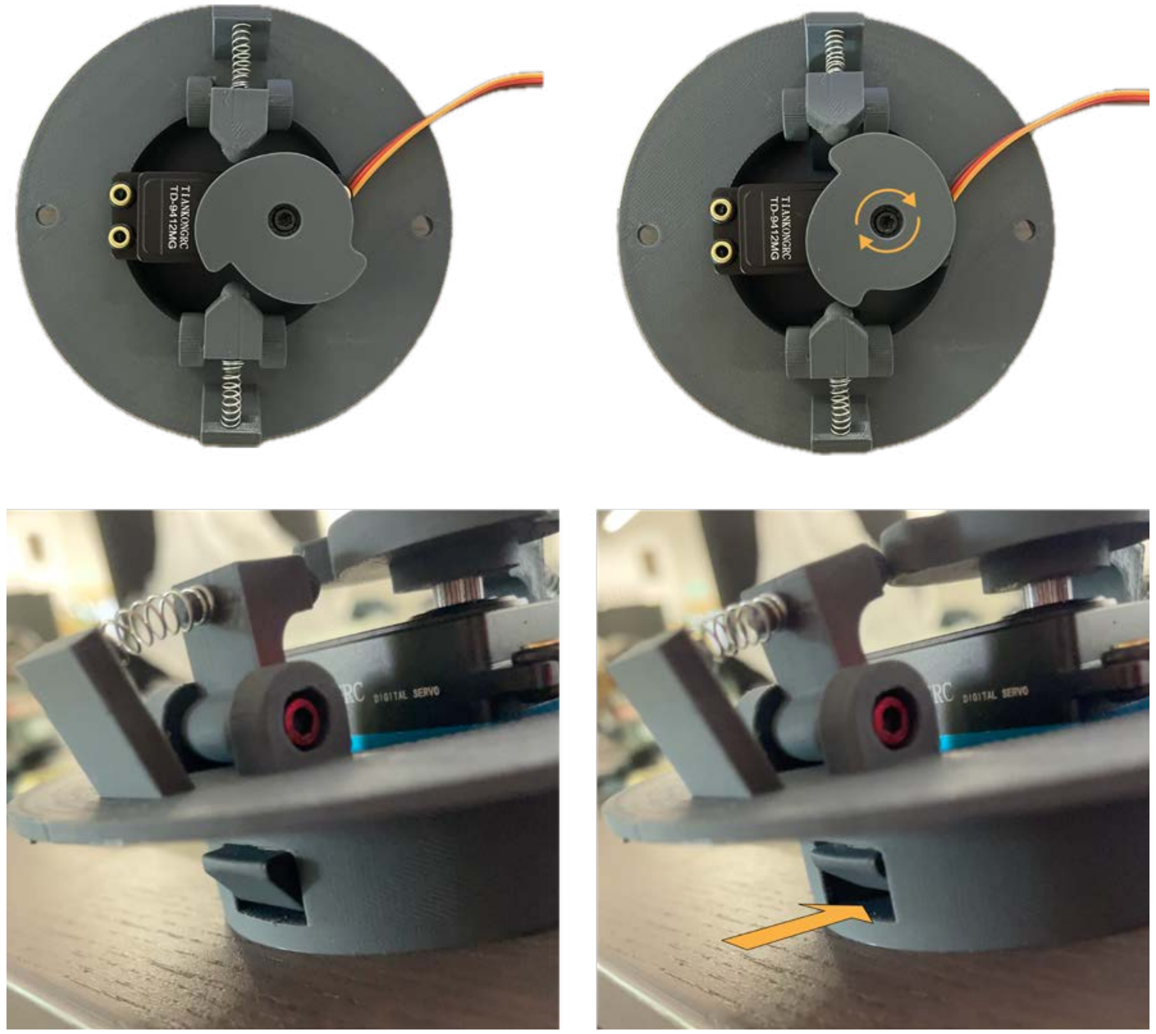


Figure 63 - Top and side view of the prototype actuating the latches

Figure 65 - Lemur with the powerbank powered prototype as it was locked

7.4 Locking mechanism tests

7.4.1 setup

This prototype was consequently hung twice in the lemur enclosure to see whether it would hold up to the lemur's abuse and stay locked, and whether they would return to the fruit after some time after failing the first time.

7.4.2 Testing

After initial interest while the system was locked, the lemurs could not pull the fruit loose and went away to feed on the conventionally provided food. When they returned after 20-30 minutes, lemurs found the prototype unlocked and pulled the pod off after a few tries. (Figure 66)

7.4.3 Results

Overall, the lemurs reacted as expected to the prototype: At first, they interacted with it for a short while, looking at how to open it but it doesn't open (since it is locked). Then, they go away to do other stuff and eat the food spread around the exhibit.

When they are away the pod is unlocked. The servo can be heard, yet lemurs do not react to it (although they might in the future). After some time, the lemurs start a new round of exploring the pod and interacting with it. After a few tries it falls.

7.5 Improvements

As a result of the pod interaction tests and the tests with the locking mechanism, as well as conversations with the zookeepers, multiple things on which the design can improve were identified. These are highlighted in Figure 67.

Prototype improvements

- Ensure food does not get stuck too hard by creating an in-between size with less steep internal ribs
- Improve cleanability by removing holes in the pod
- Mark the orientation in which the pod needs to be clicked on

Figure 67 - Improvements design

Figure 66 - Lemur removing the pod from the prototype

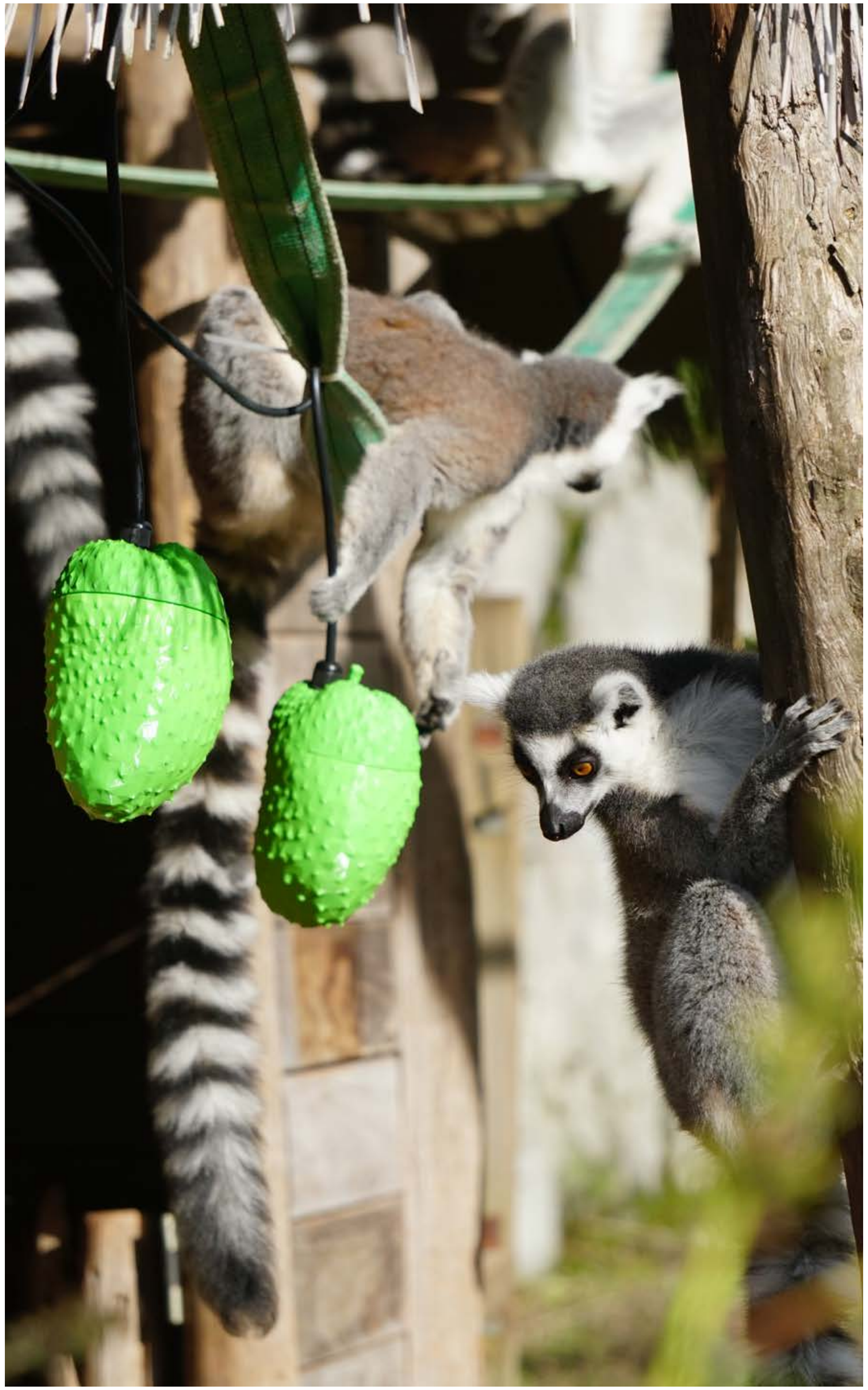


Figure 68 - Final prototype in lemur exhibit

7.6 Final prototype

The final iteration of the prototype then aimed to look more like the intended design (see Figure 68) – no big box on top with a power bank, but a full fruit with a wire connected to a box where the power and control components sit. As well as solving the improvements mentioned in Chapter 7.5.

The main goals of this prototype are shown in Figure 69.

7.6.1 Creation

After multiple iterations, the mechanism was able to fit reliably in the top of the soursop (figure 70), allowing a cable to go in through a cable gland (figure 71) which connects the mechanism to the ESP32 microcontroller and a power source (more on these iterations in appendix O and the power connection in appendix P). 2 servos were proven to work at the same time when connected to a power outlet. Still, for flexibility in the animal exhibit, both

Goals final prototype

- Optimise the internals to fit everything in a fruit shape
- Test the prototype connected to the power grid
- Test controlling multiple (2) servos at the same time
- Test how good the increased size is for lemurs to handle and food to fit inside without getting stuck
- Create something presentable as final design

Figure 69 - Main goals final prototype

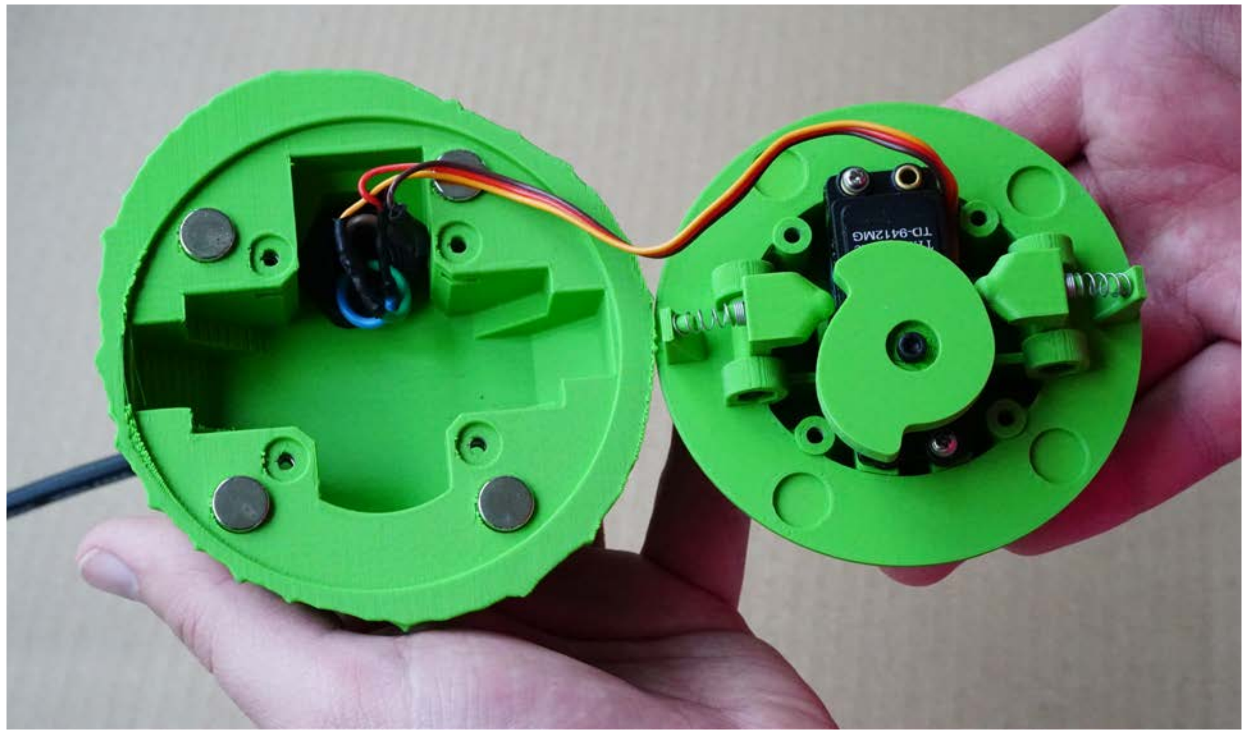


Figure 70 - Final prototype inside

Figure 71 - Cable through cable gland

Figure 72 - Two soursop prototypes connected to an esp32 and power bank

pods were connected to a power bank (Figure 72). As a result, this prototype now resembles a fruit in its entirety.

In this prototype, instead of 3, four magnets were used (since zookeepers observed the magnetic prototypes being pulled off too quickly), and the inside geometry of the fruit pod was changed to generate based on the shape of the fruit model imported, optimising the internal space (briefly mentioned at the end of appendix M.1).

7.6.2 Tests

Four tests were conducted with the two soursop pods. For the final 2 tests, one pod with 3 magnets instead of 4 was used, and a small hole was added to the bottom to see if this would increase their interest. Three of the tests were conducted outside, and the final one inside, with tamarind given in the pods as a more desirable food in the final two tests.

7.6.3 Results

Outside, lemurs did not have much interest in the fruit pods. Inside there was much more interest in both pods, which can be explained by it being a more comfortable temperature for them inside than the Dutch autumn weather (around 15ºC). It did not seem to matter if there was a hole in the bottom – the only difference was that lemurs tried to access the food from there. During the inside test, lemurs interacted with the pods at different times, moving away to feed or relax, then returning. This went on multiple times.
When the pods were unlocked, lemurs were unable to pull them off, no matter how hard they pulled (Figure 73). Even the one with 3 magnets, and the ones that were hung more loosely by rotating it so that only two magnets are connected. Only one fruit (which was rotated to hang loose) came off. This was seemingly done accidentally when jumping down (Figure 74).

7.6.4 Conclusion

Overall, these tests did not yield as much results as hoped mainly due to the weather. The main conclusion, however, is that with the number of magnets used, it was too difficult for the lemurs to remove the food container. At least inside, there was once again sustained interest from the lemurs in the same ways as observed before – interacting, moving away, returning to interact again.
As the internal space is a bit bigger, food seemed to not get stuck in the pod as easily. The lemurs did not seem to mind the size change, grabbing food out of it the same way as before.

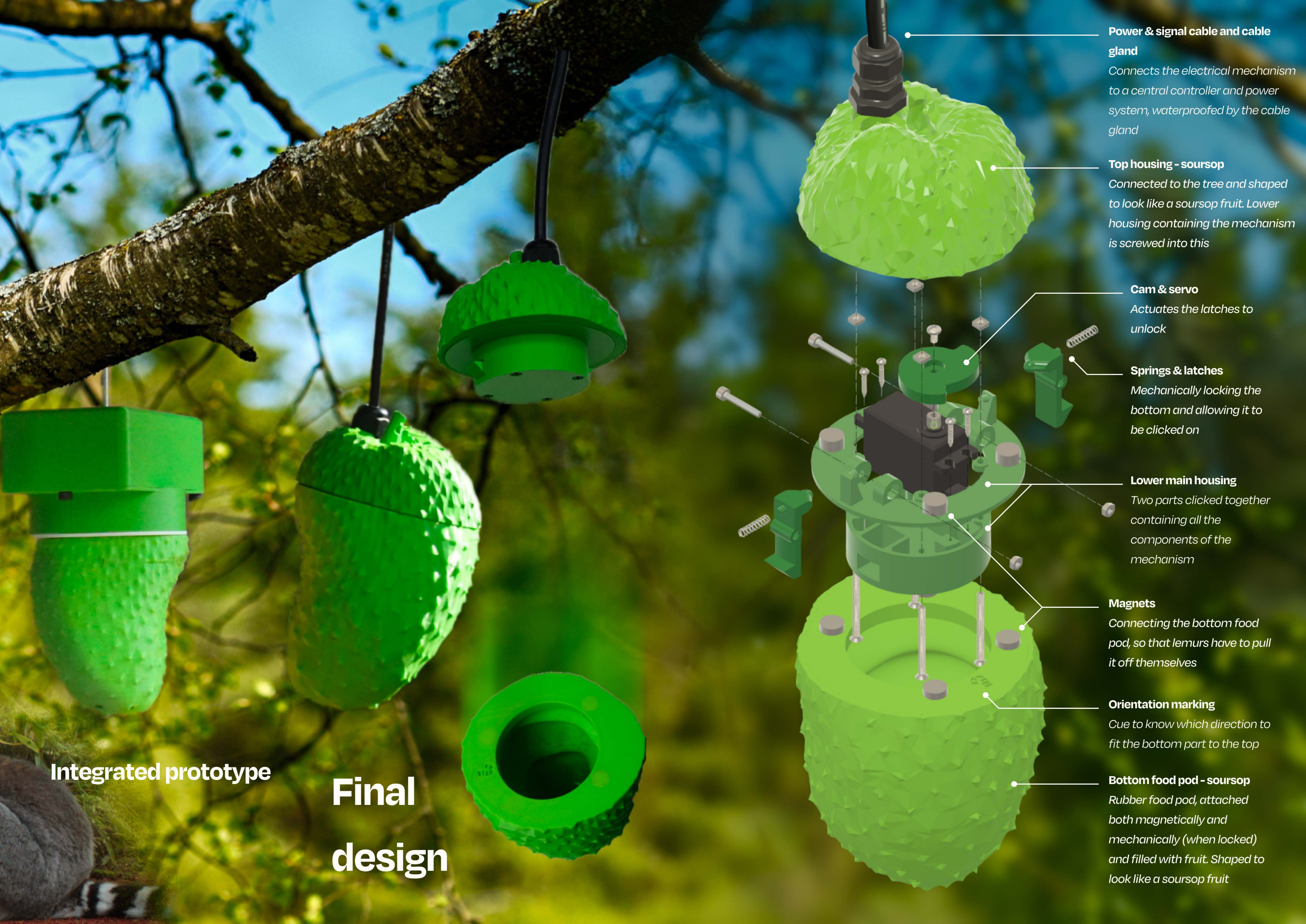
7.6.5 Discussion: magnet strength

One reason lemurs were unable to pull the fruit pods loose was that the magnets used in these final prototypes were stronger than those in earlier prototypes, as they came from a different supplier. Another reason might be the added friction of the compartment containing the locking mechanism that is placed partly inside the food container.

Figure 73 - Lemurs pulling very hard

Figure 74 - Lemur dropkicking pod


Exploratory tests
Proof of concept prototyping
Concept sketching



Integrated prototype
Final design
Power & signal cable and cable gland
Connects the electrical mechanism to a central controller and power system, waterproofed by the cable gland
Top housing - soursop
Connected to the tree and shaped to look like a soursop fruit. Lower housing containing the mechanism is screwed into this
Cam & servo
Actuates the latches to unlock
Springs & latches
Mechanically locking the bottom and allowing it to be clicked on
Lower main housing
Two parts clicked together containing all the components of the mechanism
Magnets
Connecting the bottom food pod, so that lemurs have to pull it off themselves
Orientation marking
Cue to know which direction to fit the bottom part to the top
Bottom food pod - soursop
Rubber food pod, attached both magnetically and mechanically (when locked) and filled with fruit. Shaped to look like a soursop fruit

8. Final design

We started this project off with the goal to create a naturalistic device to stimulate and engage captive ring-tailed lemurs. And now at the end of this project, a system of artificial fruits has been designed as a result.

On the previous pages, an overview is given of the milestone steps in this design process, finishing ending with the final design and its exploded view showing all its components. But before talking about that, we first need to understand the specifics of this final design.

8.1 Main presentation

Presented in this report is an electronically controlled foraging system specifically tailored to ring-tailed lemurs, which is visualised in Figure 75.

8.1.1 Foraging behaviour

It consists of multiple artificial fruits filled with food that are locked so lemurs cannot access the food, and unlocked at different times, which they are notified of by a scent cue provided by a scent machine at the edge of the exhibit. As a result, lemurs return multiple times throughout the day to grab the food, and since unlocked pods stay hanging, the lemurs need to come close and pull on all of them to find the ones that are unlocked. This all increases the time spent actively foraging and the distance they move.

The system is meant as a supplement to their normal feeding regime, which can be used every day. As such, lemurs can gather food in more ways than before, thus are more stimulated.

These artificial fruits hang in an artificial tree branch, which gives the lemurs increased opportunities to forage above ground. Looking for fruits in trees is a big part of natural foraging behaviour; as such, the design simulating this can yield positive welfare results.

8.1.2 Soursop fruits

These fruits hang from a large artificial branch. They are shaped like a fruit ring-tailed lemurs would eat in the wild: the soursop (Annona Muricata), a species introduced to Madagascar with a unique, prickly exterior.

8.1.3 Zoo visitors

This exotic plant can intrigue visitors, which then gives the zoo an opportunity to educate them about exotic nature and the welfare enhancement of animals. Besides, lemurs spending more time in the branches close to visitors enhances the experience of the latter greatly.

They are hung on artificial branches emerging from outside the view of the visitors. Some holes are added in these branches to stick twigs of browse feed into.

8.1.4 Usage

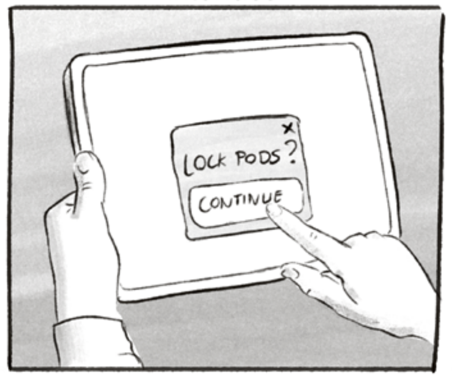
The use of this foraging system is shown in the scenario in figure 76.

Figure 75 - Visualisation of the final design and its interactions with the lemurs, zookeepers en visitors

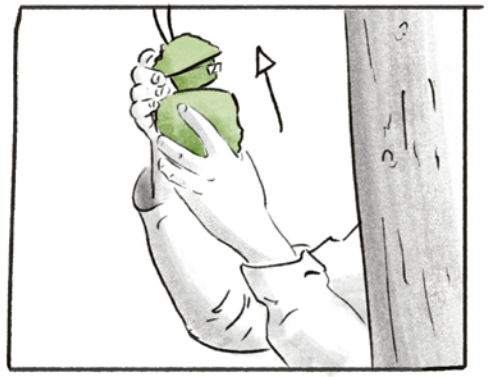
Final design usage journey

Zookeeper grabs food pods and fills them with food

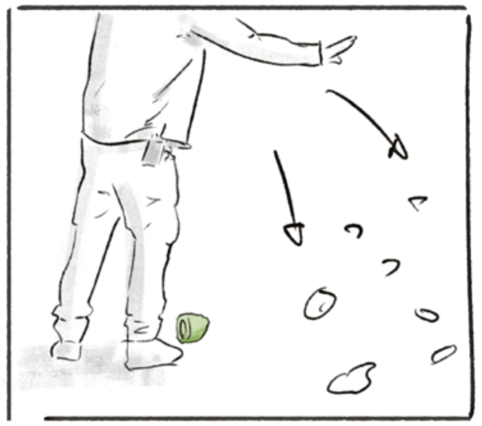
Resets all the pods to their locked position using tablet interface



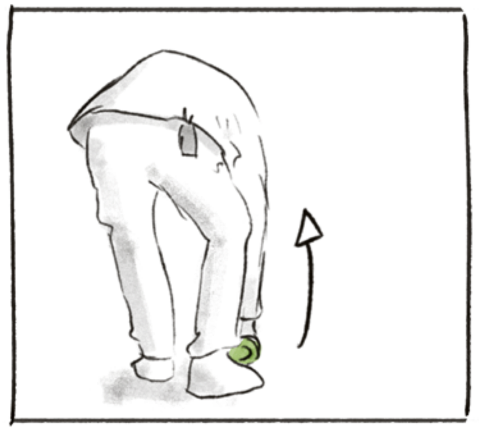
Zookeeper then enters the lemur enclosure and clicks the food pods onto their bases



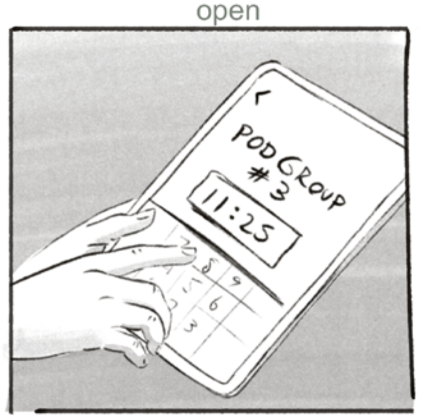
At the same time, the zookeepers scatters around some food



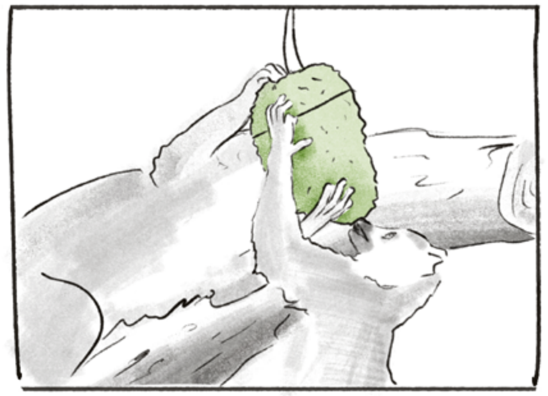
After which they pick up the empty, laid around pods of the previous day and wash them



Then, the zookeeper inputs the times at which the pods should open



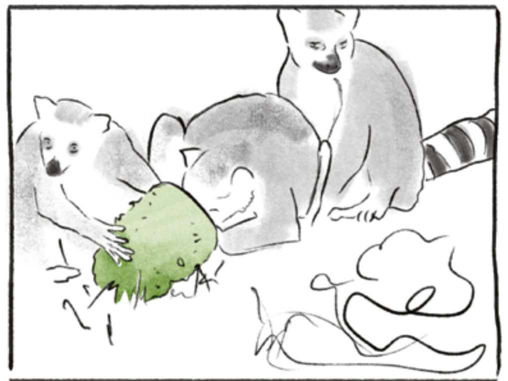
After the zookeeper is gone, lemurs come to inspect the fruits but are unable to remove one



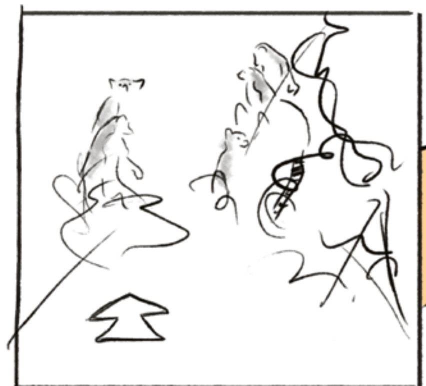
Lemurs then move away to go about their day, until they smell something

When they return to the pods, the lemurs find out some of them can be pulled off

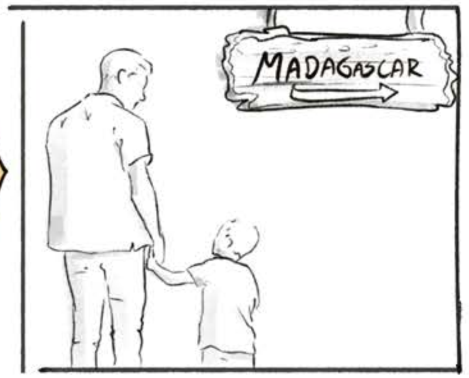
Other lemurs join and they eat the food out of the pod



When they are done, the lemurs move away to relax at the back of the exhibit



Visitors come to the lemur exhibit

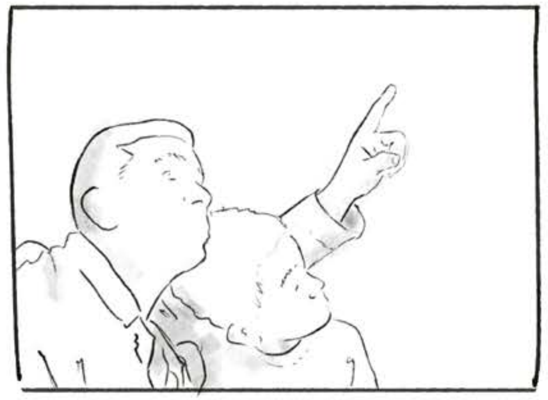


but they do not see any animals

but they do notice it says that the lemurs are fed in a few minutes and decide to wait

Shortly after, lemurs smell something again and approach the fruits again, which are hung closely the visitors

Here, they forage again and the visitors enjoy watching



Later in the day, the same happens again

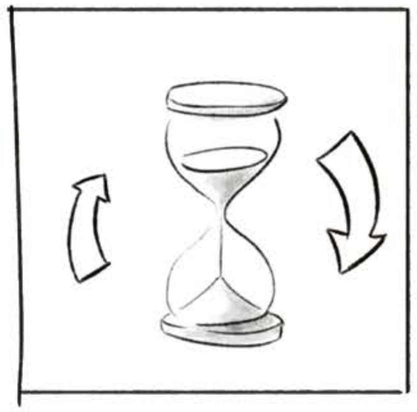


Figure 76 - Usage scenario of the final design

8.2 System usage - specfics

Because the use of many pods has not been tested, the following usage scenario is based primarily on expectations and conversations with the zookeepers.

8.2.1 Number of artificial fruits needed

2 branches are hung in the enclosure, and on each hang around 8 soursops. This should be great for a bigger ring-tailed lemur troop of around 15, since one fruit fits around the amount of 1 to 1 and a half lemur's food intake for one feeding round, of which there are three per day.

Food is put in the food pods in the morning, and they are hung up during the first feeding round. At the same moment, fruit pods used the previous day are collected from the ground and put in the dishwasher.

8.2.2 Timing of the fruit unlocks

Shortly after eating the scattered food, 2 or 3 pods are unlocked at the same time to limit fighting between the lemurs. If the troop is restless, more are unlocked simultaneously.

As might already seem clear from this, it is essential that zookeepers have full control over when which pods are unlocked. At first, it is important to test the effectiveness of different timings and amounts unlocked simultaneously, the lemurs' reactions to them, and whether all individuals receive sufficient food intake. And after the system is better explored, it is to keep the peace in the lemur troop.

8.2.3 Zookeeper handling

As explained, zookeepers have much control over the timing of the system. This is done by setting a time per pod for when it unlocks on a tablet that is connected to the same local network. Through this same interface, the pods can be reset to their locked mode every morning.

The other main tasks of zookeepers consist of gathering the empty pods strewn around the enclosure by the lemurs and cleaning them. In the mornings, fresh pods are filled with vegetables and they can all be clicked onto their bases during the first round of feeding.

A small lemur tail shaped marking to identify the orientation of the bottom part to the top was added to make attaching them correctly easier (Figure 77).

Figure 77 - Marking to identfy the correct orientation

8.3 Materialisation & manufacturability

The bottom part of the soursop is cast from slightly flexible (shore 40) silicone rubber – a material used in many animal products (explained in more detail in Appendix Q1). During his casting process, magnets are embedded into the rubber part. The top part and its internal components are 3D-printed from ASA plastic because of its strength and its durability in the outdoors conditions. These parts underwent multiple iterations to optimise their manufacturability using a 3D printer, which is shown in Appendix Q2)

8.4 Assembly

Figure 78 shows all the components that go into one soursop pod. They have been designed to all slot together and be connected by 4 screws that go all the way through. As a result, everything should stay together very well when hung in the animal enclosure. Unscrewing these 4 screws then allows direct access to the servo and its cable connections (if something electrical were to fail, this is it) and the latches and their springs (where mechanical failure is expected to be most likely – facilitating relatively quick repair.

Appendix R gives an overview of all components needed and guidelines on how to print them, as well as a detailed assembly guide.

8.5 Costs

As there is a central system to which multiple pods are connected, the cost of just one pod depends on multiple other factors. Appendix S shows an entire overview of this for the system in the context of this project in Rotterdam Zoo.

As can be seen, without the system around it, the price per pod is around €35. This includes the entire top (including servo and fasteners), bottom, and average wear and tear of the 3D printers.

For the system to function optimally, twice the number of bottom parts is needed. One group can be in use in the enclosure, while the other batch (that had been used the previous day) is being cleaned. Since some will inevitably get lost in the enclosure, some spares are needed as well. This means that for 10 pods in use, one would have 10 top locking mechanism and in total 24 rubber bottom parts, giving a total of €500.

Each servo is then controlled by a microcontroller and PWM servo controller and powered by a high current power supply. Adding the scent machine and a tablet to control the opening times of the pods on, around €600 will be added. This excludes the cost of building a branch system for the pods to hang from and a dishwasher (around €1000) or other cleaning solution for the pods (around €200), as these costs are very subject to change.

Assuming two sets of 10 fruits, and using a simple glasswasher as the cleaning solution, the total comes up to around €1800.

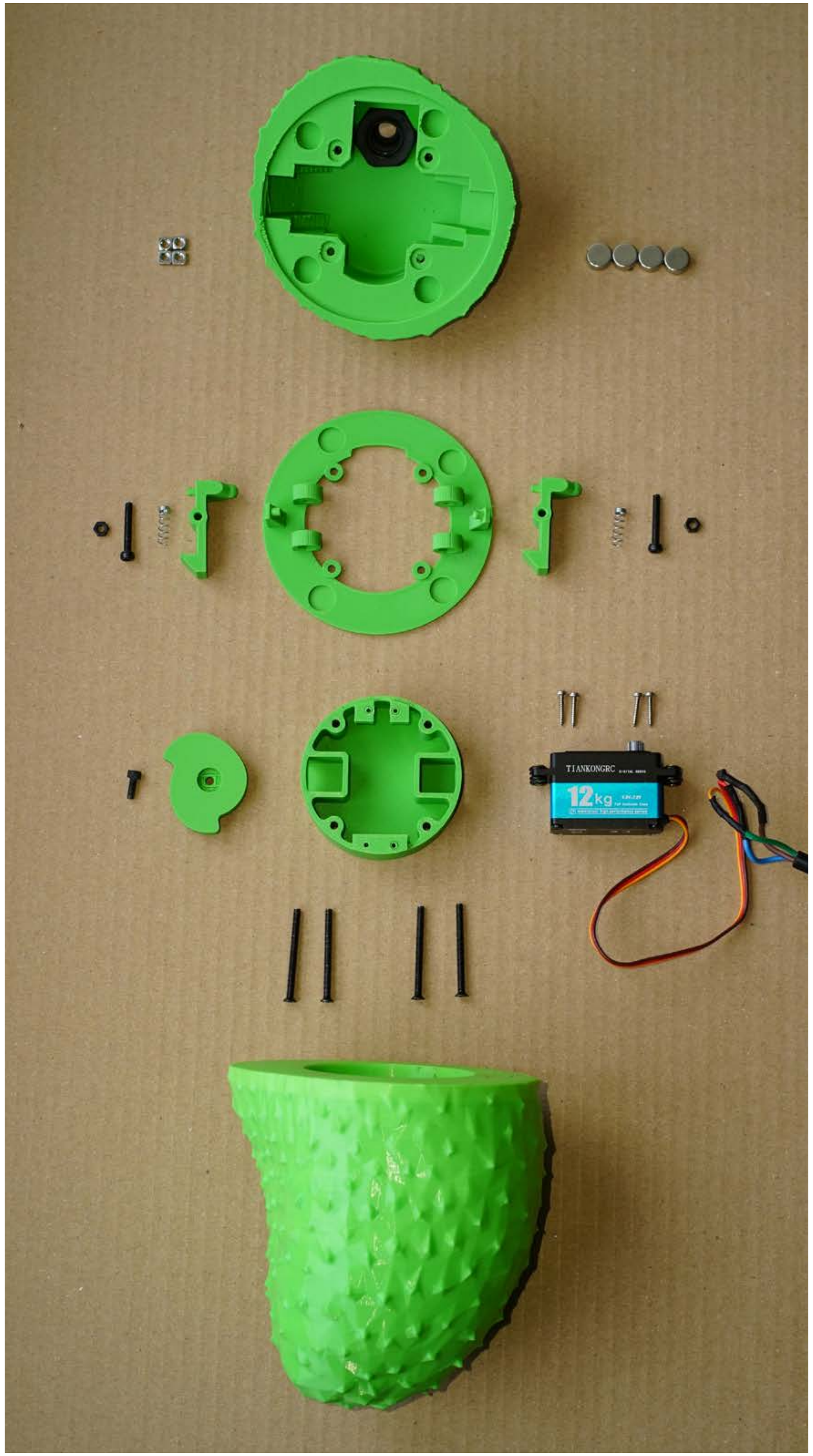


Figure 78 - Knolled picture of the final design

Figure 79 - Final design

9. Discussion of the design

9.1 Goals and requirements

Figure 80 reprises the design goals of this project as they were phrased in Chapter 6. Overall, the final design reaches these goals, which shall be elaborated on in the next section.

The final design also meets most requirements, as can be seen in its assessment in Appendix E.

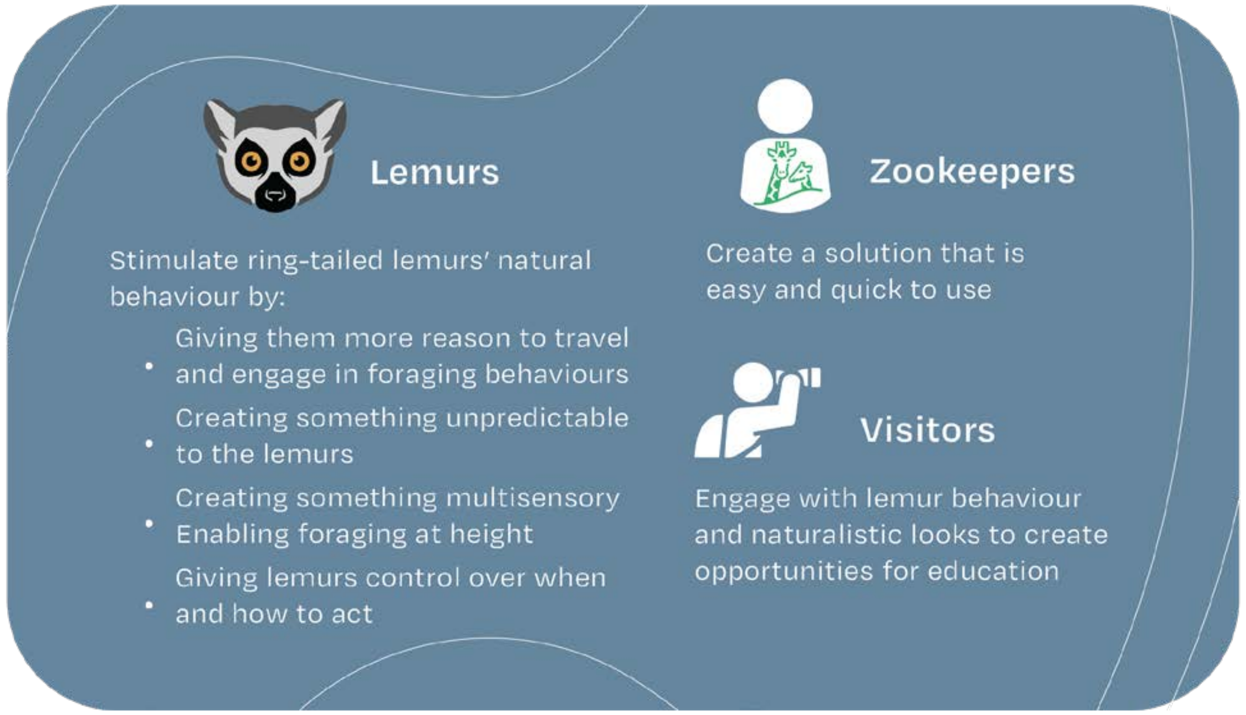


Figure 80 - Design goals

9.2 Overall assessment of the design - Desirability

9.2.1 Stimulating lemurs

Over the course of this project, the lemurs have shown they are engaged with the food pods and keep returning and trying when they do not open at first. As such, they engage in foraging in a different way than in their conventional feeding. As they are fed "normally" at the same time, lemurs are stimulated more than before. Not knowing when and which fruits are openable, as well as one suddenly dropping down due to another lemur interacting with it, there is a degree of unpredictability.

The sudden movement and sound of a pod falling on the ground, preceded by an interesting smell and followed by the scent of fresh food, make the experience for lemurs multisensory.

As the pods are hung up high, lemurs are given more opportunity to forage in conditions they would find in nature.

The real effectiveness of the design can only be observed over a longer period of time – as is simply the case in working with animals.

9.2.2 Zookeeper handling

The design adds a bit of extra time to the zookeeper's routine. Filling the pods and gathering them up takes the most time, but this is something they are fine with since it is a positive addition to the lemur's welfare.

As the pods are made of rubber, it can safely be put in a dishwasher to be cleaned. This is the easiest and least time-consuming way for zookeepers. Washing all by hand takes considerable time, which is less ideal.

9.2.3 Visitors

As new fruits unlock, the lemurs have a reason to periodically appear close to the visitors' viewing area, where they will then be actively foraging by interacting with the fruit pods to search for the ones that open. This is something zoo visitors love to see, thus giving them a positive experience at the lemur exhibit.

The soursop fruits on a tree give an opportunity to educate visitors both on the ring-tailed lemurs' homeland Madagascar, as well as the use and importance of designing things that improve animal welfare.

9.3 Overall assessment of the design - Feasibility

9.3.1 Proven working

The final prototypes have proven that the mechanism works and lemurs are unable to pull the fruit off when locked. Multiple of the locking mechanisms can be controlled over Wi-Fi and the servos can handle being put in the unlock mode for long times with no problems and everything can be powered using one power supply connected to mains power.

9.3.2 Manufacturability & repairability

In terms of manufacturing, the final prototype was discussed with the technical department of Rotterdam Zoo who did deem it possible to produce in the numbers envisioned. Due to most parts being 3D-printed, when parts break a replacement can quickly be made. 4 screws allow access to the internals. However, as the wires of the servo are soldered onto the main wires, these are not easily attachable and quickly repairable.

9.3 Overall assessment of the design - Viability

9.3.1 Budget and market position

Manufacturing most components in-house results in a relatively affordable price per pod. Due to the design's niche and custom context, there is nothing to clearly compare against – but it does fit well into the allocated budget. In talks with different stakeholders, there seems to be nothing similar on the market.

9.2.7 Research possibility

The final design could also possibly be used or adapted to be used for research in which animals need to be blocked from accessing food at one point and be allowed to access it at a later point, such as in research to test how animals remember feeding patterns.

10. Limitations and recommendations

10.1 Limitations

10.1.1 Little observation time & data

To be scientifically sure of the effect of an enrichment device such as this one, rigorous observations using mainly activity budgets would have to be done over as long a time span as possible. As this project's focus lay on the design process, this has not been done, making it difficult to be 100% sure of the effect of the design.

Ring-tailed lemurs are luckily very curious creatures, so they were eager to investigate any new devices added to their enclosure and use them. However, this does not negate the chance they might stop caring about the concept in a couple of weeks as it grows old, as there have been no long-term tests done yet, and perhaps some changes will need to be made to the design's workings.

10.1.2 Change in troop dynamics

As the size of the troop of lemurs was greatly reduced during this project, it makes comparisons between tests, especially the LoFi and HiFi ones, quite difficult to make. In a smaller troop, there is less competition for food, especially one without males. This results in the individuals of the troop reacting differently to the available food and items containing food.

Due to this, it is quite difficult to assess the final prototype and design on whether it really improves activity and locomotion. There is less incentive for the dominant females in a smaller group to run away with the pod.

10.1.3 Magnetic differences

Between the earlier and boxy power bank testing prototypes, and the final prototypes, there is a noticeable quality difference between the magnets used since new ones needed to be ordered. This second batch of magnets is noticeably stronger – which impacted the final prototype tests, resulting in most of the time the lemurs being unable to remove the food compartment. These differences were not accounted for well, as a comparison should have been done.

An added difference is the addition of the locking mechanism, which partly is inside of the rubber pod. The addition of the friction between these two materials may also have been part of the reason why lemurs had too much difficulty with the final prototypes.

10.2 Recommendations - introduction

First, recommendations on direct improvements to the final design are given. These should best be implemented in the continuation of this product and have already been relayed to stakeholders. Secondly, interesting aspects to research with a close relation to the product are highlighted. These could be interesting to consider when looking to implement the design in other spaces. Thirdly, some heavily research-based recommendations are given.

10.3 Recommendations for direct implementation

10.3.1 Magnets & holding strength

The final prototypes showed that the 2 sets of 4 magnets used were too strong for the lemurs to pull the fruit pod down. Even 3 magnets instead of 4 yielded too much magnetic force for the lemurs to pull down the final prototype. As highlighted in the discussion, the first prototypes used weaker magnets than the later ones, making it difficult to offer a recommendation beyond: this should be tested.

So, less powerful magnets should be used? Yes, well – maybe. A silicone rubber pod will be double the weight of the TPU ones, so it might just be enough difference to make it challenging to remove but not impossible. I would, however, still urge to use less strong or smaller magnets and then test whether the lemurs are able to pull the fruit loose.

10.3.2 Cable connection between servo and power wire

In the final prototypes and design, the cable of the servo is soldered directly to the power wire. In the top, there is little space for these connections and wires, and you must make sure they are not interfering with the cam. As a result, this assembly step is relatively difficult and inconsistent and should be improved. Ideally, this is done by creating a bit more space in the top of the soursop for the cables and the connection by shelling a section of it. Then to limit interference with the cam, a small divider between the 2 compartments should be modelled.

10.3.3 Artificial tree and attachment

Designing and building the artificial branches on which the pods hang will be done by a party experienced in building these kinds of things for zoos. The attachment of the pod to this branch should be further developed, however. Ideally the pod should be hung by a steel cable with the power cable running alongside it, with some sort of cable sleeve around it to make it look like a natural plant attachment.

10.3.4 Waterproofing

The final design did not focus on making a fully waterproofed mechanism, as this was not possible to achieve in the time and scope of the project. Due to the latches sticking out, there are holes in the body through which water can enter and which are difficult to mitigate.

In any case, the servo used is waterproof, and the cable connections can be ensured to be waterproof by e.g. encasing them in glue. As such, the product should not fail because of water but two possible improvements are suggested:

- Adding holes in the bottom of the mechanism component. This would allow water that entered to flow out.
- Creating a slope at the entrance of the latches, which would help standing water drip out the sides.

10.3.5 Scent cues

Researching the effect of (artificial) smells on animals takes time and as such was deemed out-of-scope for this project to prove. It is, however, and important aspect of the final design so it is recommended to test the effectiveness of using it as a cue, and here it might be interesting to test different types of smells as well – although a sweet, fruit smell is definitely recommended. Ring-tailed lemurs can learn certain cues, something I saw in person in Apenheul when they reacted to a learnt audio cue.

In case lemurs do not understand that a scent cue means some fruits are unlocked, a recommended change would be to create a mechanism through which the fruit either slightly opens or creates a small opening which lets the scent of the food inside escape. In that situation, the lemurs might be lured directly to the fruit pods better.

How to connect the scheduled opening times of the pods to the scent machine should be investigated, both in terms of a physical connection and the coding. Then, the timing of the scent machine's activation should also be tested. As scent takes some time to spread, the scent should be emitted a short time before the pods unlock.

10.3.6 Timer at the visitor location

For the visitors, a screen that shows how long until the lemurs are fed (using the system) would be a good addition that can enhance their experience and the time spent at the lemurs' exhibit. The infrastructure to achieve this needs to be created and programmed.

10.3.7 Testing feeding regime

It is expected that when filling the pods with food A during the morning feeding round and allowing this to overlap with food B in the afternoon feeding round, this could result in lemurs getting a suboptimal diet. The higher-ranked lemurs will claim exclusive access to the preferred food A, leaving lower-ranked lemurs with mostly the less preferred food B. As a result, the higher-ranked lemurs would eat too little of food B, and the lower-ranked ones would not get enough of food A. Due to this, testing what food should be put in which pod and at which times these are to be unlocked is essential – this can only be achieved by giving zookeepers direct control per pod.

10.3.8 Sound of the servo motor

When testing the final prototypes in the ring-tailed lemurs' exhibit, the servo motor could be heard from around 5 metres, albeit relatively quietly. In the tests, no lemur looked up or at the prototype and none came to investigate the origin of the sound. It could that they do not notice it due to all kinds of other sounds in the zoo, like visitors talking and pallets of food being moved, however, they might also learn at some point that this sound means food and thus react to the system based on sound instead of the intended cue scent. This could probably be mitigated by optimising the code to rotate the servo motors more slowly.

10.4 Recommended additional improvements

10.4.1 Modularity

It might be interesting to look at implementing modular features to the design. Different bottom parts could be created that fit onto the existing top part of the device. Then, parts with handles from which the lemurs can hang or pull, or items filled with an interesting scent or noisy items that can be rattled can be used and experimented with.

10.4.2 Lifting system

Hanging the pods high up is ideal for making the foraging more challenging and different to the lemurs. In the current system, it is not possible to hang them much higher than a human's height, as zookeepers need to reach them to click the food portion onto it.

Thus, the idea to implement a lifting system for the pods is an interesting development to investigate. This could be either manual with pulleys and a crank, or an electrical system that works with a button press. The tops of the pods can then be lowered when attaching the newly filled bottom parts, after which they are pulled up so that the lemurs can forage at much higher heights.

10.4.3 Other animals

It can be interesting to adapt the design for other animal species, specifically in the domain of primates. Two examples of these are illustrated below.

Gibbons

Near the end of this project, two students of the course Evolutionary Psychobiology used two of the earlier magnetic prototypes in a pilot study on effort discounting at the gibbon enclosure in ARTIS Zoo in Amsterdam (Figure 81). The gibbons were interested in the foreign object, at first touching it cautiously before learning to pull it off quicker the days after. While further research into the ideal strength of the magnets, the shape, and whether it would be interesting / frustrating for them long term, there seems to be some animo from the animals.

The fruit could then be shaped to resemble a fig or a mango, to better fit their natural foraging behaviour (Clink et al., 2017)

Diana monkeys
A species that it might be relatively easy to adapt the product to is the Diana monkey. This is a species that in the wild also forages quite a lot for fruits. They are heavier and stronger than ring-tailed lemurs, and are – just like the gibbons – more capable at grabbing and handling items with their hands. As such, to use this concept in their exhibit, the locking mechanism (which while it is locked can currently can be pulled open by a human, but not a lemur) as well as the magnetic strength would need to be strengthened.

In their case, it could be shaped to resemble a Khaki fruit (Kane et al., 2022)

10.5 Recommended future research areas

10.5.1 Shape morphing materials

It might be an interesting case to look into the possibility of using shape-morphing materials. There are multiple Malagasy fruits that the ring-tailed lemurs eat, which have distinct changes in their tactile structure when ripe versus unripe, especially their staple food, the tamarind (Kane et al., 2022). Creating an artificial fruit that is able to change its physical structure in a similar way might be an interesting way to make the foraging experience feel more natural to the animals. How much lemurs utilise tactility in determining ripe food sources is a very lacking study area, so further research would be necessary to determine the worth of investigating shape-morphing materials as a cue for faux-ripeness.

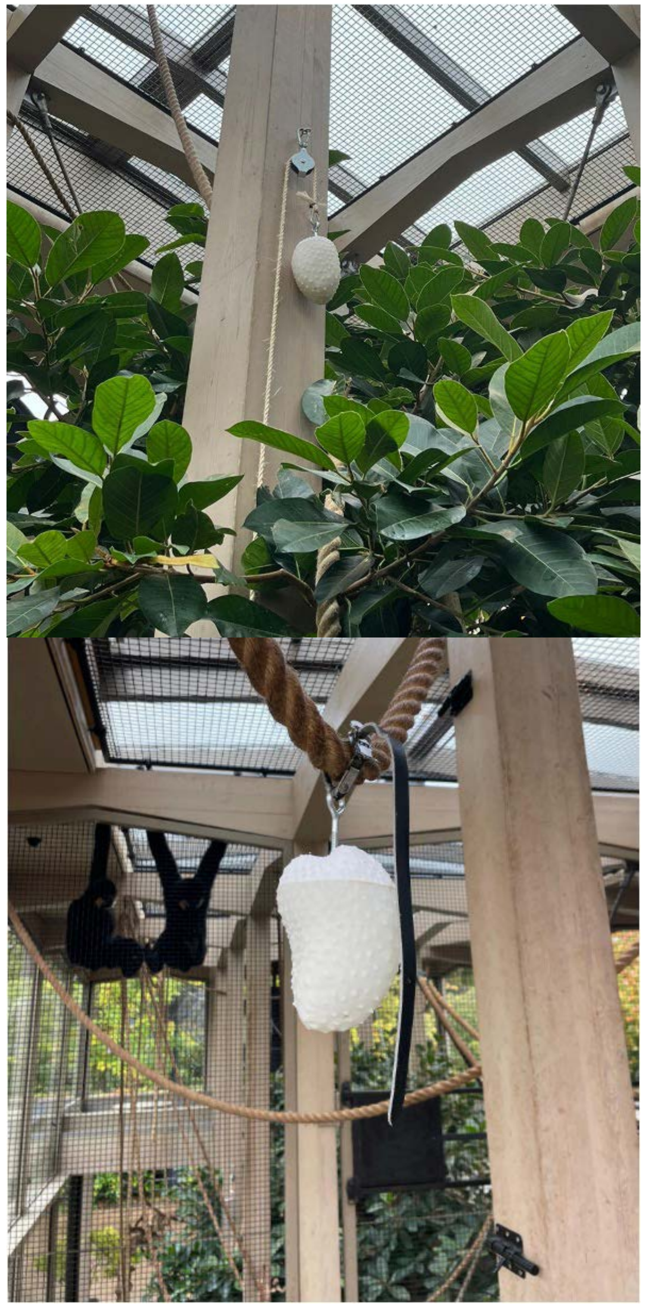


Figure 81 - Bottom; gibbon holding the fruit prototype after pulling it off of. Top; Magnet prototype hung in the gibbon enclosure

10.5.2 The effect of artificial light on ring-tailed lemur behaviour

In researching ring-tailed lemurs' sunbathing behaviour, it came to light that research on the effect of artificial light on these kinds of natural behaviours is lacking / non-existent. This could be an interesting avenue for future animal-welfare research on ring-tailed lemurs, especially ones in countries with a colder, less sunny climate than Madagascar.

11. Conclusion

The goal we started this project with is:

This project aims to create a naturalistic addition to Rotterdam Zoo's ring-tailed lemur enclosure that engages them more than they currently are, while keeping the visitors' experience in mind.

Based on the tests shown and stakeholders' feedback, we can with relative confidence conclude that this report has presented a solution to this goal

This thesis project started with the goal of creating an addition to Rotterdam Zoo's ring-tailed lemur enclosure that engages them in a natural way, whilst keeping visitor experience in mind. Research found that this was best achieved by focusing on lemurs' foraging behaviour, as most tangible improvements could be made there.

As a result, the final design was created, featuring multiple artificial fruit pods containing food that hang from an artificial tree branch and can be remotely unlocked at different times.

The lemurs have repeatedly shown interest in the prototypes of this design; as such, we can say with relative confidence that the design successfully engages them in the following ways that, in current zoo conditions, are relatively underrepresented:

- Lemurs are given more reason to travel around to forage, for which they are given the freedom to do on their own accord
- Lemurs are then encouraged to explore and interact with multiple artificial fruits to identify from which ones they can eat, and the unlocking of these feels random.
- Lemurs receive multisensory stimuli: smells from a scent machine, and visual and auditory stimuli from pods falling on the ground
- The system's location and automation ensure lemurs can forage at heights and at times when this was previously not feasible.

This is done whilst adding little extra load on the zookeepers, who deemed it no problem, especially when noticing it was improving the animals' welfare.
Zoo visitors are more engaged since the final design results in ring-tailed lemurs more often showing natural foraging behaviour close to the viewing spaces.

A significant challenge of this design project was that the end users were captive wild animals. As such, there was much uncertainty on what ideas could work and how, which could either be explained by presenting it to experienced animal staff but mostly by testing things and observing how the animals react to this. For the same reason, the proposed final design needs to be tested over the long term to determine whether it has a lasting effect on improving the welfare of ring-tailed lemurs.

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Appendices

Appendix A. Project brief

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Name student Joshua de Ruijter **Student number** 4,920,996

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Designing an engaging system to stimulate natural behaviour and improve well-being for ring-tailed lemurs.

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

This project is run in collaboration with Rotterdam Zoo, which is heavily focused on animal welfare and becoming a more research-oriented institution to help save endangered species of animals and plants (Diergaarde Blijdorp, 2023).
Captive animals that exhibit natural behaviours provide critical insights for species research. For example, research at Rotterdam Zoo on red pandas examined how GPS collars influence their behaviour (van de Bunte, 2021), which is interesting knowledge that can be used in research with wild species to - like in this case - map their natural habitat (Bista ,2022).
Besides, zoo animals play an important part in educational efforts, as their natural behaviours provoke curiosity and can foster a deeper appreciation for wildlife, with the goal being to inspire visitors to engage more actively in conservation efforts.

This project focuses on the ring-tailed lemur. They are relatively well-researched, curious, and eager to interact with new things they find in their enclosure (Hall et al., 2018). Also, this year, renovations will start on their exhibit, which yields a great opportunity to design and implement a new system.
Next to the lemurs, a crucial stakeholder is the zookeepers, who provide daily care and manage the lemurs. Their insights are essential to understand the animals' needs, wants and preferences. Additionally, enhancing the visitor experience and educational impact are important aspects for visitors and zoo management. Researchers benefit from improved conditions for observation.
The main limitations include constraints related to budget and space, as well as the necessity to ensure the safety of both the lemurs and humans regarding the mechanisms and materials used.

Diergaarde Blijdorp. (2023). Blijdorp Masterplan 2050 (p. 34). Diergaarde Blijdorp. https://blijdorp.cdn.prismic.io/blijdorp/2d841896-74a2-4d96-ae60-caa452a7a158_BLIJDORP+MASTERPLAN+2050.pdf

Bista, D., Baxter, G. S., Hudson, N. J., Lama, S. T., & Murray, P. J. (2022). Effect of disturbances and habitat fragmentation on an arboreal habitat specialist mammal using GPS telemetry: A case of the red panda. Landscape Ecology, 37(3), 795–809. https://doi.org/10.1007/s10980-021-01357-w

Hall, B. A., Melfi, V., Burns, A., McGill, D. M., & Doyle, R. E. (2018). Curious creatures: A multi-taxa investigation of responses to novelty in a zoo environment. PeerJ, 6, e4454. https://doi.org/10.7717/peerj.4454

van de Bunte, W., Weerman, J., & Hof, A. R. (2021). Potential effects of GPS collars on the behaviour of two red pandas (Ailurus fulgens) in Rotterdam Zoo. PLOS ONE, 16(6), e0252456. https://doi.org/10.1371/journal.pone.0252456

➔ *space available for images / figures on next page*

introduction (continued): space for images

image / figure 1 A ring-tailed lemur in its exhibit in Blijdorp

image / figure 2 An automatic food scattering device for Gorillas by Georgia Tech students which slings fruits everywhere

DESIGN FOR our future

TU Delft

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

The main problem is that ring-tailed lemurs tend to be less stimulated in a zoo in certain circumstances than in the wild. They have evolved to live in a certain way in nature. In captivity, it is difficult to stimulate this same behaviour due to a lack of motivation and little need to move around and forage. Also, this problem is made worse when it is cold and overcast outside, where the lemurs tend to just stay inside, lying under heat lamps.

Additionally, the layout of their exhibit is long and lacks incentives for the lemurs to approach viewing areas, limiting visitors from seeing them up close, making their experience less engaging.

A major challenge is designing a sturdy and safe system for the exhibit that operates autonomously or by lemur interaction, without requiring constant supervision from zookeepers. It must be tailored to the lemurs' physical characteristics and natural behaviours while also being easy and ergonomic for zookeepers to use, clean, and easy to repair.

Stimulating natural behaviour of the lemurs improves their health, supports essential research, and enhances the visitor experience, which in turn supports Rotterdam Zoo's educational efforts.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design and prototype a device for the ring-tailed lemurs in Rotterdam Zoo to stimulate their natural behaviour; improving their wellbeing and aiding Rotterdam Zoo's conservation efforts.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

Designing a product to facilitate the lemurs natural behaviour will be done by analysing what challenges the lemurs face in the wild (literature review) and what they like to do during their day (literature review & zoo interviews). From this, multiple ideas will be generated using (e.g.) brainstorming, how to's. Based on tests with prototypes, interviews, and MCA's, a final concept will be chosen.

The effectiveness will be tested and validated by user tests with zookeepers and observational tests with the lemurs.

The device will be tailor-made for the ring-tailed lemurs but adaptability to other animal enclosures and species will be kept in mind and possibilities for this will be discussed in the discussion.

The final deliverables will be a tested prototype device, a report and a showcase (e.g. poster or video).

Project planning and key moments

To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a ***kick-off meeting, mid-term evaluation meeting, green light meeting*** *and* ***graduation ceremony****. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	29 Apr 2025
Mid-term evaluation	26 Jun 2025
Green light meeting	11 Sep 2025
Graduation ceremony	9 Oct 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	
For how many project weeks	
Number of project days per week	

Comments:

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

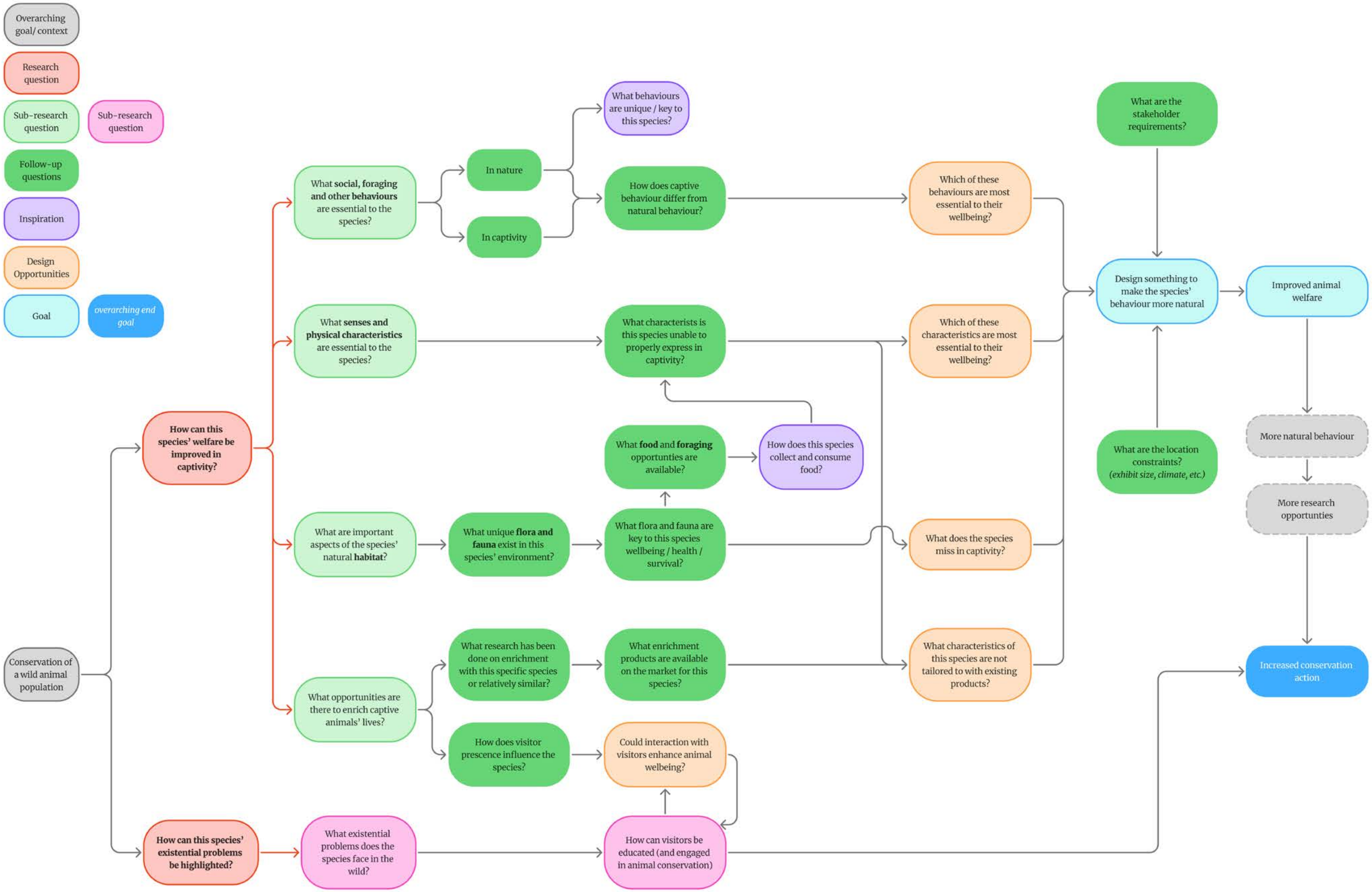
My main motivation for this project is the opportunity to enhance the lives of zoo animals - specifically lemurs - by developing a product using a hands-on approach. The possibility for this project to inspire or directly improve other species as well is then another driving force.

One of the most interesting aspects of this project is how to design for a user that cannot communicate using human language, the lemurs. How to create a user-centred design for both the animals and the zookeepers who will operate the device is an interesting challenge.

In this project, I aim to improve my prototyping skills by creating a hi-fi prototype that will be tested and validated by the different users. Additionally, I see this project as an opportunity to improve my stakeholder management and project planning skills. This then provides a great opportunity for me to step out of my comfort zone by initiating contact with relevant people.
I also want to learn how to integrate different types of ergonomics - that of the animals and the zookeepers - in one complete product.

Appendix B. Flowchart research process

In this appendix, a flowchart is presented which can be used as a guideline when one wants do design something for an animal in a zoo. It tells what questions to ask and what to investigate during the research phase.



Appendix C. Extinction threats of ring-tailed lemurs in Madagascar

Ring-tailed lemurs, as well as many other lemur and animal species are heavily threatened with extinction. The main reasons for this are elaborated in this appendix.

C.1 Poverty and political turmoil

The root cause of these human-driven threats is often poverty. Madagascar is a big and rapidly growing, but very poor country (WorldData.info, 2025). Around 75% of the Malagasy people live on less than a dollar per day (World Bank, n.d.). As is completely logical, people struggling to make ends meet often do anything to make sure they survive.

Since its independence, Madagascar has been politically quite unstable (The World Bank in Madagascar, 2022), and due to this, enforcement of the law has often been lacking significantly, contributing to the endangerment of its native species of animals and plants.

C.2 Destruction of habitat

Due to extensive human logging activities – including logging for settlements, agricultural expansion, charcoal production, and the illicit yet lucrative trade of rosewood (Sussman et al., 2003; WWF Wildlife Practice, 2022), Madagascar has lost around half of its natural forest cover since the 1950s (Global Forest Watch, 2024; Vieilledent et al., 2018). This reduction of habitat makes it difficult for the ring-tailed lemur to find food or places to live safely, resulting in it (and other lemurs) being endangered.

Next to direct human impacts, accelerated changes in the lemurs' environment resulting from climate change play a big role in the endangerment of lemur species. Dry spells in the season are longer / sparser / more irregular, and the storms on the island are often more intense. The speed at which this is happening makes it difficult for many animals to adapt. Finding food is increasingly difficult as there is less growing and more sources are destroyed by cyclones.

Figure C1 - Cut Rosewood (Bois de Rose) logs in Madagascar – illegal but highly profitable (Ford, 2014)

C.3 Hunting and pet trade

Lemurs are also hunted, both for food (called bushmeat) and to sell to rich foreigners as exotic pets. While the hunt on lemurs is illegal and is often considered fady – taboo – by many ethnic groups, this does not stop it (Kinver & Gill, 2011; Reuter, 2016). Rampant poverty combined with the fact that many lemur species are not well adapted to counter human hunting, many of them end up above a fire (Borgerson et al., 2016; Jenkins et al., 2011). The ones that get captured and not killed tend to suffer for the rest of their lives. Due to their eccentric-looking tails and worldwide fame, ring-tailed lemurs are sought after as exotic pets (Figure C2). But they are highly social creatures and need their troop to be healthy. Often kept in cages, they also get suboptimal diets and too little exercise. Increased knowledge and funding can help relocate victims of illegal trade done by instances such as WJC (2025) (Figure C3).

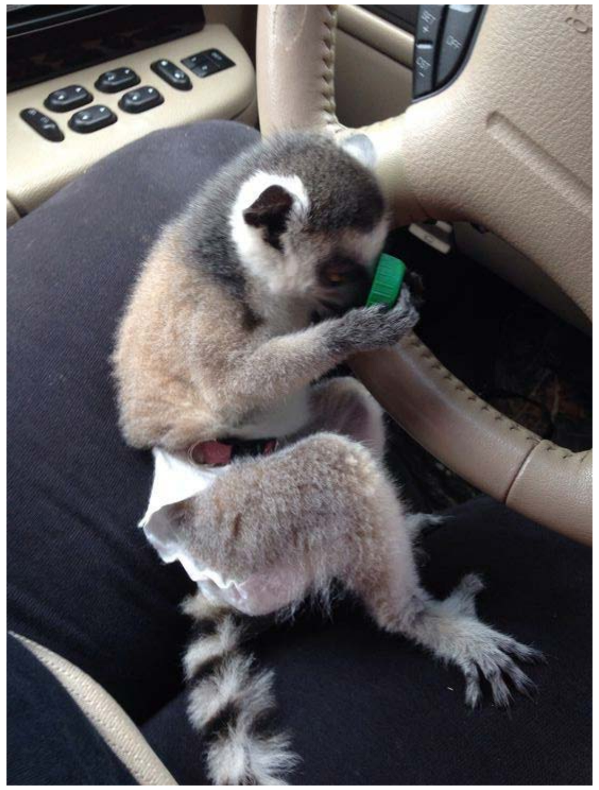


Figure C2 - A ring-tailed lemur being kept as a pet in – clearly – suboptimal conditions

Figure C3 - A primate being saved WJC (WJC, 2024)

C.4 Aid initiatives

There are some positives, however. Multiple foundations aiming to conserve Madagascar's wildlife and forests through local initiatives exist. From 2003 to 2016, Madagascar quadrupled its protected areas (Gardner et al., 2018). While it is still quite far from the international target of 30% (Cbd, 2022), and enforcement is still too little, it is a trend in the right direction. There are also a lot of local initiatives helping to reintroduce lemurs caught for the pet trade or bushmeat sale back into nature.

The sad part is, though, that due to Madagascar's high poverty, it will take a lot of time for the environment of the lemur populations to stop being threatened. Education, lawmaking, even fady, can only go so far – when your only option is either no food on the table for your starving family or capturing a lemur, the choice is quickly made.

Captive breeding programs in zoos help maintain a stable backup population, allowing for research to better understand the needs of these unique animals and – while hopefully not needed – allowing for supplementing the wild populations with captive-bred lemurs. The populations in zoos all over the world also play a big role in educating visitors on these conservation efforts.

Appendix D. Table overview of the differences between wild and Rotterdam Zoo's lemurs

The differences between wild and captive ring-tailed lemurs have been laid out against each other in the coming sections in this appendix. This has resulted in the identifications of multiple areas where tangible benefits for the lemurs can be gained:

Areas for welfare improvement:

- **The lemurs lack travel to different foraging sites**
- **There is a lack of dynamics and change in the ring-tailed lemurs' housing.**
- There is a lack of olfactory stimulation.
- The captive lemurs tend to be hyper-focused on feeding moments and show much less of their relaxed and social eating habits.
- **There is a lack of feeding at heights.**
- There is a lack of possibility to feed throughout the night, resulting in more human-like night rhythms
- Some challenges from eating Malagasy fauna are underrepresented in captivity, such as breaking open hard tamarind pods.
- **Due to the cold Dutch weather, lemurs tend to stay inside a lot in winter**

***Bold** opportunities are key points of the final design

The lightbulb icon highlights differences that are deemed areas of opportunity.

D.1 Environmental differences

Madagascar	Rotterdam Zoo
Around 30°C year-round (Climates to travel, n.d.), consisting of a cooler dry and a hotter rainy season with many cyclones	From around 0°C in winter to 25°C in summer with rain all throughout the year and less sun hours
The days are of similar length all year long	In the summer days are long, and in the winter short
Lemurs deal with drastically different dynamic environments, from forests to barren mountain ranges and deserts.	The lemurs have one outside enclosure and a few connected rooms of indoor housing, which all is a lot less dynamic.
Lemurs face existential threats, ranging from resource scarcity caused by cyclones to hunting and habitat loss, both due to human activity.	The lemurs are safe from these threats; they always get enough food and have a veterinarian looking after them.

D.2 Feeding difference

Madagascar	Rotterdam Zoo
Two long periods in which feeding is done simultaneous to active and non-active social behaviours	3 short bursts of feeding activity (max. 1 hour) that are mainly focused on feeding
Breakfast just after waking up high up in trees after which foraging continues in the lower trees and on the ground.	Food is given only on lower levels, few hours after the lemurs waking up. There is little opportunities for leaf feeding until that time, none for fruits and vegetables.
Foraging also happens (although limited) in the sleeping trees at night	Very little to no foraging opportunities during the night
Diet mainly consists of (tamarind)fruits, flowers and leaves, rarely insects	Diet mainly consists of (European) vegetables and leaves with sometimes (tamarind) fruits. (the diet is calculated to be nutritionally good for them)

D.3 Environmental differences

Madagascar	Rotterdam Zoo
Travel ~ 500m in a day to find fresh food sources, which is needed due to food sources being eaten up, activity of other animals, or environmental factors like cyclones, droughts	Travel max. a few hundred metres a day due to size of enclosure and less need to travel as the animals know they get their food from zookeepers and there are no social reasons for which they need to travel.
Activity patterns stay relatively the same year-round	In summer similar activity levels, in winter way less physical activity – lemurs tend to stay inside or near heating elements.
Do not seem to care for novel non-food items	Are very interested in anything new that enters their enclosure.

D.4 Social differences

Madagascar	Rotterdam Zoo
Many direct interactions with other lemur groups and other types of animals	No direct interactions with any other animals (except humans) and some indirect interactions, like seeing birds fly over and smelling nearby animals
Many opportunities to apply and reapply scent and to investigate scents of other lemurs, animals, and ripening plants.	Less olfactory sensations as the area stays the same and places that the lemurs have scent marked stay scent marked. Different feeding items
Alarm calls are given when a predator is sighted followed by avoidant behaviour of hiding in trees or near the ground. Sometimes the troop will attack one target together (mobbing)	Alarm calls are given when a heron or helicopter flies past and avoidant behaviour is shown, though there is less actual danger. No opportunities/need for mobbing
Sunbathing occurs all year	Sunbathing occurs less with lemurs preferring to stay inside in the colder months

Appendix E. List of requirements

Category	Requirement	Source	Achieved? (assessment)
Behaviour	Accessing the device must be challenging by making the lemurs have to do intricate balancing manouvres		
	It should be challenging to get the food out of the device		
	Lemurs should be given multiple items at the same time to limit fighting over it	Nutritionist	
	It should promote purposeful locomotion, having the lemurs move and search around more to forage	3.1	Expected. In prototype tests they moved away from pods and returned later.
	It should allow for the lemurs to use their sense of smell	3.1	
	it should be possible for the lemurs to choose when to receive rewards	4.6	
	It should feel random		
Interactions	The product should invite the lemurs to interact with it - through colour or smell	3.1, 3.2, 4.3	
	The product should not be too difficult for the lemurs to use	zookeeper	
	The product should be multisensory	Ch 3.3	
	The product should be unpredictable/varied; not be learnt just one time so that each following time the lemurs are done with it in no-time	Nutritionist, park development	Expected, but long term testing needed
	It should take the lemurs much longer to use than it takes staff to set it up	zookeeper, nutritionist	
	amount of manipulation to feed should increase	4.3	
	Items should be spread out throughout the enclosure	4.3	Depends on implementation -> 1 or 2 or more branches
Visual / visitor aspects	The products needs to look naturalistic	Nutritionist, Park Development	
	The product needs to fit in with the story told by aspects in the enclosure	Nutritionist, Park Development	
	The product should nudge lemurs towards the viewing platforms	Park development	
	It should enhance a "real" connection with the animals	Park development	Done by telling the story of enrichment & showing the visitors
	The device should be of a realistic soursop size (10-25cm)		
Zookeeper handling	It should take little time for the zookeepers to use the product	zookeeper, nutritionist, park development	Zookeepers have used the early prototypes for a month and are content
	The product should achieve a maximal effect with a minimal amount of feed	Nutritionist	
	It should be easy to clean the device	TD, Zookeeper	Hand-washing works well. Easier rinse system or dishwasher probably implemented
	Being unable to use the system due to running out of pods should not be possible	Zookeeper	Extra backup pods limit this
	Directly controllable by zookeepers	zookeeper	
Safety	It should be safe to use by the lemurs	zookeeper, technical department	Use of food-safe materials; waterproof components; no sharp edges
	The product should be safe to use by zookeepers	zookeeper, technical department	
	The product should not require heavy physical effort by zookeepers	zookeeper, technical department	Pod weighs <500g
	KISS -> as little points of failure as possible		
Food	The device needs to fit all food in the normal diet of the lemurs	Zookeepers, nutrition department	
	The device should not enhance rotting of food	TD	Limits sunlight hitting it. Depends on system usage though, refreshing every day there should be no problem
More technical req	Should be waterproof	TD	Waterproof components, but should be improved
	Reliably powered		
	The mechanism should reliably keep the pod unlocked for 12+ hours		1 day test showed this works
	No pest animals like rats should be able to get into it	TD	Hangs up high
	Sturdy connectors	TD	Soldered connections and clickable wire connectors
	Repairable	TD	Soldered not ideal for repariability, rest is accessible after losening 4 screws
	Accessible electrical components	TD	Most of the electrical system is placed in an easy to access spot outside of the animal exhibit
	Non-toxic materials (food safe grade)	TD	PLA & TPU/rubber
	Documentation for reproduction	TD	

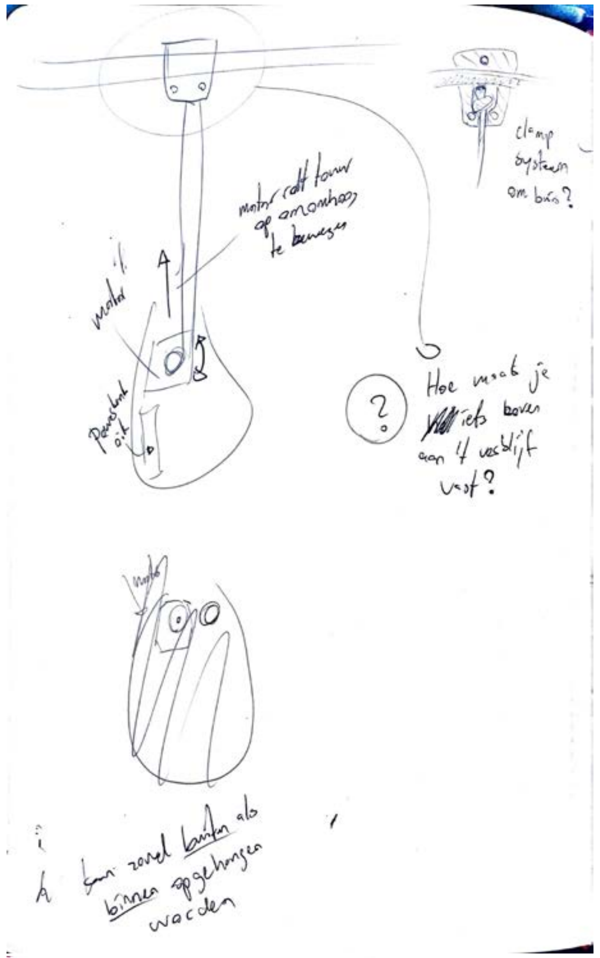
Appendix F. Early idea sketches

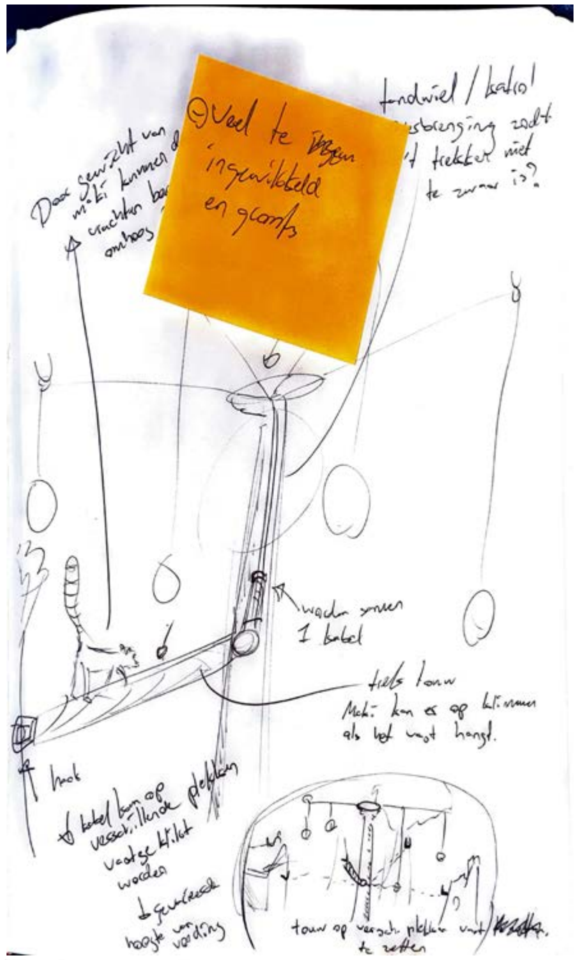
This appendix contains multiple early exploratory sketches. The first sketches are a mix of ideas that came to be because of brainstorming and that came to mind after early discussions with staff on what is needed of the device and some research. The second part of this appendix then shows multiple ideas generated using the How To's method.

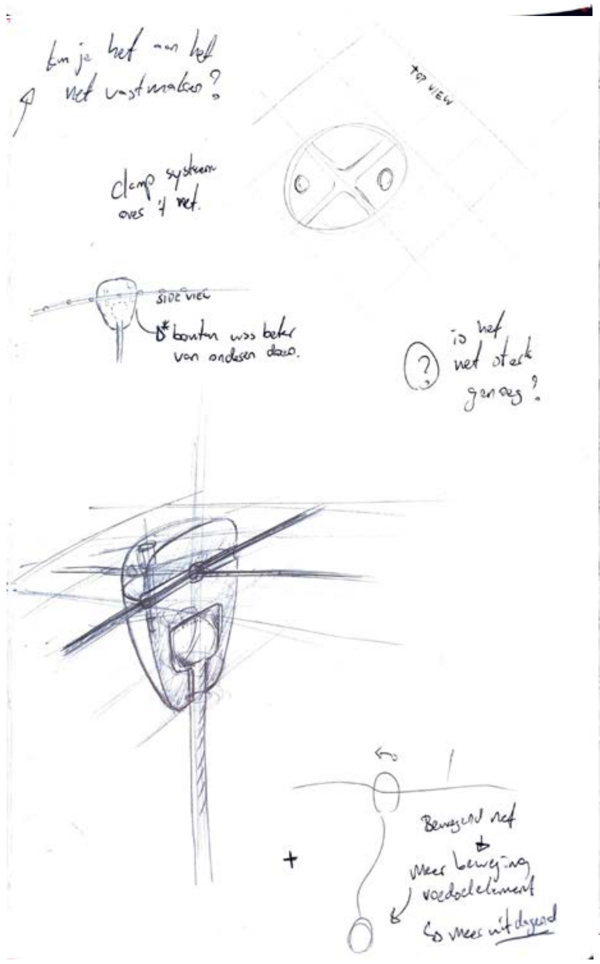
The third section then shows some further idea's resulting from conversations about the previous ones, as well as a brainstorming session with another industrial designer.

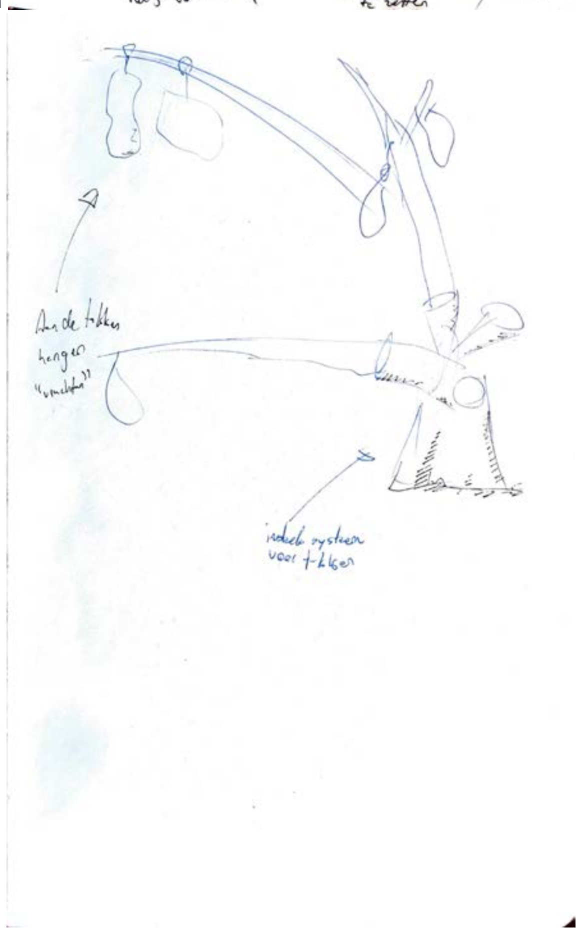
Later, these ideas were assessed on how feasible they are (both in terms of lemur research and actually being possible to create in the context and in budget) and similar ideas were grouped together to form idea directions to start the next design step from. Using a simplified PMI-method with post-its, these choices were made.

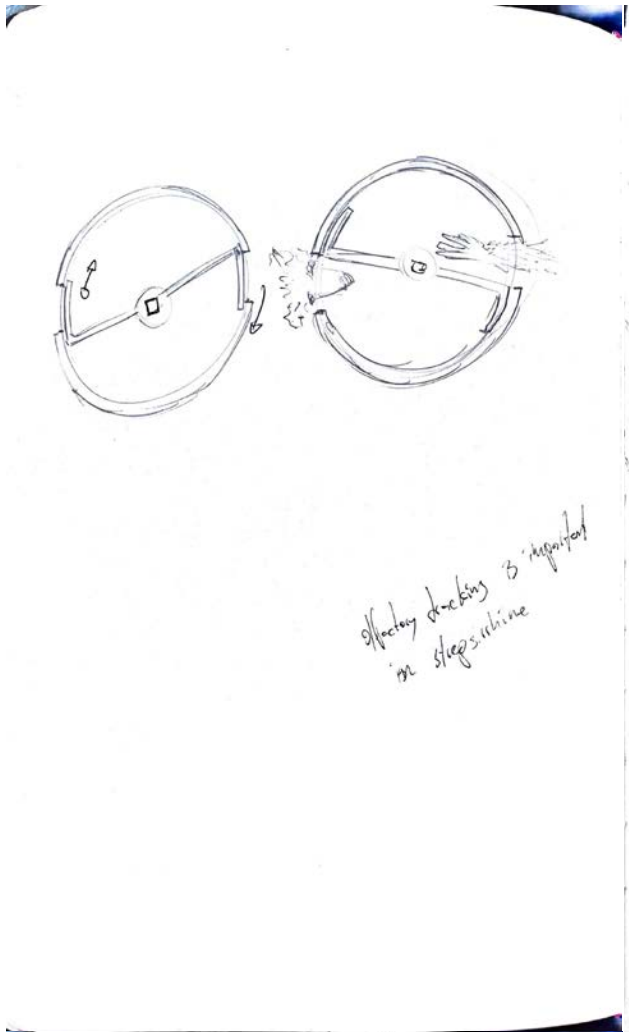
F.1 Brainstorming

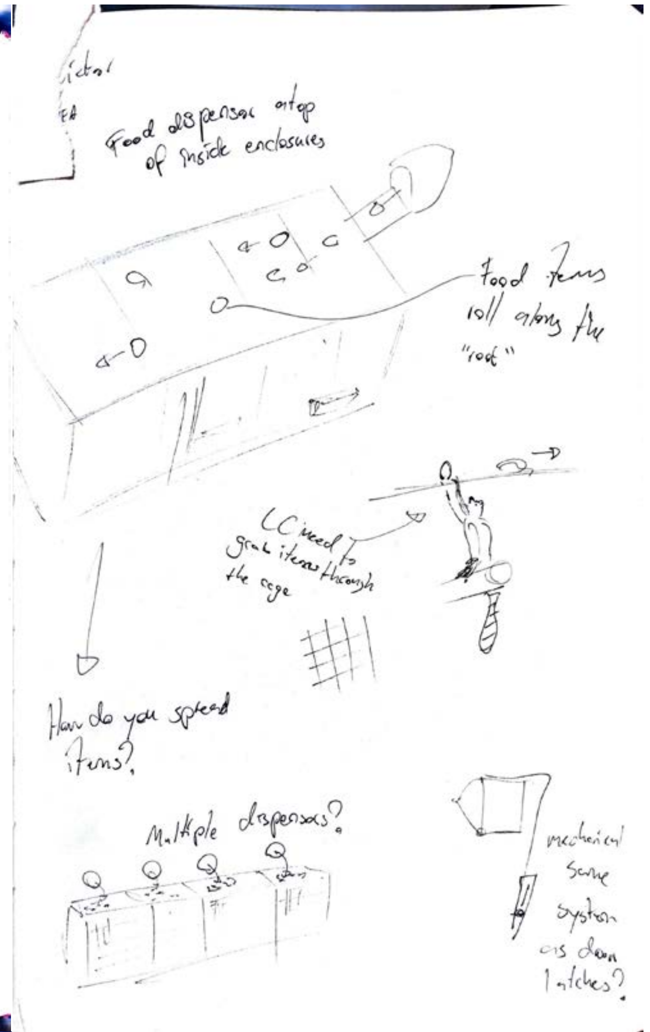


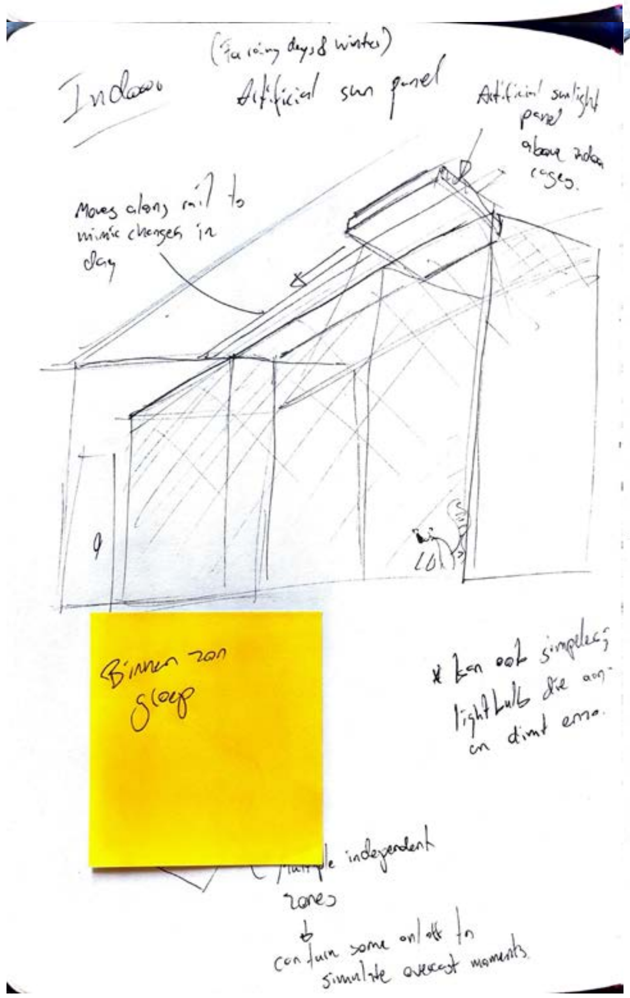


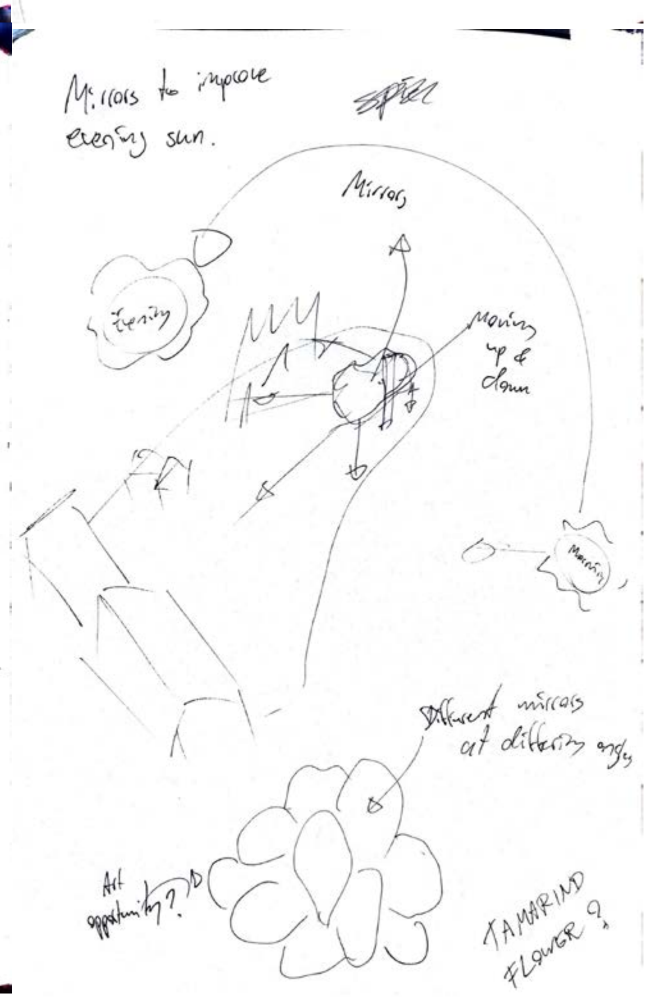


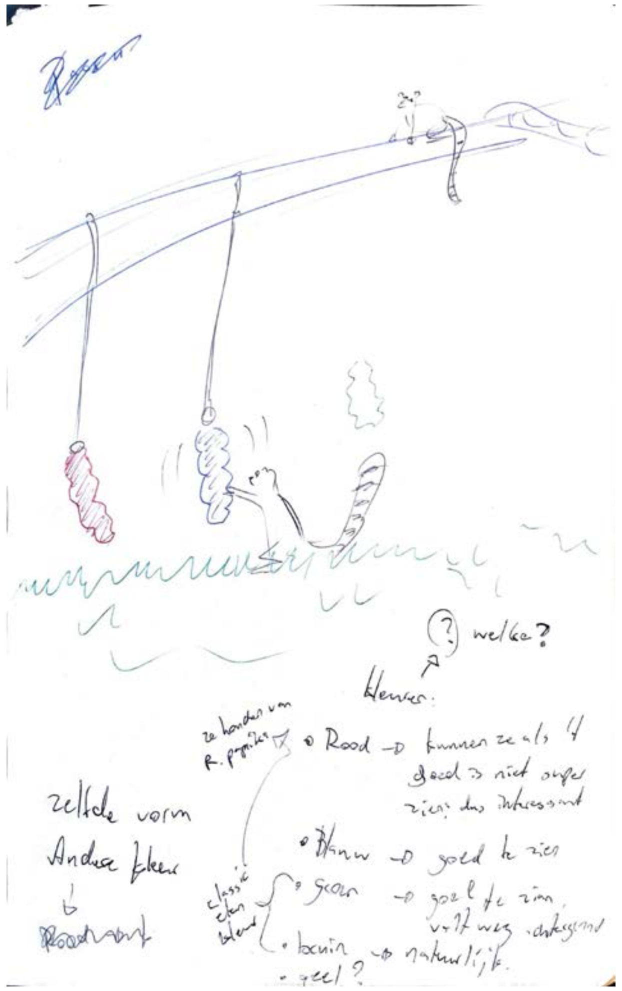


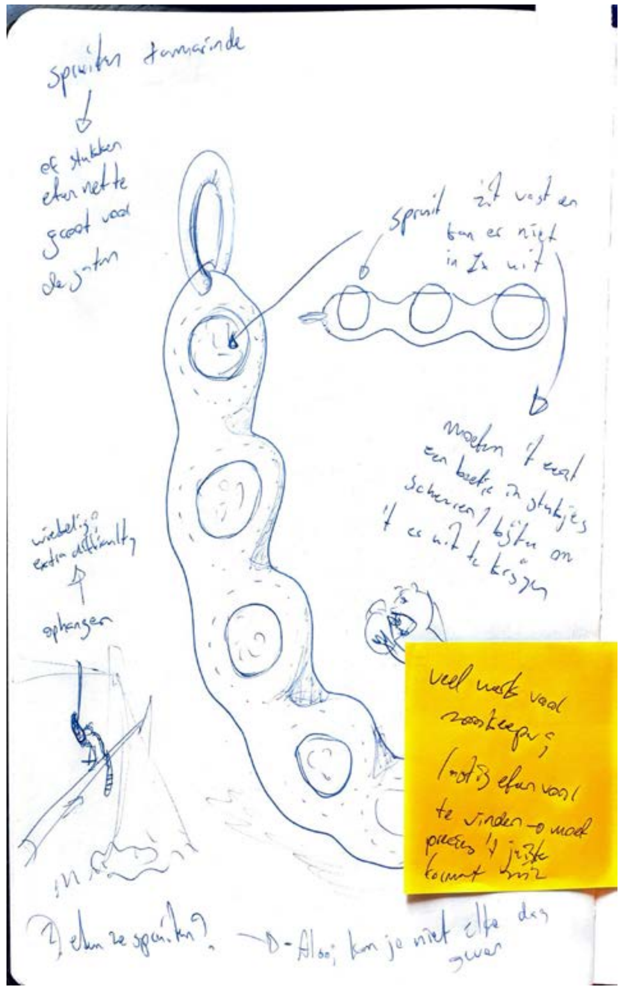


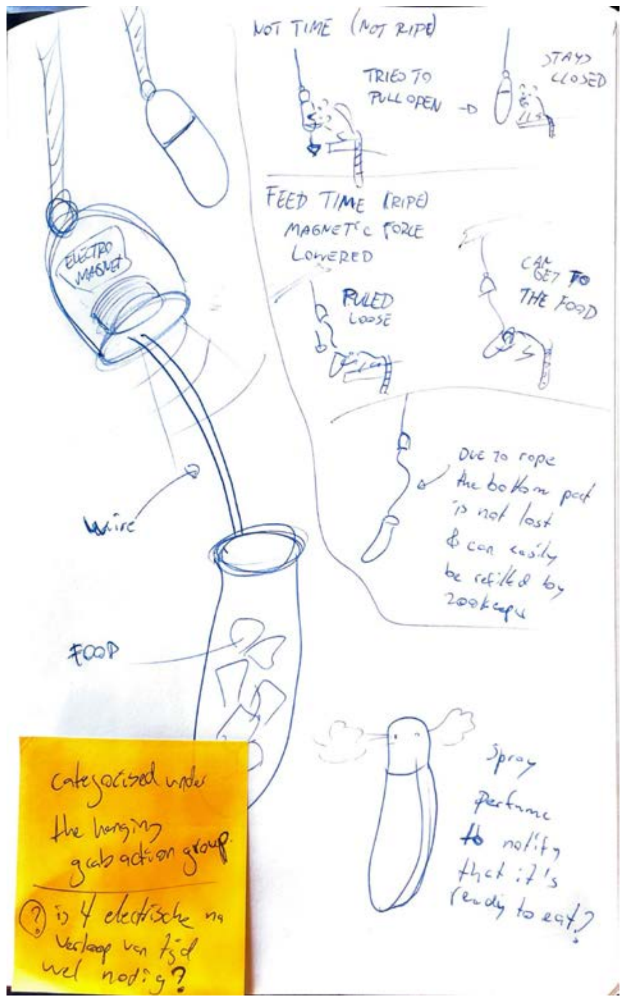


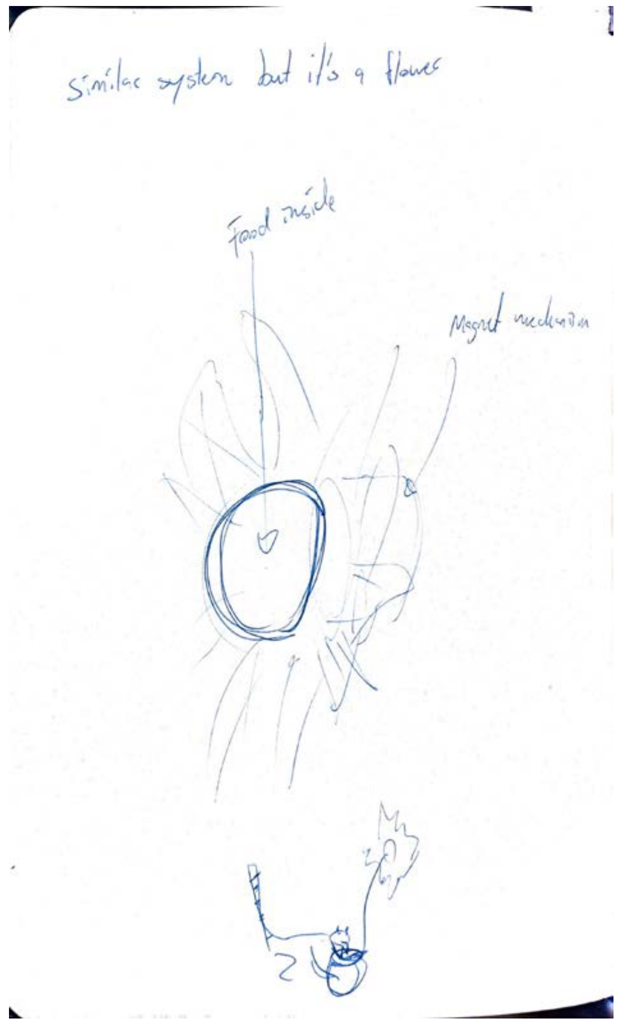




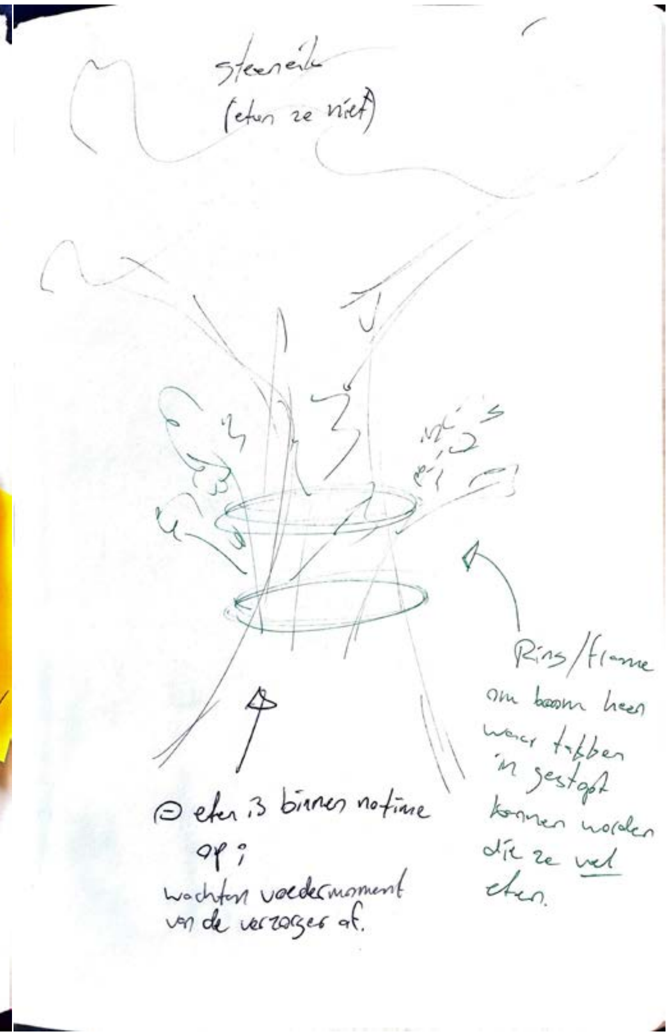

zelfde vorm
Andere kleur
Blevers:
Rood
Blauw
Groen
bruin
welke?

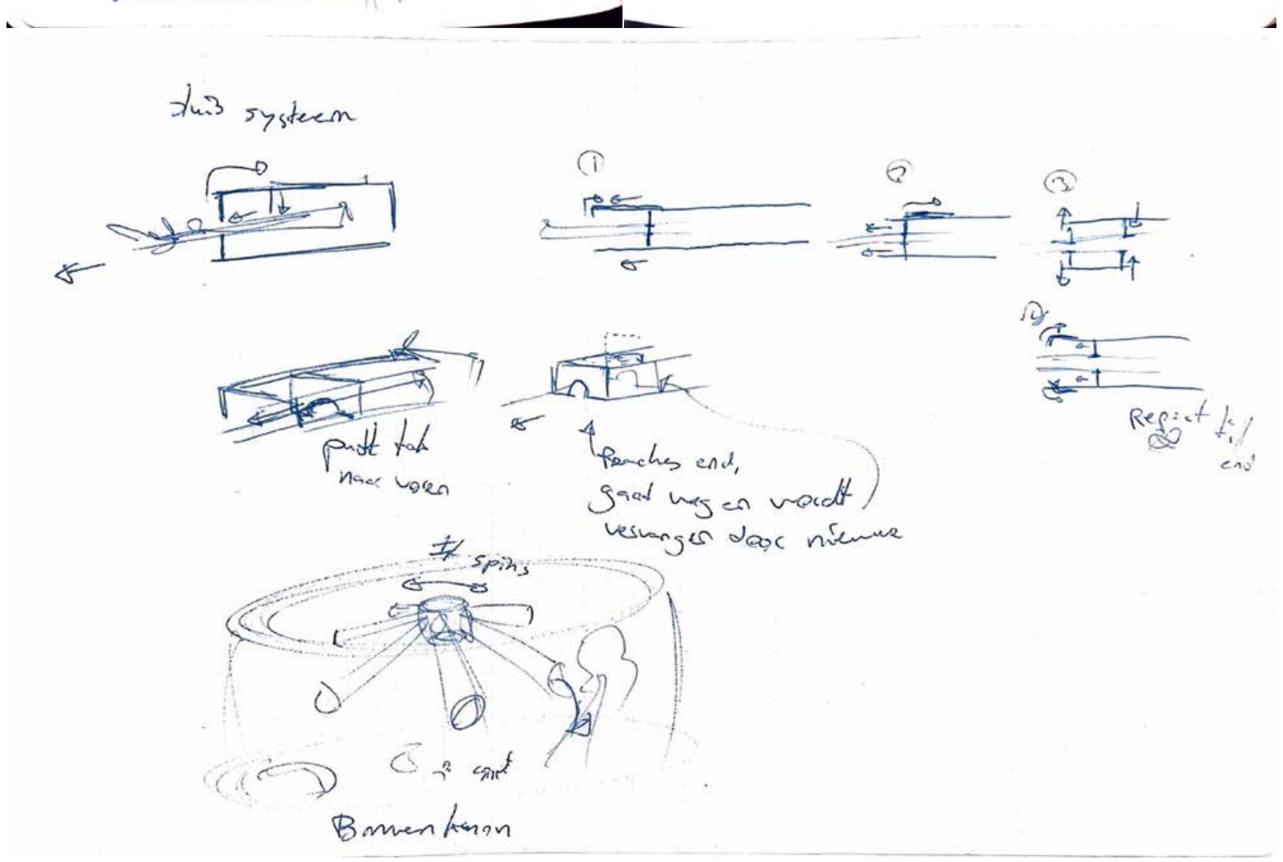

spuiten tamarinde
spruit zit vast en kan er niet in 't uit
ophangen
veel werk voor zookeeper;
(niets) eten voor te vinden

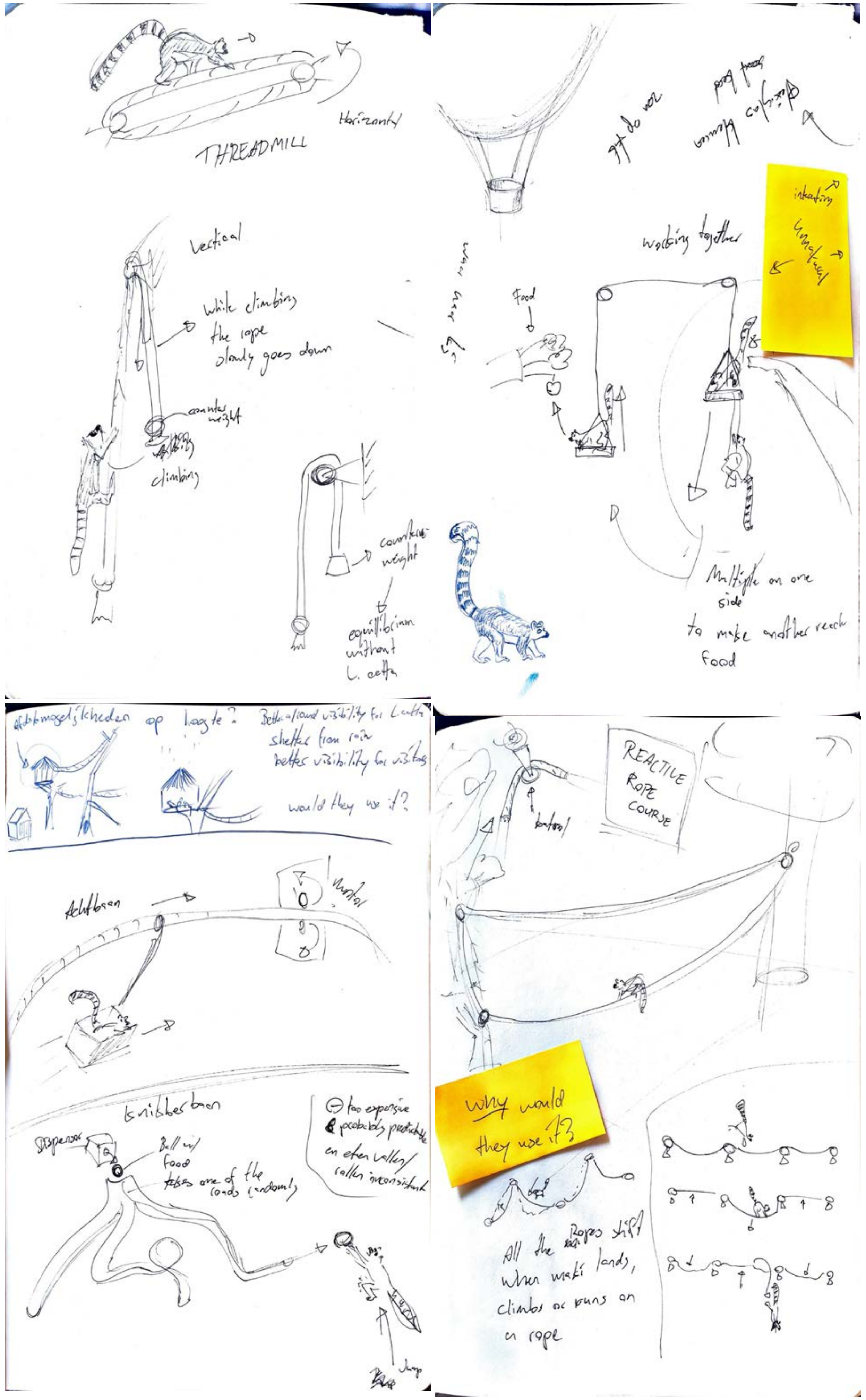

NOT TIME (NOT RIPE)
TRIED TO PULL OPEN
STAYS CLOSED
FEED TIME (RIPE)
MAGNETIC FORCE LOWERED
PULLED LOOSE
CAN GET TO THE FOOD
ELECTRO MAGNET
Wire
FOOD
Due to rope the bottom part is not lost & can easily be refilled by zookeeper
Spray perfume to notify that it's ready to eat?
categorised under the hanging grab action group
is 't electrische na verloop van tijd wel nodig?


Similar system but it's a flower
Food inside
Magnet mechanism


Dicht

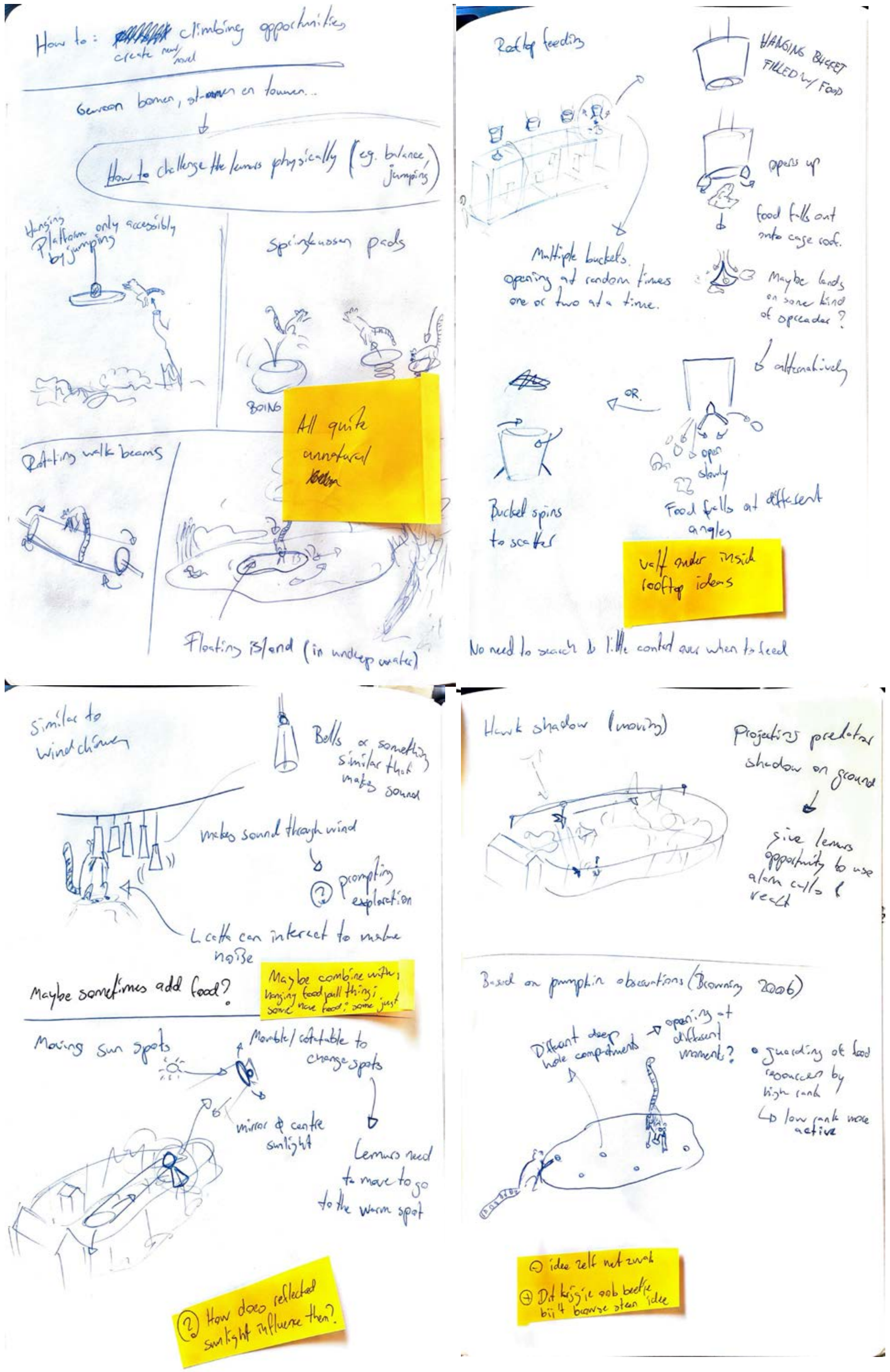

Steeneik
(eten ze niet)
Ring/frame om boom heen waar takken in gestopt kunnen worden die ze wel eten.
wachten voedermoment van de verzorger af.


Binnen kooi

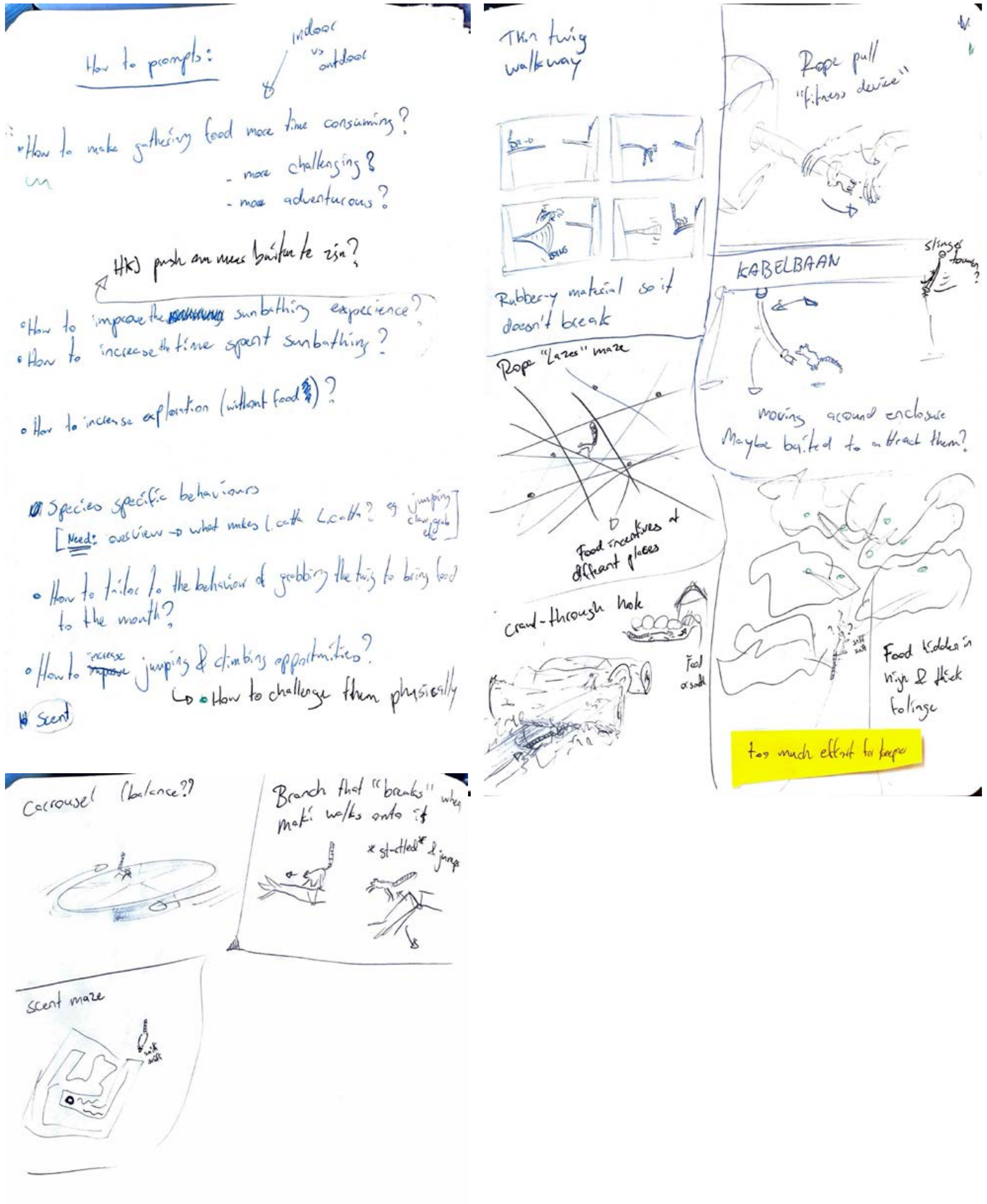


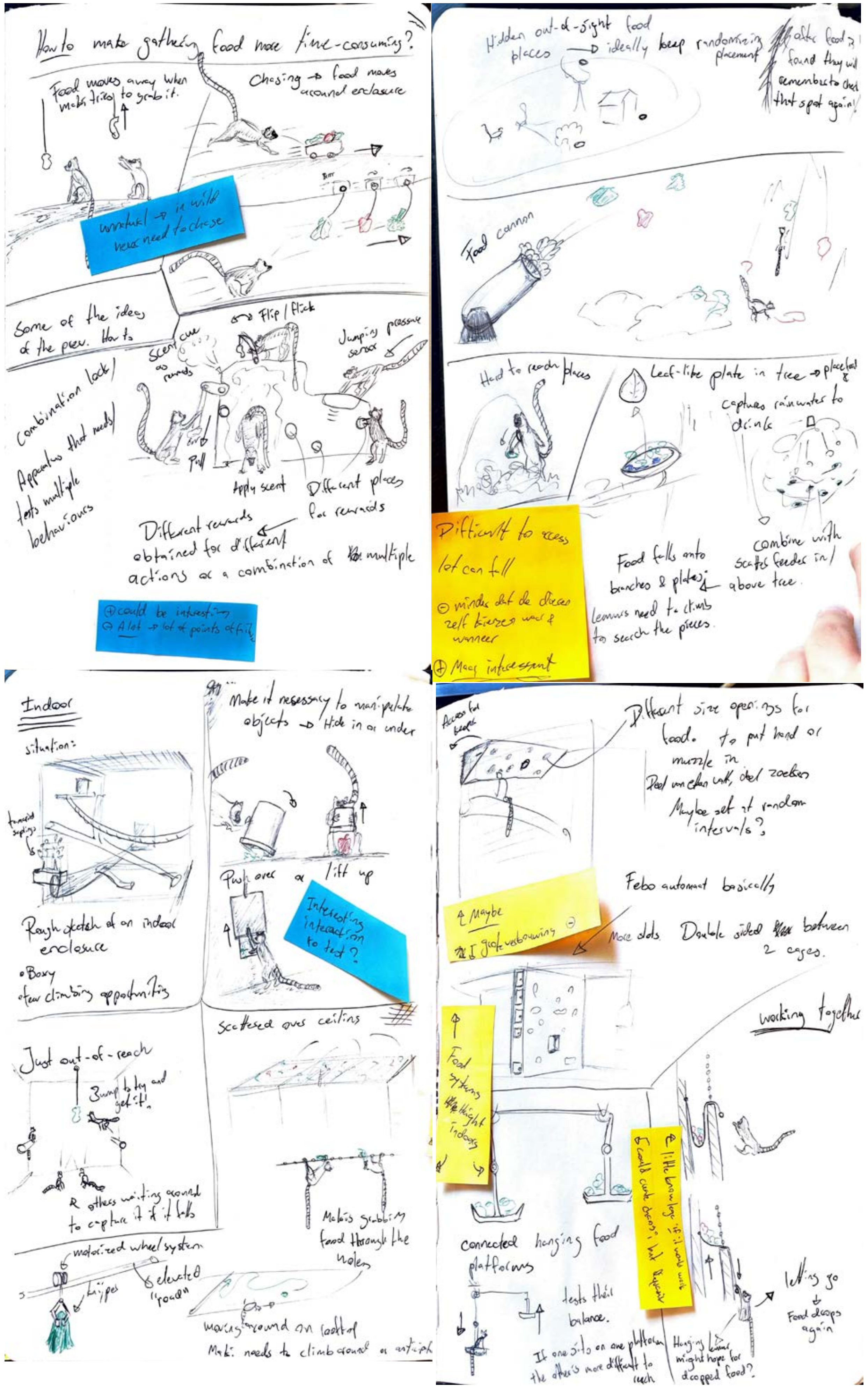
THREADMILL
Horizontal
vertical
while climbing the rope slowly goes down
counter weight
climbing
counter weight
walking together
Food
Multiple on one side to make another reach food
REACTIVE ROPE COURSE
control
why would they use it?
All the Ropes shift when makí lands, climbs or runs on a rope
would they use it?
shelter from rain
better visibility for visitors

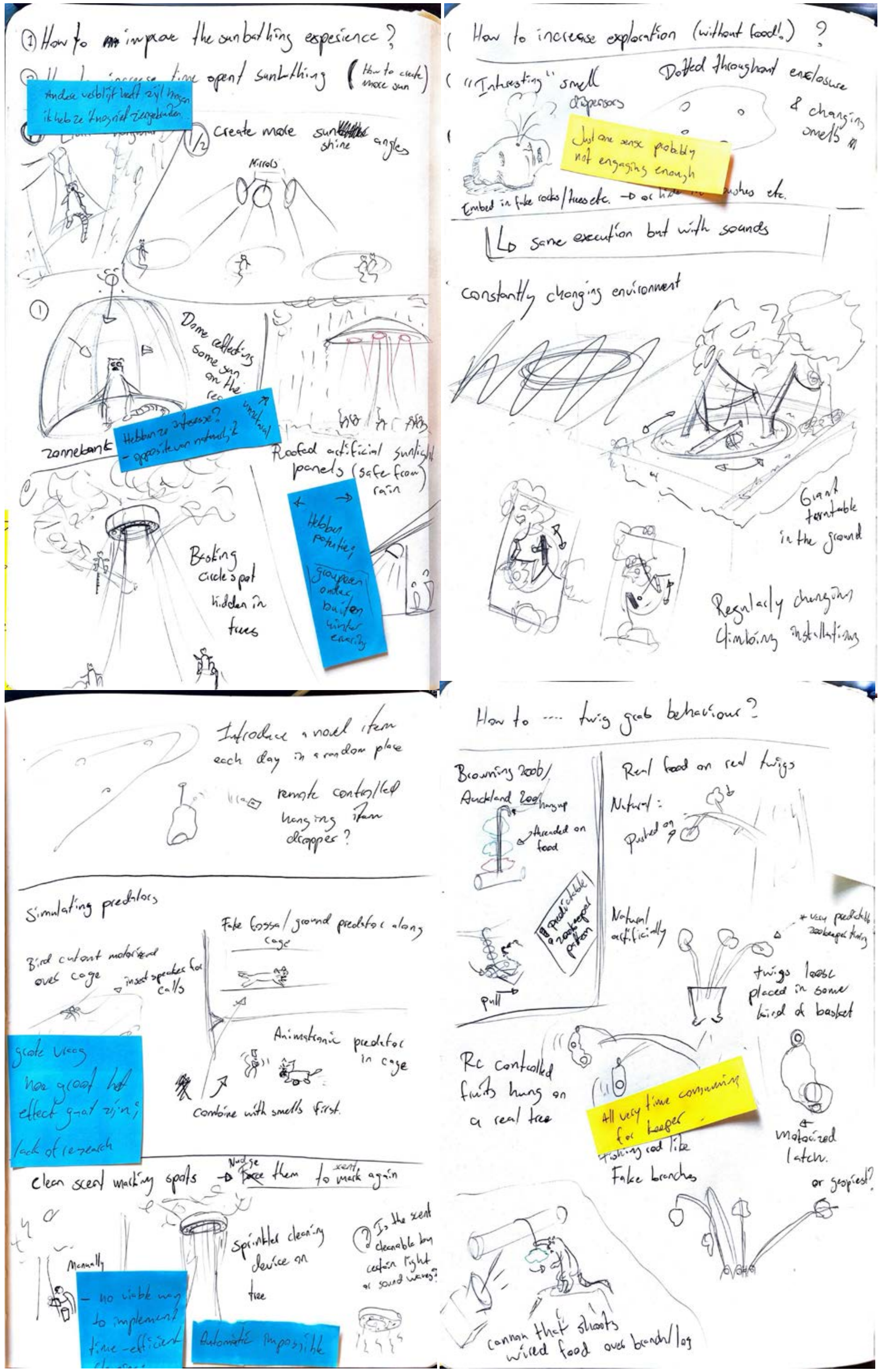
G.2 How to's

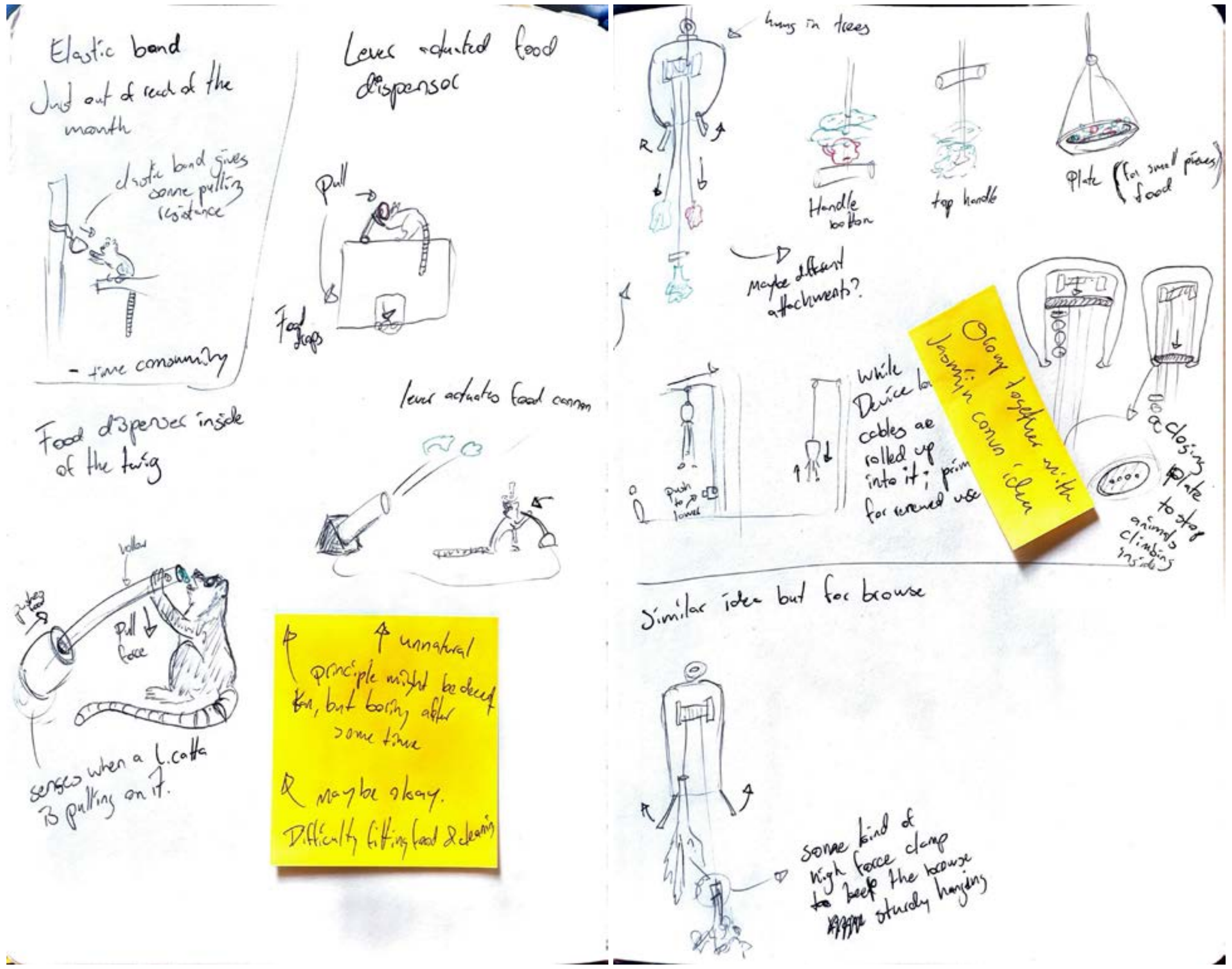


How to: climbing opportunities
How to challenge the lemurs physically (e.g. balance jumping)
Springkussen pads
BOING
All quite unnatural
Rotating walk beams
Floating island (in undeep water)
Rooftop feeding
HANGING BUCKET FILLED W/ FOOD
opens up
food falls out onto cage roof.
Multiple buckets opening at random times one or two at a time.
Bucket spins to scatter
Food falls at different angles
No need to search & little control over when to feed
Similar to wind chimes
Bells or something similar that makes sound
makes sound through wind
L catta can interact to make noise
Maybe sometimes add food?
Moving sun spots
mirror & centre sunlight
Lemurs need to move to go to the warm spot
How does reflected sunlight influence them?
Hawk shadow (moving)
Projecting predator shadow on ground
Based on pumpkin observations (Browning 2006)

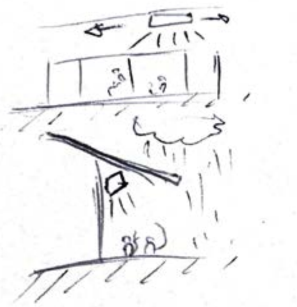

How to prompts:
indoor vs outdoor
How to make gathering food more time consuming?
- more challenging?
- more adventurous?
How to improve the sunbathing experience?
How to increase the time spent sunbathing?
How to increase exploration (without food)?
Species specific behaviours
How to tailor to the behaviour of grabbing the twig to bring food to the mouth?
How to increase jumping & climbing opportunities?
How to challenge them physically
Scent
Thin twig walkway
Rubbery material so it doesn't break
Rope pull "fitness device"
KABELBAAN
Rope "Lazer" maze
Food incentives at different places
Crawl-through hole
Moving around enclosure
Maybe baited to attract them?
Food hidden in high & thick foliage
too much effort for keeper
Carrousel (balance?)
Branch that "breaks" when maki walks onto it
Scent maze


How to make gathering food more time-consuming?
Food moves away when maki tries to grab it.
Chasing → food moves around enclosure
Some of the ideas of the prev. Hunts
Combination lock
Apparatus that needs tests multiple behaviours
Scent cue as rewards
Flip / flick
Jumping pressure sensor
Pull
Apply scent
Different places for rewards
Different rewards obtained for different actions or a combination of multiple
Hidden out-of-sight food places
ideally keep randomising placement
Food cannon
Hard to reach places
Leaf-like plate in tree
captures rainwater to drink
Difficult to access
Food falls onto branches & plates
Lemurs need to climb to search the pieces
combine with scatter feeder in/above tree
Indoor
situation:
Rough sketch of an indoor enclosure
Boxy
few climbing opportunities
Make it necessary to manipulate objects → Hide in or under
Push over or lift up
Interesting interaction to test?
Scattered over ceiling
Makis grabbing food through the holes
Just out-of-reach
motorized wheel system
elevated "food"
Different size openings for food. to put head or muzzle in
Maybe set at random intervals?
Febo automat basically
Double sided between 2 cages
working together
connected hanging food platforms
tests their balance.
letting go
Food drops again

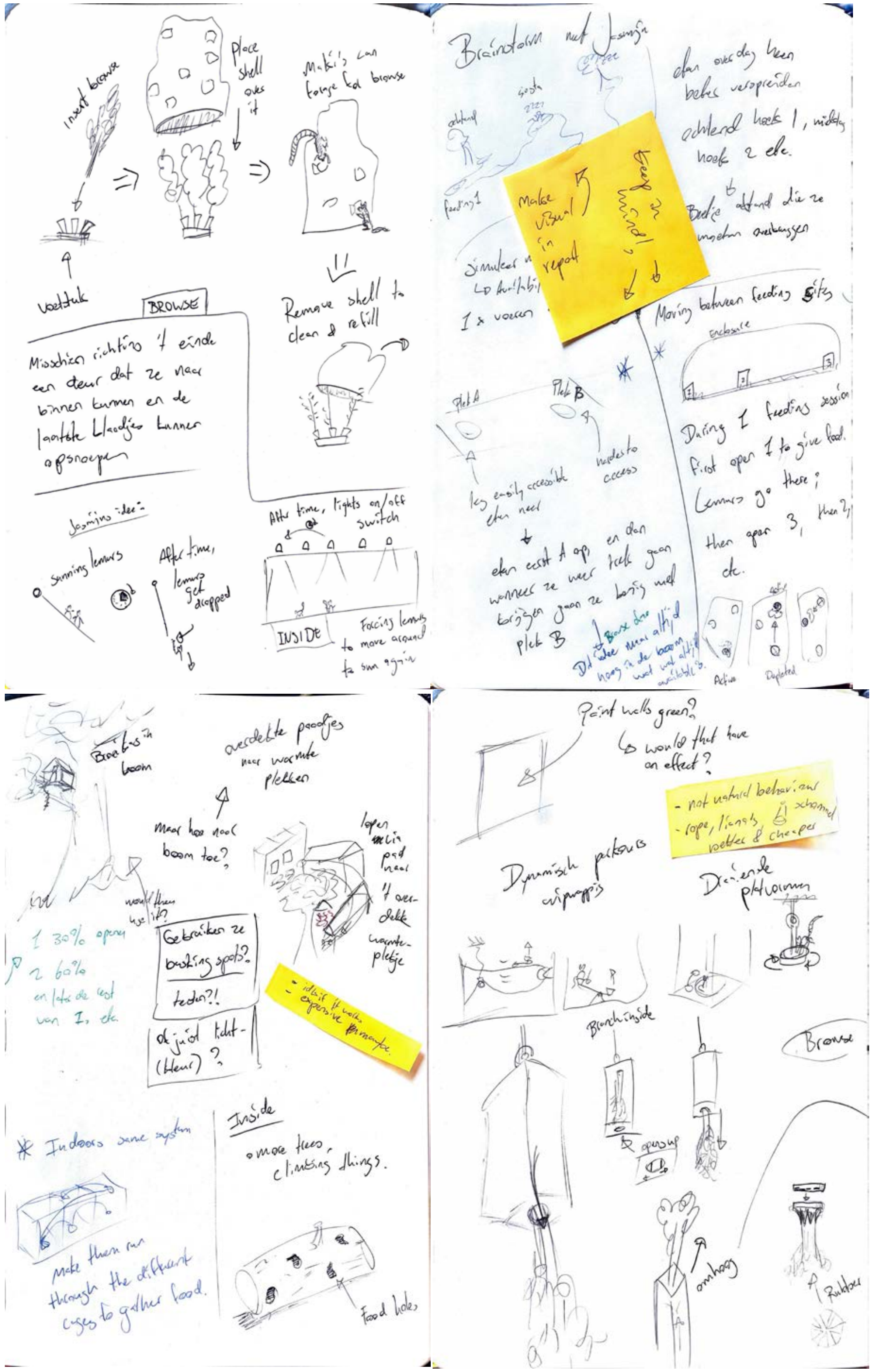

How to improve the sunbathing experience?
How to increase time spent sunbathing
Create more sunshine angles
Dome collecting some sun on the rocks
Zonnebank
Roofed artificial sunlight panels (safe from rain)
Basking circle spot hidden in trees
How to increase exploration (without food!)?
"Interesting" smell dispensers
Dotted throughout enclosure & changing smells
Just one sense probably not engaging enough
Embed in fake rocks/trees etc.
Same execution but with sounds
constantly changing environment
Giant turntable in the ground
Regularly changing climbing installations
Introduce a novel item each day in a random place
remote controlled hanging item dropper?
Simulating predators
Bird cutout motorised over cage
insert speaker for calls
Fake fossa/ground predator along cage
Animatronic predator in cage
Combine with smells first.
Clean scent marking spots → Nudge them to scent mark again
Sprinkler cleaning device on tree
Manually
- no viable way to implement time-efficient
Automatic impossible
How to .... twig grab behaviour?
Browsing zoo/Auckland Zoo
Real food on real twigs
Natural:
Natural artificially
twigs loose placed in some kind of basket
Rc controlled fruits hung on a real tree
All very time consuming for keeper
Fake branches
motorized latch
cannon that shoots wired food over branch/log

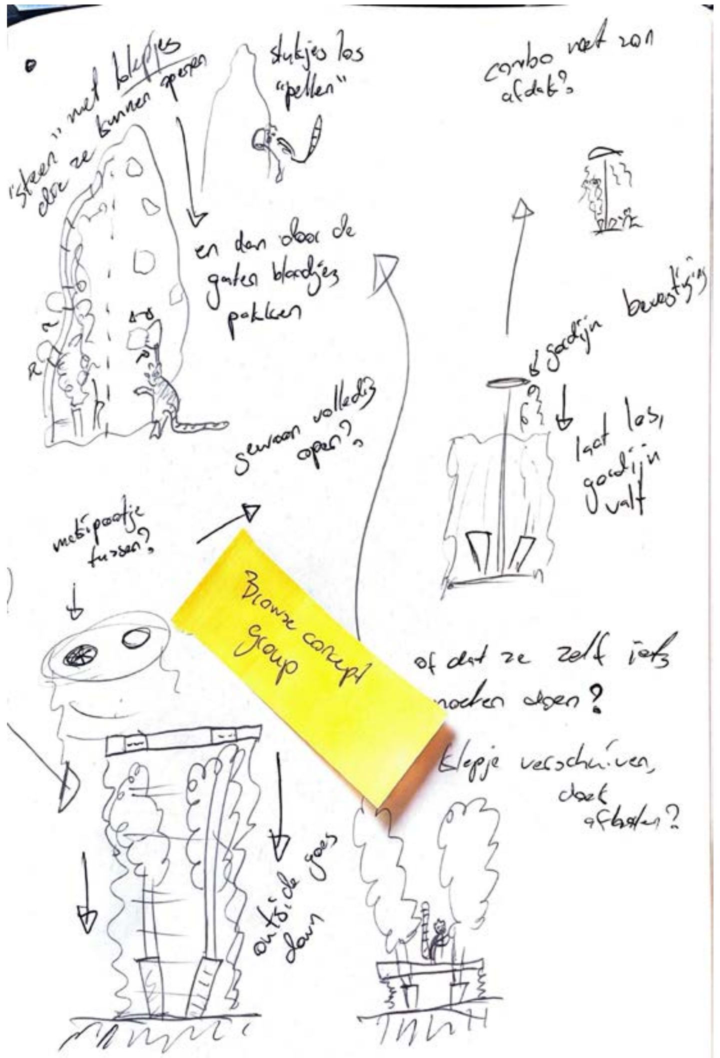

Elastic band
Just out of reach of the mouth
elastic band gives some pulling resistance
- time consuming
Lever actuated food dispensor
Pull
Food drops
Food dispenser inside of the twig
lever actuates food cannon
senses when a L.catta is pulling on it.
unnatural principle might be cheap fun, but boring after some time
maybe okay.
Difficulty filling food & cleaning
hung in trees
Handle bottom
top handle
Plate (for small pieces of food)
Maybe different attachments?
While Device has cables are rolled up into it, prime for renewed use
Along together with Jasmijn canon idea
closing plate to stop animals climbing inside
Similar idea but for browse
some kind of high force clamp to keep the browse sturdy hanging

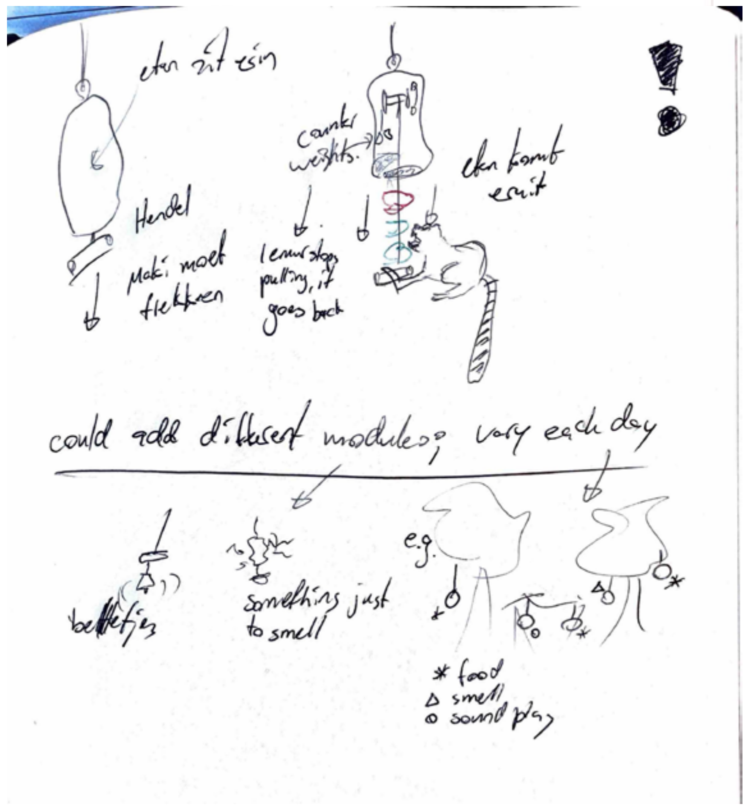

Visitor interaction
sound
Button
vaatjes (digital)
Bezoekers drukken knop in → gebeurt iets bij maki's
Maki drukt → gebeurt iets bij bezoekers
of bezoekers drukt → geur/geluid lokt maki.
Maki drukt knop → voedje verschijnt bij bezoekers
verhaal verteld door de maki's
Smell released
Maki comes
Maki jumps to press button
visitors can feed the lemurs
Not concept alone but good idea to keep in mind for further conceptualisation



F.3 Further ideas







Appendix G. Reasoning for the choice of the final 3 concept directions

Concept direction 1 (tamarind opening), 3, and 4 (pulling system) were chosen to continue on. Below, the reasons for not continuing with the other directions are discussed and where applicable, take-aways from these ideas are highlighted.

(2). Scatter feeder in the trees

Safety is a big issue here. If a part of a lemur would go into the scatter feeder, the animal would get wounded when it turns on. Thus, the scatter feeder would have to have an opening small enough so the lemurs cannot put their hands, muzzles, or even tails inside. This results in very few types of food that can be given; just things like corn and kibble, which are not that often given to the lemurs due to their fat percentage.

- Takeaway: Placement of food at higher levels is a positive for the lemurs. Although too much hidden in the trees is great for lemurs, but a negative for the viewer experience. This is something that needs a right balance.

(5). Interactive browse system

The ring-tailed lemurs do not like browse enough to go through the effort of using an interactive feeder for this. Browse is often given as a secondary food, next to their normal vegetables. It is intended for them to not go for it straightaway but use it as a constantly available "snack".

Using this idea for other types of food the lemurs get would result in a device more similar to 1, 3, 4.

(6). Heat & sun system

Heat sources are already installed in tactical locations in and around the enclosure. The effect of UV lamps on lemur behaviour is not studied though due to the size and expense of UV lamp needed it was not possible to "easily" test this idea with the lemurs to see if their activity improved.

Besides, sunbathing accounts for a low number of lemurs' daily activity, especially here in the Netherlands. The amount spent doing this is clearly less than foraging. Also, the location of the enclosure does allow for quite some sun hours and when the sun is visible Rotterdam Zoo's lemur troop is often observed sunbathing – so (when the weather allows for it), this behaviour is not lacking.

Multiple stakeholders were also motivated to try and implement more UV-spots in the overhauled enclosure, especially in the inside housings.

(7). Predator simulation

Predator simulation experiments on captive Tamarins and Marmosets (Chamove & Moodie, 1990; Sánchez-Barroso Cano, 2019) resulted in improved behaviours, however, There is no research on how much effect they have on(ring-tailed) lemurs. Next to that, it is an ethically difficult task to test something scary with non-verbal animals, as there is a definite risk of generating negative or damaging mental effects.

Also, according to caregivers, the survival instinct of the lemurs does often kick in in the case of a low flying plane, medical helicopter, or a heron moving over the enclosure. This results in a chorus of lemur screams.

Appendix H. LoFi prototype test observations

Here, the main things observed per observation session are shown. Prototype 1 was tested first and the overall conclusion of these sessions is written down to the right. Later, prototypes 2 and 3 were used in the enclosure at the same time, which is why they are grouped together and often compared. The conclusions of these sessions are also noted down. The next appendix shows how these prototypes compare against each other clearly and in line with the requirements.

1. Kong toy observations

Session 1
3 Juli

Dry weather just above 20°C
Midday 2nd feeding peroid
Other available food: endive

3 filled with peeled tamarind
1 with kibble

total time active and observable 2 hours

Many chases observed (multiple lemurs)
From start very high energy, near end slower.
Did not really seem dependent on available food (prefer tamarind over endive?)

Manipulations mainly with mouth; stablise with hands and put muzzle in to search for and grab food

1 put their hand into the big kong - grabbing the last bit of food

bigger kong with kibble stayed at a similar location.
Moved up and dropped one time → after this it was empty, little more interaction

Smaller tamarind filled kongs moved around the entire animal enclosure multiple times.

2 were found by zookeepers, 2 not. **Next day in the morning the other 2 were found**

*Meaning: **there was also interaction with the objects during the evening/ night / early morning***

Session 2
4 Juli

Dry weather just above 20°C
Midday 2nd feeding peroid
Other available food: aubergine

3 filled with peeled tamarind
1 with aubergine

total time active and observable 1 hour

Almost no chases observed, less interest in the kongs. (they were emptied)
2 slow chases near end of observation period

The lemurs spent a lot more time manipulating the aubergines *(big pieces; 1/3rd of the fruit)* than they did endive on previous day

The lemurs like aubergine a lot, and spent considerable effort eating those pieces, which could explain the lower interest in the kongs.

Some lemurs did eat from the kongs at the same time as others were eating from the "free" food

Session 3
11 Juli

Dry weather just above 24°C
Midday 2nd feeding peroid
Other available food: Venkel

3 filled with peeled tamarind
1 with venkel *

** One of the kongs had not been found and has been replaced with a bigger one*

total time active and observable 1 hour

Less chases than test 1, more than test 2. around 8 in total. 1 high speed, rest slow

Empty kongs left laying around were regularly checked, the ones that were filled with tamarind were checked the most

Patience of the different lemurs differs greatly. Some give up after interacting a couple of seconds while a few others kept trying for minutes to get the last crumbs out of seemingly empty kongs

Lot of interaction with the vegetable filled

**notable:*
The kong filled with fennel was eaten from at the same time as others were eating loose laying fennel; and there was some left laying around.

OVERALL CONCLUSIONS *KONG SESSIONS*

There is lots of kong interaction when the food in the kong is something they like more than what is given freely.

This resulted in a lot of chasing behaviour.

When the food inside is not more tasty than the free food (like in the case of the aubergine), there was less interaction.

While lemurs still interacted with the kongs while others fed on "free" food, there was less chasing & stealing food behaviour

Each time the food is finished, the entire group travels to their inside enclosure

It was difficult to find the loose kongs in the enclosure.

After the first session, 2 were lost but turned up the next day. After the second session, one was lost which is still lost at the time of finishing this report

2. Blind box & 3. pulldown box observations

Box A = blind box
Box B = pulldown box

Session 1
17 Juli

Dry weather just above 20°C early midday - close after morning feeding
Food: aubergine
Few pieces on ground

Box 1: Aubergine
Box 2: Aubergine + pellets

total time active and observable 40 min

First the easy food on the ground.
Then food in the box 2→ relatively easy to get.
Then food in box 1 → more difficult

Box 1:
Short burst of interest at start, then more interest in box 2 and food on the ground.
1 lemur kept trying to manouvre food out, while the rest ate the ground food.

The lemurs mostly grabbed food through the side entrances. Pulled towards the exit with a paw then used muzzle to get it fully out to eat.

Near the end, a few other lemurs gathered food through the underside.

Box 2:
Quite some interest after starting ground feeding & during.
A lemur would sit on the branch near and put its paws on the side pulling it diagonal, resulting in the food moving to that side & being easy to grab.

Interesting until it was quite quickly emptied. Then no interest anymore.

No antagonistic interactions were observed, a few sat under the box eating the dropped aubergines

Session 1
17 Juli

Changes:
The boxes were hung closer to each other (5m)

Box 1: Added a rope to grasp and hang onto.

Box 2: Upper lid secured more tightly to keep the top lid level

Dry sunny weather just above 20°C
Morning feeding period.
Food: lettuce
Very few on ground

Box 1: lettuce
Box 2: lettuce + pellets

total time active and observable: 1 hour

First food on ground while we hung the two boxes. The lemurs first interacted with box 2 then box 1. Straight away there was a lot of intrigue in box 2, still while we hung box 1 *(the lemurs are often very interested in what the zookeepers are doing)*

Constant switching attention. both for 1 and 2 there was always at least one lemur busy with either.

Box 1:
Used rope to hold and move box for stabilisation. No hanging (only juvenile once)
A few antagonistic interactions

Interaction mainly through side and bottom. Bit more bottom feeding (due to maneuvering with rope)

More antagonistic interactions could be explained by morning feeding (more hungry than midday)

Box 2:
Lemurs would jump in the box and sit in it.

Multiple antagonistic interactions (~10/15 total)

The lemur(s) sitting inside would not change much. Highest ranks sat in the box & ate the best food for period of 5-10 min.
Approaching lemurs were often not allowed near.

A few lemurs sit below the box eating food dropped from above

When one jumped out, the movement and sound of box would frighten all lemurs around, prompting them to run and jump away. Due to sudden movements the box swung heavily and a lot of food fell to the ground.

OVERALL CONCLUSIONS *BOX SESSIONS*

Both boxes resulted in very little locomotion, lemurs would just sit in and around the area of the boxes or under them to eat fallen food.

Box 1: The time interacted with it was longer as it took more effort and arm/snout manipulations to gather the food

Lemurs used a combination of pulling motions with their arms and finally grabbing items with their mouth

Box 2 was both times more quickly interacted with, but the food was quickly taken out/eaten (little effort needed)

Lemurs tended to sit and stay inside the box. There were multiple territorial antagonistic interactions, mainly won by the lemur already inside the box.

Appendix I. Choice final idea direction

This appendix shows two tables to substantiate the choice for the final "pod" idea direction. The first is a comparison between the three prototypes. This information is then used to better estimate the reactions to the full 3 concept directions, which are compared in the second table.

Using a Plus (green), Minus (red), and Dot (orange), the table directly compares the three prototypes/concepts against each other. A plus means it is the best, dot average/middle, and a minus means it is bad/worse than the others.

Comparison between 3 tested prototypes

Compared against eachother:
- Better (green plus)
- Neutral (yellow square)
- Lacking (red square)

	Observed				Hypothetical		
	Interest shown by the lemurs	Movement	Social interactions	Physical manipulation	Availability throughout the day? Spreading of feeding activity	Enhances movement / activity inside (in winter) & interactions	Ease of use for zookeepers
Kong toys 	Constantly interacting while there is "free" food lying around. Even with same food in the kong. [Better]	More meaningful locotmotion. Chases (quick & slow). Running towards dropped kong. moving away when potential thief comes near [Better]	Some antagonistic and protective interactions When kong is dropped, other lemurs sprinted to take a look → some (antagonistic) interactions ensue [Better]	Many types of manipulation (mainlu snout, holding with paws or feed, movement, dropping) [Better]	Possible to drop / open some at pre-determined intervals [Better]	Chases, searching activity increases Lower rank lemurs can get away with food [Better]	Preparing & filling up takes a few min. Hanging as well. Gathering also takes some time, although this can be done while cleaning [Neutral] *Orange because: Zookeepers have noted that they are fine spending this time, it is no extra burden. Gathering can be done during cleaning & enclosure overhauls*
Blindbox/ grabbelton 	Tended to prefer the easier options, then later this one. First looked at the "good" lying food and the ones in the other box [Lacking]	Little locomotion [Lacking]	A few antagonistic interactions. Some give up after no succes & watch other do it. Other lemurs sometimes gathered under the box to eat the fallen stuff. *(less food than pulldown box, so less gathering)* Little interest → preferred food inside either box [Neutral]	Snout and arm used to manouvre food to exit. Arms used to position box diofferently [Better]	Possible when desiging multiple compartments (kind of like a maze inside) [Better]	Stay in the area of food box. Lower rank lemurs get the scraps. High rank could give up, allowing lower rank to try & run away with some food [Neutral]	Pre-prepped food is thrown in the box at once, few compartments, very quick. Hanging up similar to already used food baskets → also quick [Better]
Pull box 	Was quite interesting from the start until the box was empty. Something which happened quite quickly [Neutral]	Little locomotion [Lacking]	Some antagonistic terretorial interactions Other lemurs sometimes gathered under the box to eat the fallen stuff. Not that much interest → preferred food in either box [Better]	Few types of interaction. Same interactions as ground laying food. Sit, grab and eat (eather in the box or besides it) [Neutral]	Not really possible with this design [Lacking]	Stay in the area of food box. Lower rank lemurs get the scraps [Lacking]	Pre-prepped food is thrown in the box at once, very quick. Hanging up similar to already used food baskets → also quick [Better]

Continues on next page

Requirements

Staying unpredicatble / dynamic environment	Multisensory	Maintenance and cleaning	Choice & control	time spent interacting	Feeding at height	Rat-proof
Items can drop, or stay hanging but available to pluck at different moments in time Can be hung at different places	Possible to implement scent, visual or auditory cues. + tactile experience	Pods can be made to be put in industrial dishwasher (used already). Hanging mechanism would stay clean (does not touch food)	Interaction when item is dropped but also when they keep checking if they can	Need to come back to check & feel	Partly on ground *(dropped items)*, Partly plucking high up *(climb up and grab)*. Possible for lemurs to take pod and move higher up to evade others	Most of the food is kept inside the pods. Few leftovers
Doors open at different moments. Interior stays the same. can be hung/ placed at different spaces	Possible to implement scent, visual or auditory cues. + tactile experience Inside different shapes, materials can be intriguing	hanging in enclosure → cleaned with hose. (not possible with animals outside) → So, would probably need to take it off to clean outside of enclosure. Still quick with hose.	Only allows animals to interact when it is opened	Need to return and keep watch	Can be hung in trees or on the ground. Lemurs stay around that area or below	Lot of food dropped and left on the ground
Interior stays the same. can be hung/ placed at different spaces	Possible to implement scent, visual or auditory cues. + tactile experience *e.g. filling box with food and sometimes a scented item etc.*	hanging in enclosure → cleaned with hose. (not possible with animals outside) → So, would probably need to take it off to clean outside of enclosure. Still quick with hose.	Fully allows the animals to interact with it when they want	quickly done	Can be hung up high. Lemurs stay around that area or below	Lot of food dropped and left on the ground

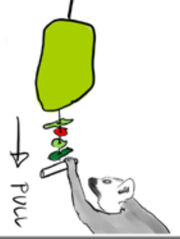
Comparison between the 3 concepts

Comparisons are based on the prototype results

Compared against eachother:

- Better
- Neutral
- Lacking

Goals

Concept	Increased locomotion Purposeful traveling		Social interactions	Natural behaviours that are increased	Movement and activity increase inside (esp. in winter)
1 Automated opening & dropping pods 	Lots. Locomotion to gather falling pod or to check "ready" hanging pods	Increased locomotion to protect gathered pod & for others to steal the pod from another (chases)	Looking at what others have, waiting for opportunity to strike (when higher rank drops it) chases	breaking open items *(they constantly tried to do this with everything handed to them)* Moving to high ground to protect their food	Increased: periodically checking food sources, running away with pods
2 automated foodbox 	Little locomotion. Group stays near food object, constantly interacting with it and standing guard.	Lower ranks might move to grab fallen food items	Guarding behaviour, higher rank doesn't care. Lower rank eats the scraps	hierarchy affirmation, grabbing inside tree trunks (only done rarely in nature)	Slightly. Mainly guarding behaviour. Some grab & run behaviour of lower ranked lemurs
3 Mechanical pods that are pulled open 	Little locomotion. Group stays near the object to interact with it, and to guard it from others	Lower ranks might move to grab fallen food items	One tries to get the food, others try to profit (if possible) Not really working together but more involuntarily	Pulling on soft items. Affirming hierarchy & looking for opportunities for themselves to get food or to steal	Slightly. Mainly interacting at the food source location. Some guarding

Continues on next page

Requirements

Choice and control	Unpredictability / variability	Rat proof-ness	Zookeeper ease of use Usage Cleaning		Maintenance, , repairs	Possibilities to use for other species
Slight control. Timer dependent, but can choose to check out the pods and might be lucky one is "ready"	Upredictable. Interaction type & time. Could fall, or be ready to pluck at any time	Very rat proof (up high and closed smallsystem)	Filling, gathering and hanging takes quite some time	Cleaning easy → simply in dishwasher	(dependent on exact design) slightly difficult → small object, thus small working area, but few moving parts (electrical)	Quite universal. Change shape & look of pods. Change strength of mechanism. Possible for other primates
Not really in control → timer dependent	Quite unpredictably. Time. Doors can open at any time	Relatively rat proof. High up difficult, but rats could get into ones on the ground that are open & that the lemurs left alone (not hungry e.g.)	Filled very quickly. hanging & placing & hanging quite easy.	Slight effort: put a garden hose to clean the scraps out. But moving it out of the enclosure little hard due to size and weight	Easy. Lot of working space and few moving parts (electrical)	Very universal, just change the "look". Possible for many other animals (e.g. ostrich can put their beak in it)
Full control	Relatively predictable in terms of time. Unpredictable in terms of what will be in it	Very rat proof (up high and closed small system)	Filling takes some time. Placing and hanging easy but a bit time consuming	Not easy → each needs to be held open to clean (might be designed in a way to unlock though?) ?	Easy. fully manual mechanism, but small working area.	Quite universal. Change shape & look of pods. Change strength of mechanism. Possible for other primates

Wishes

Nudges them to viewing places	Interaction between visitors and lemurs
Can be placed close, but animals are free to run away Which is good in terms of privacy for the animals...	Many possibilities: • Turn on attraction measures (e.g. smell, sound). • Activate dropping or opening of pod • Fill pods (prepare food) that can later be placed by zookeepers
Can be placed near viewing areas → animals will stay around there	Digital/distant possibilities: • Turn on attraction measures (e.g. smell, sound) • open/close (activate) the food openings
Can be placed near viewing areas → animals will more around in the area	Few possibilities (only physical - needs supervision) • Fill objects (prepare food) which is later hung in the enclosure

Concept direction choice

Scoring

2 points

1 point

0 points

Kong: 25
Concept 1: 21

Grabbelton: 15
Concept 2: 15

Pulldown: 13
Concept 3: 15

Concept 1 - Automated system to grab and drop food pods.

Main reasons

Lemurs

- Increased locomotion - *purposeful travel*
- Increases activity inside
- Unpredictability for the lemurs
- Facilitates many different social interactions
- Simulates natural behaviours that are missing in captivity
- Foraging behaviour / interaction at night

Zookeepers

- Good to maintain & clean and quite ratproof
- Quite simple to use though it can add some time

Zoo

- Many possibilities for visitor interactions
- Can coax the animals closer to the viewers, while still giving them the freedom to choose where to eat

Appendix J. Preliminary concept sketches

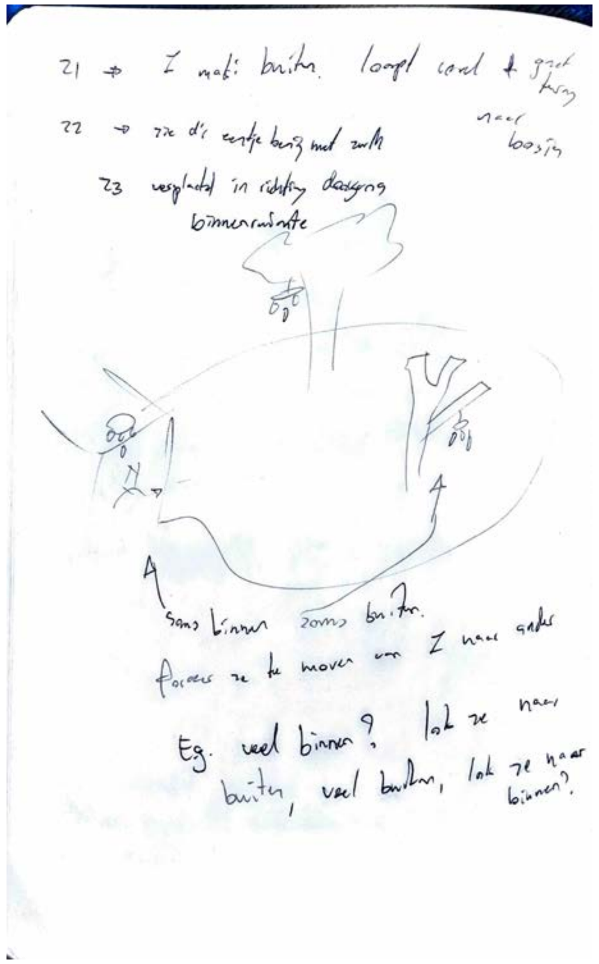
This appendix consists of four parts and shows the concept sketches leading to the preliminary concept.

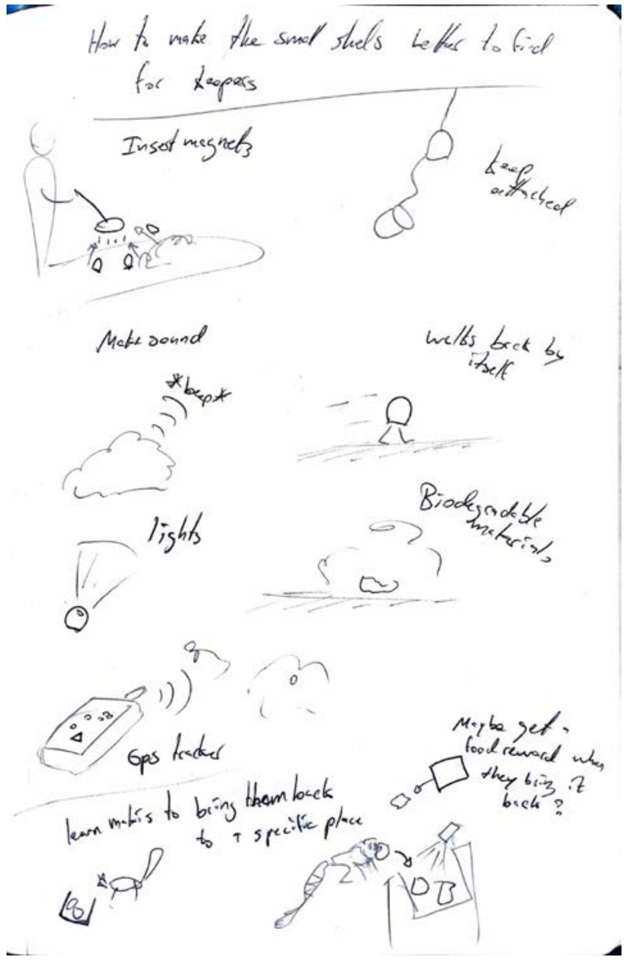
It starts with some brainstorming and how-to sketches (J.1).
Secondly, it shows the first Morphological chart and its concepts (J.2).
Then there are some explorations on using scent and the mechanisms to lock the pod (J.3).

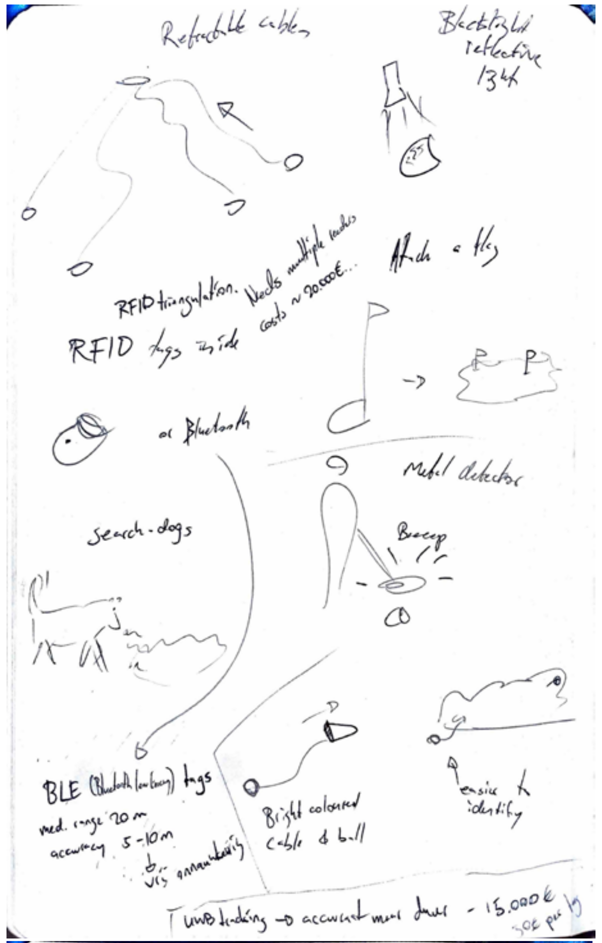
Finally, the more in detail-oriented second morphological chart is shown with its solutions (J.4).

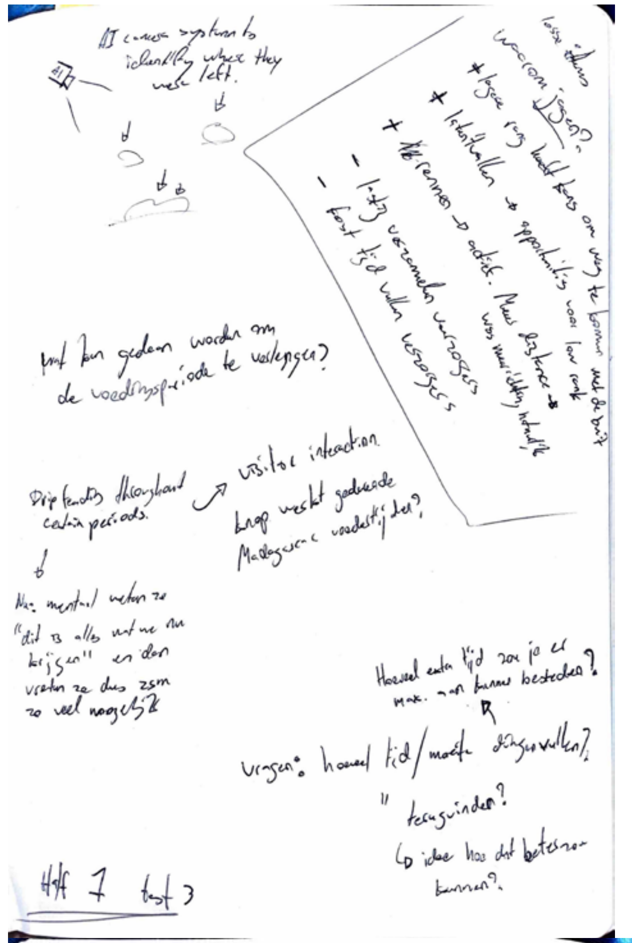
J.1 Brainstorm and how-to sketches

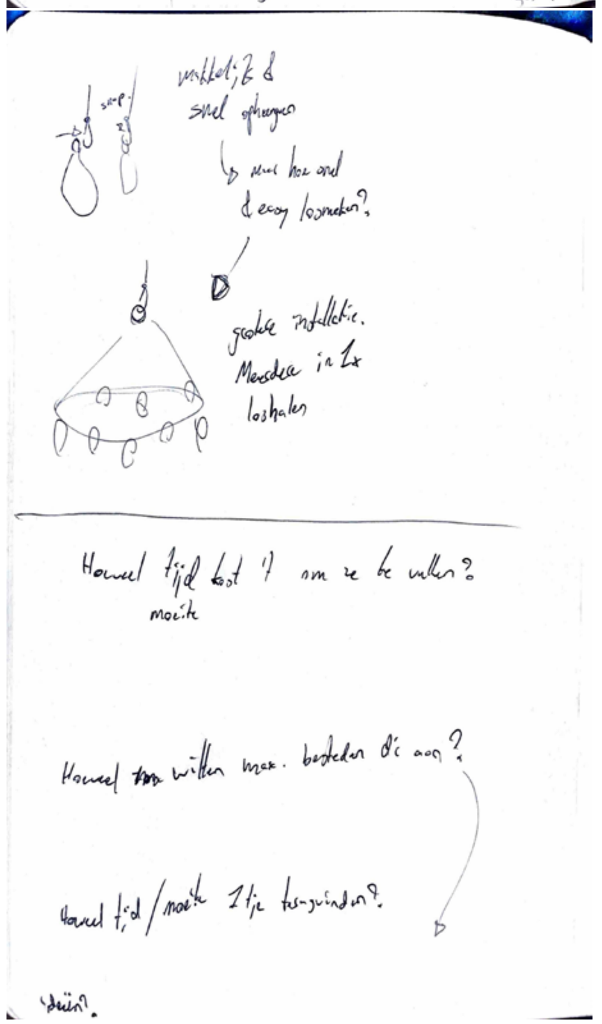
This part of the appendix shows the initial sketches before moving onto the more detailed morphological chart ideation method. Using how to's, ideas on what could be done to make the pods easier to find for zookeepers was looked into.

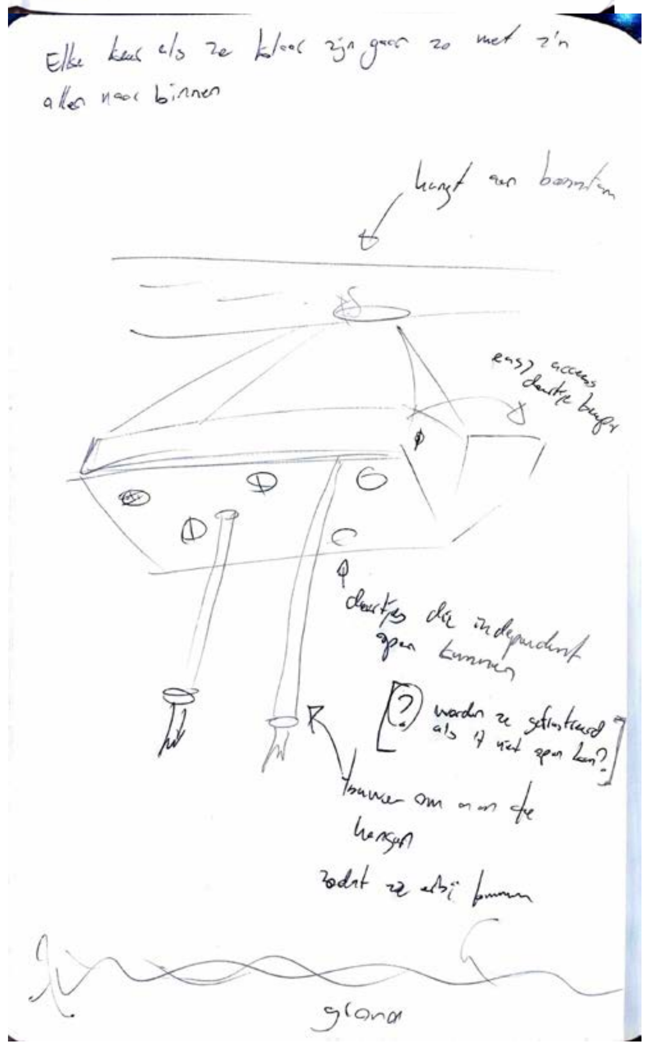


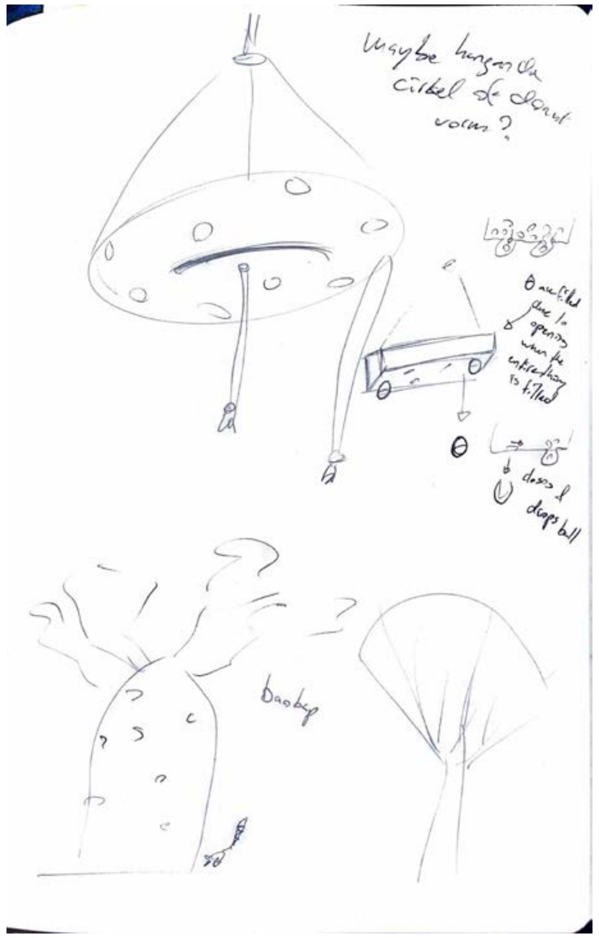






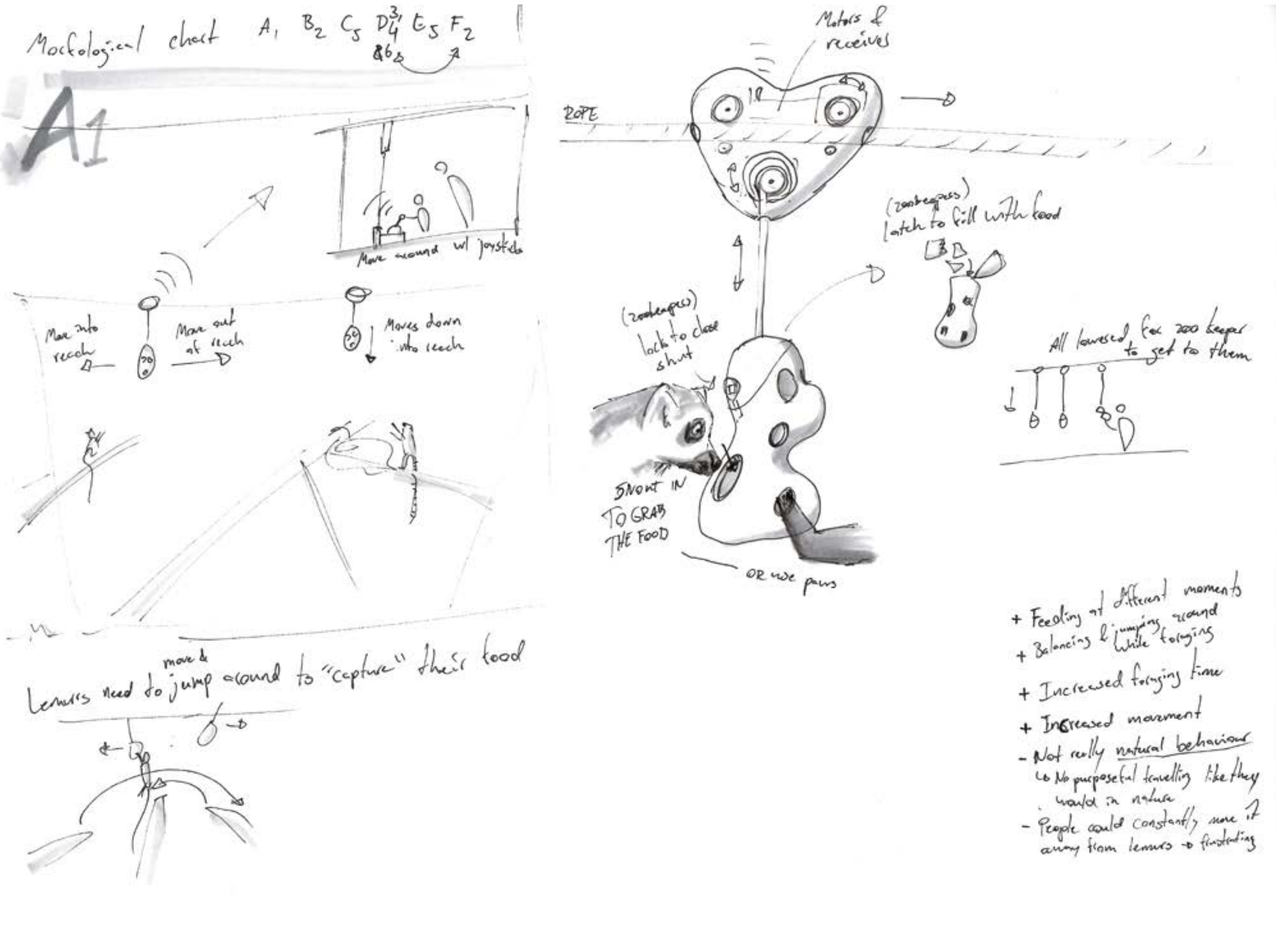


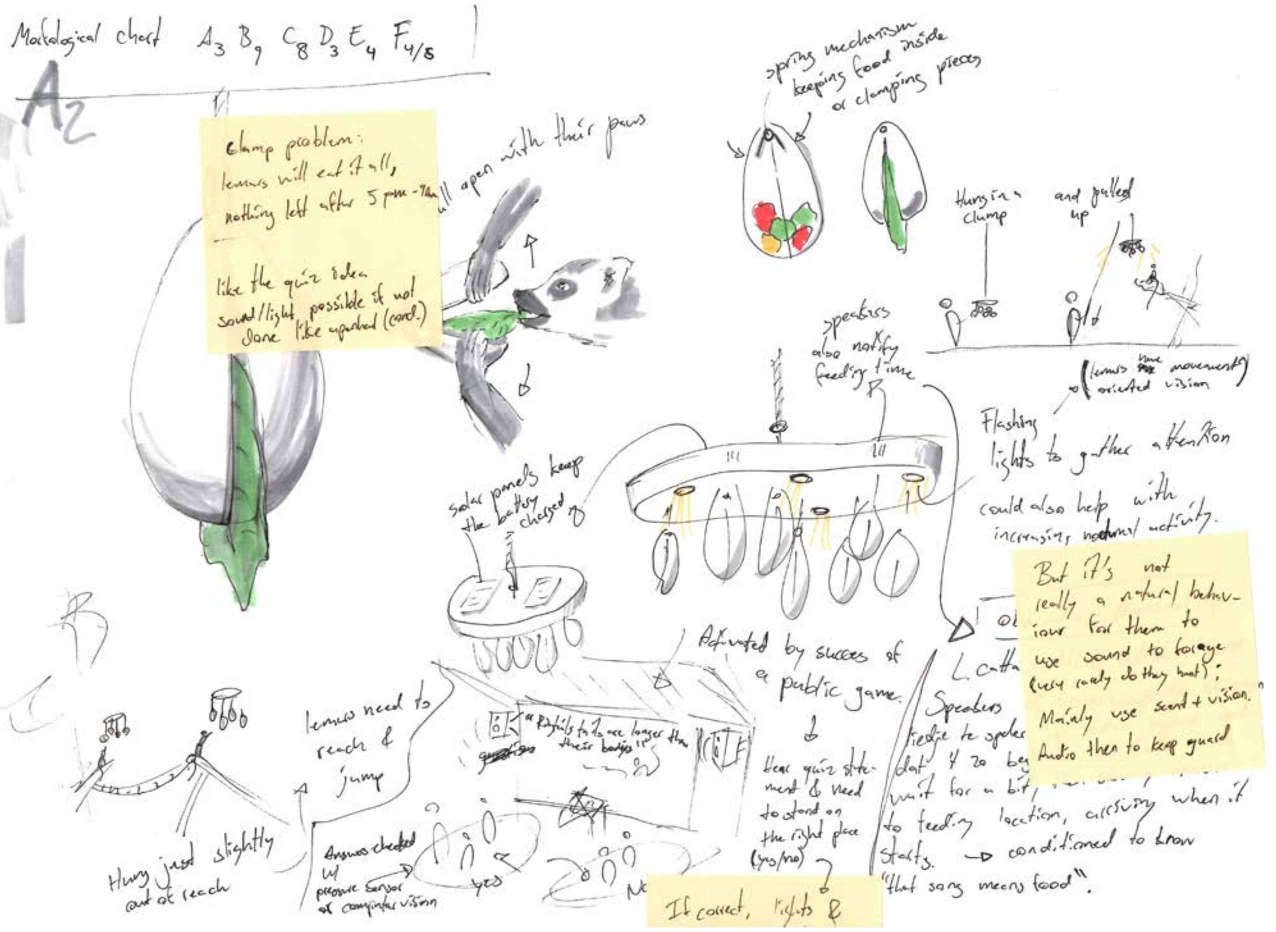


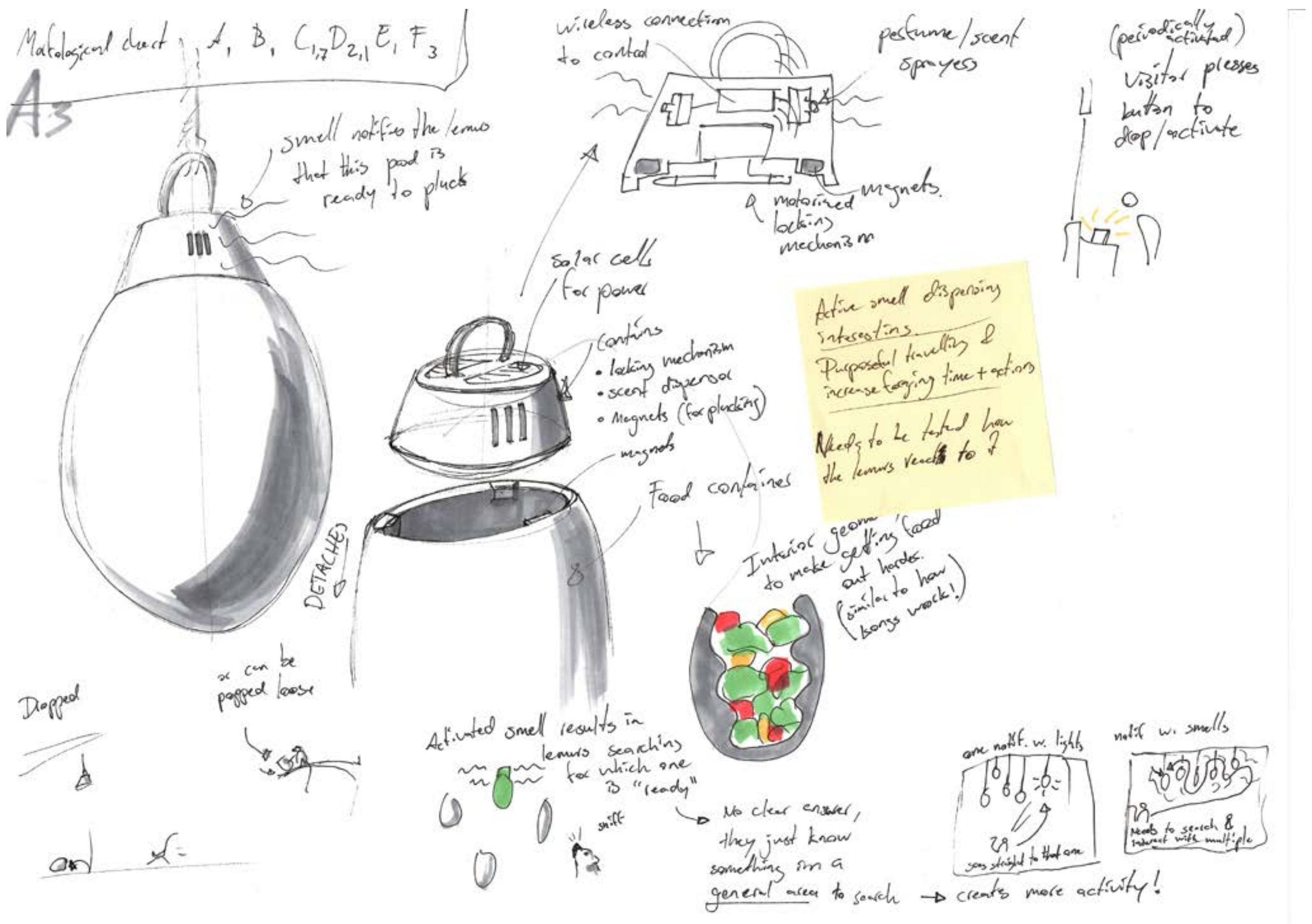


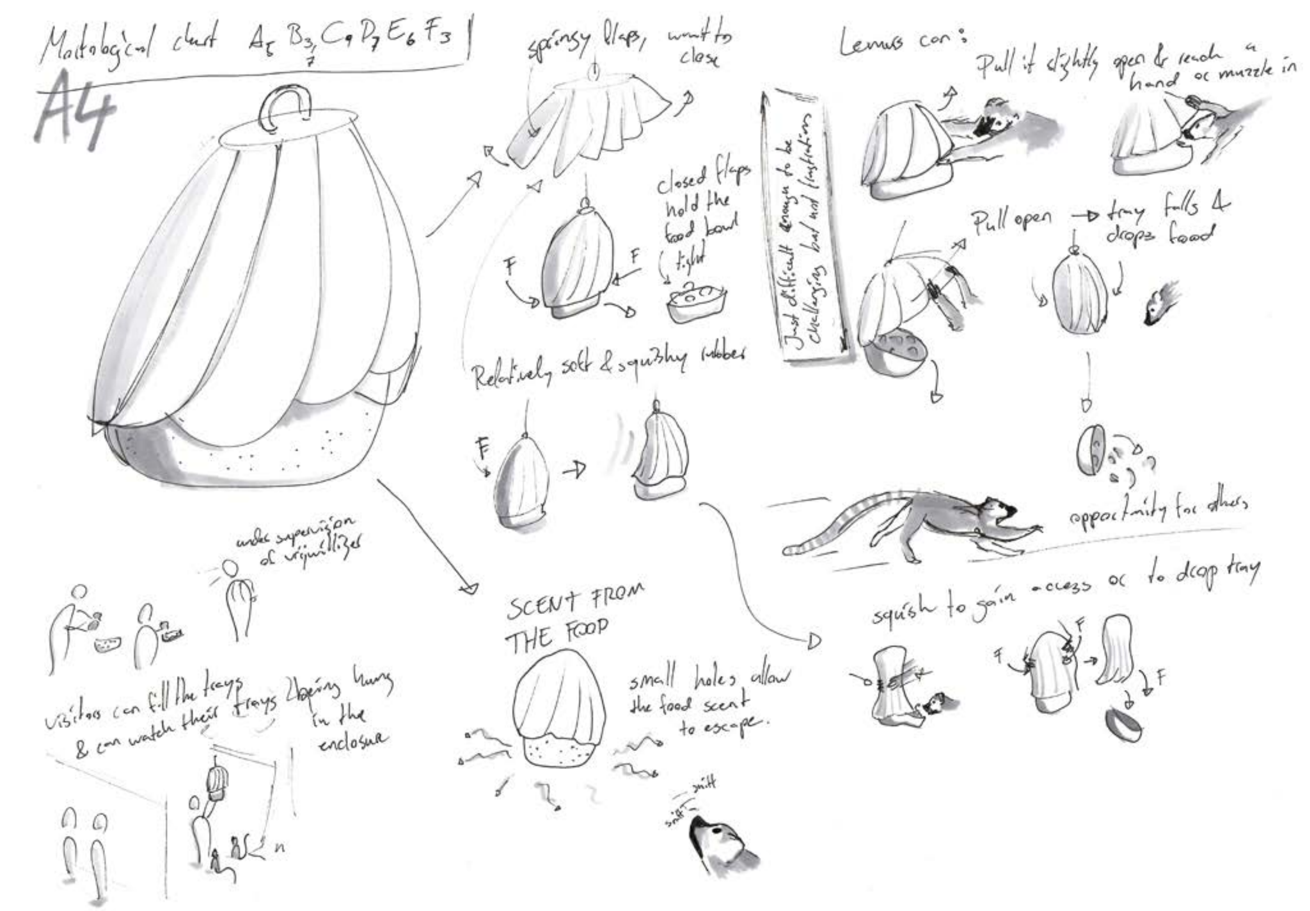
J.2 Morphological Chart A

Here, the first morphological chart used is shown followed by the concept sketches. At the top left of each drawing, the elements used from the morphological chart are shown. Post-its highlight the concepts' plusses and minuses and this section ends with a short elaboration why concept A3 was chosen.









Concept choice

Concept A3 was most preferred for the following reasons:

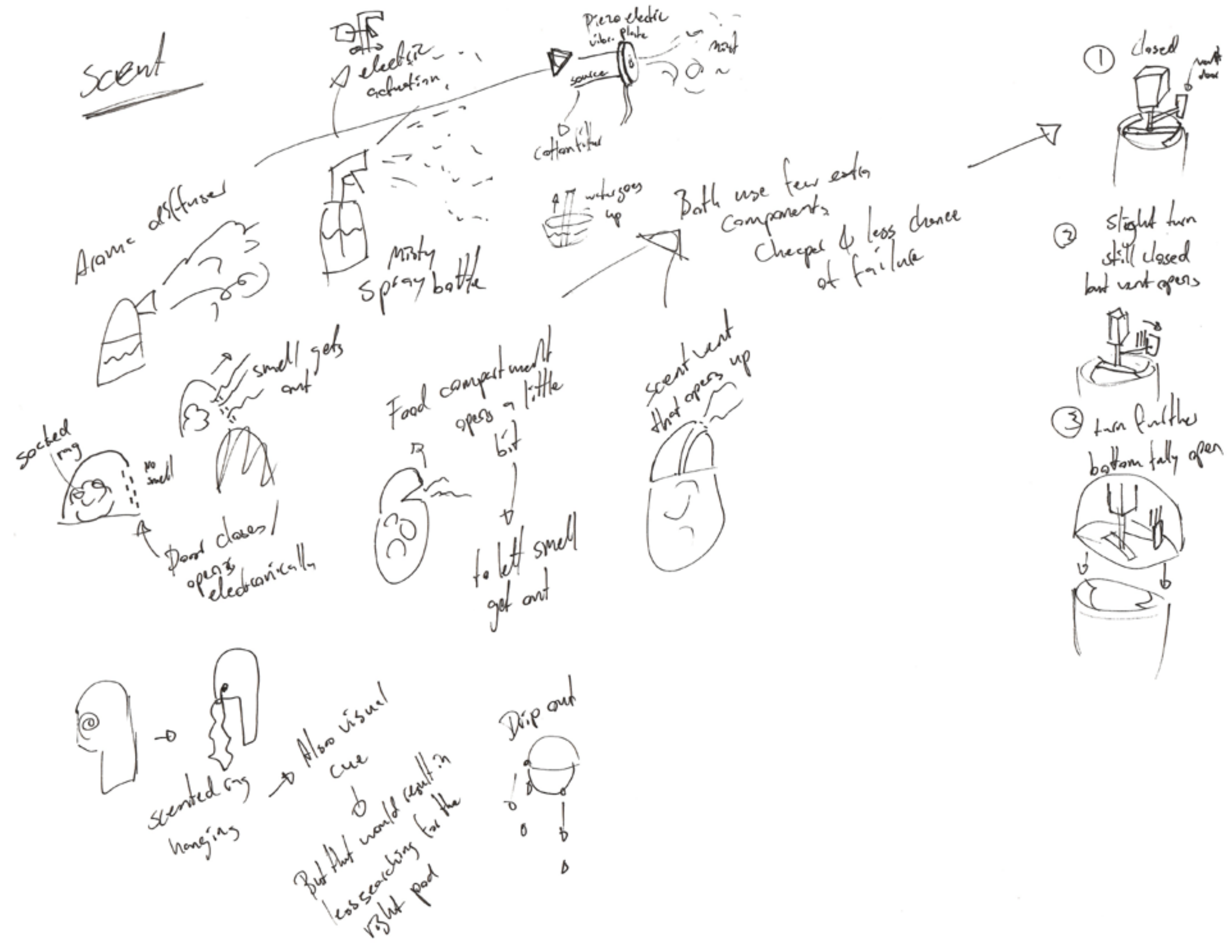
- Its main interaction with the lemurs is like the earlier Kong tests; thus, it is expected that it would intrigue the lemurs.
- It allows for natural behaviours to be exhibited
- A scent emitter that gives the animals a cue that they can search for food – mimicking the natural way ring-tailed lemurs assess whether fruits are ripe.
- its electronic control can make it feel random for the animals, extending the time spent exploring and foraging.
- Each pod is individually powered by a battery and a solar panel, which powers the locking mechanism and allows the pods to be easily moved

Concept A3 was chosen to continue with mostly due to its being the most feasible. Interest and engagement of lemurs for such a pod-like shape has already been established by the earlier prototype tests and its ability to lock so the lemurs cannot eat everything up straightaway followed by its ability to unlock combined with a scent cue results in the lemurs spending more time foraging and being much more engaged.

J.3 Scent, mechanisms, and additional sketches

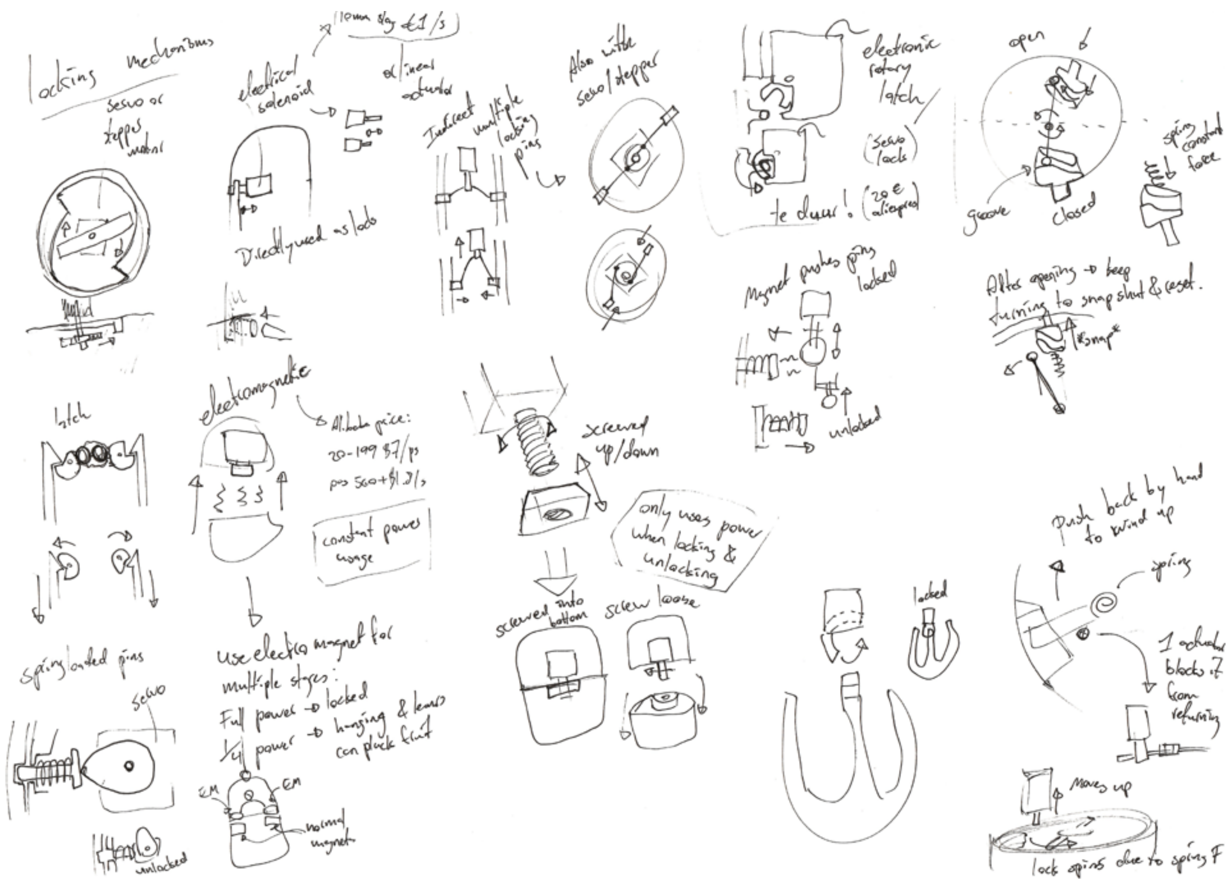
J.3.1 Scent exploration sketches

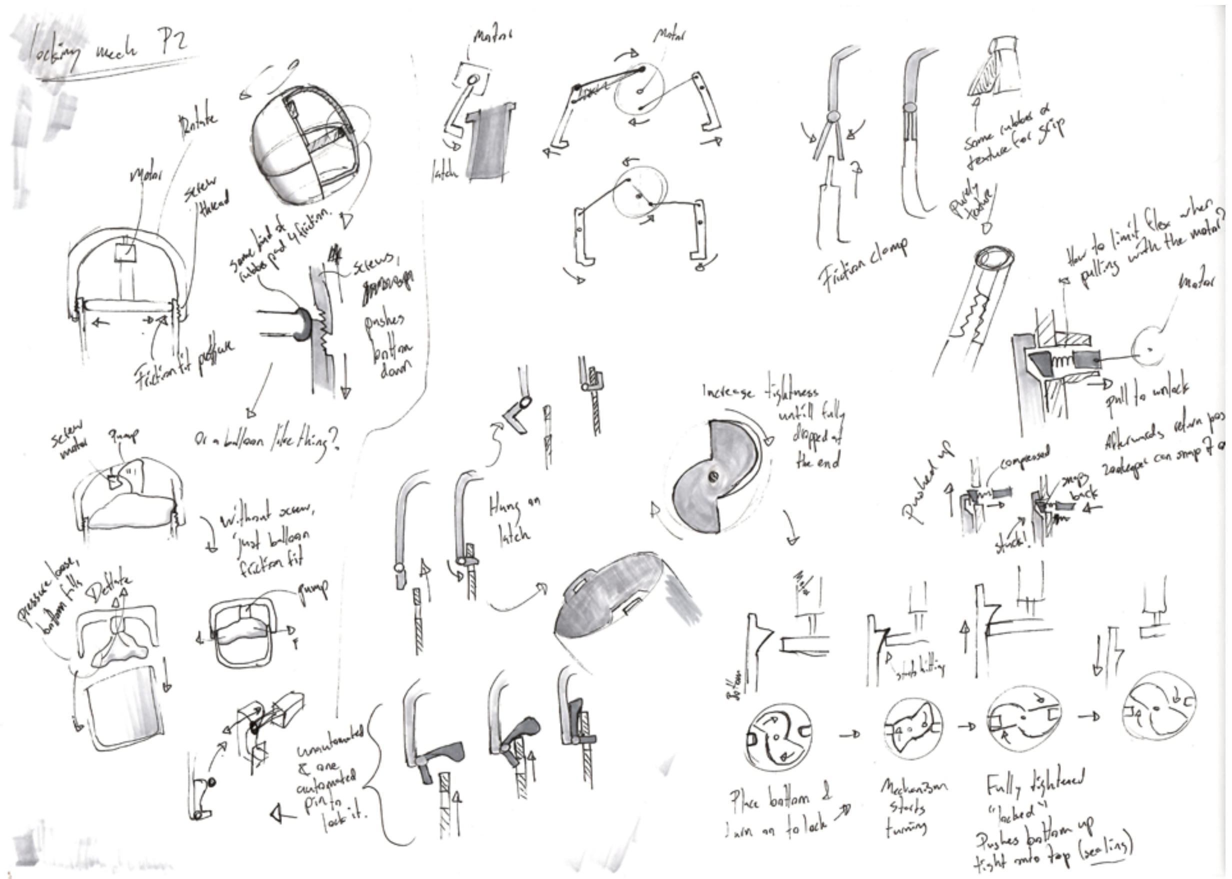
Here, some explored ideas on how to implement a way to emit scents from the pods, meant as a cue for the lemurs to know when food is ready.



J.3.2 Mechanism sketches

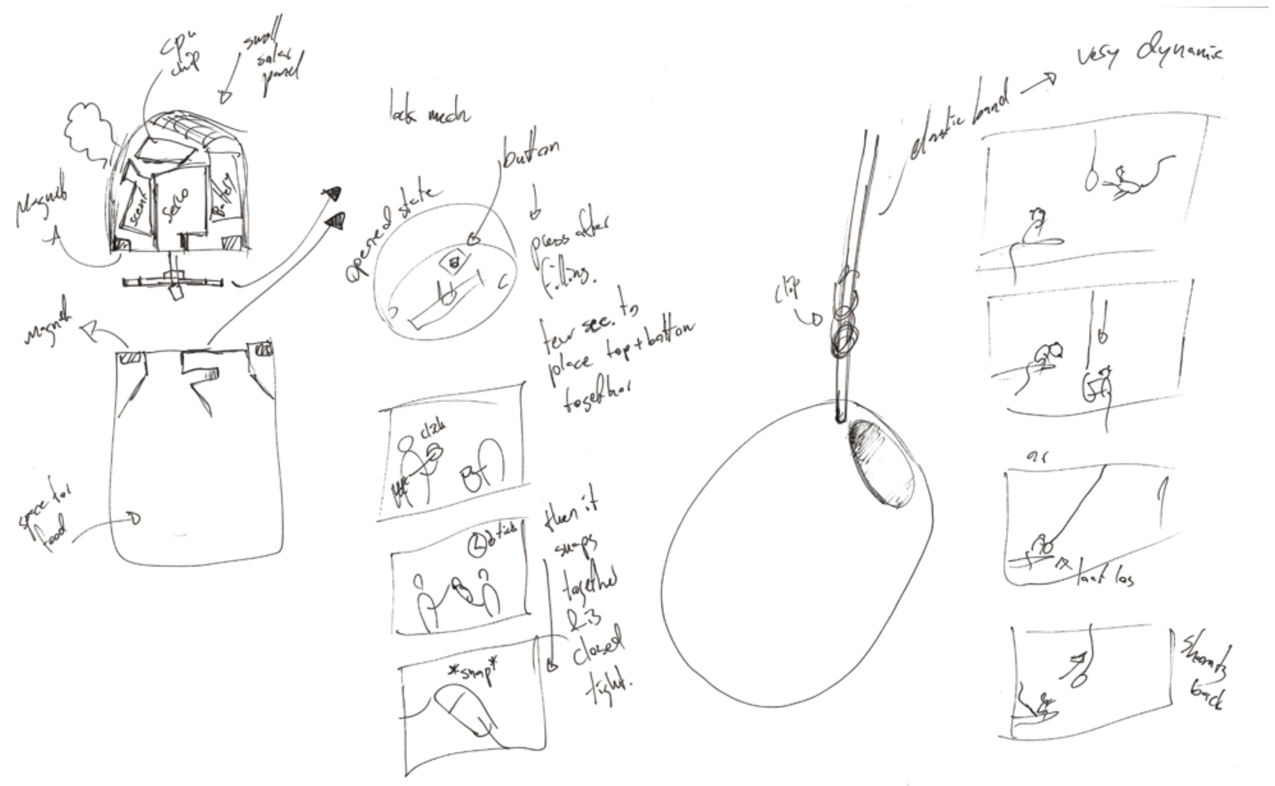
Here, multiple ways to lock the bottom part of the pod to the top are explored.

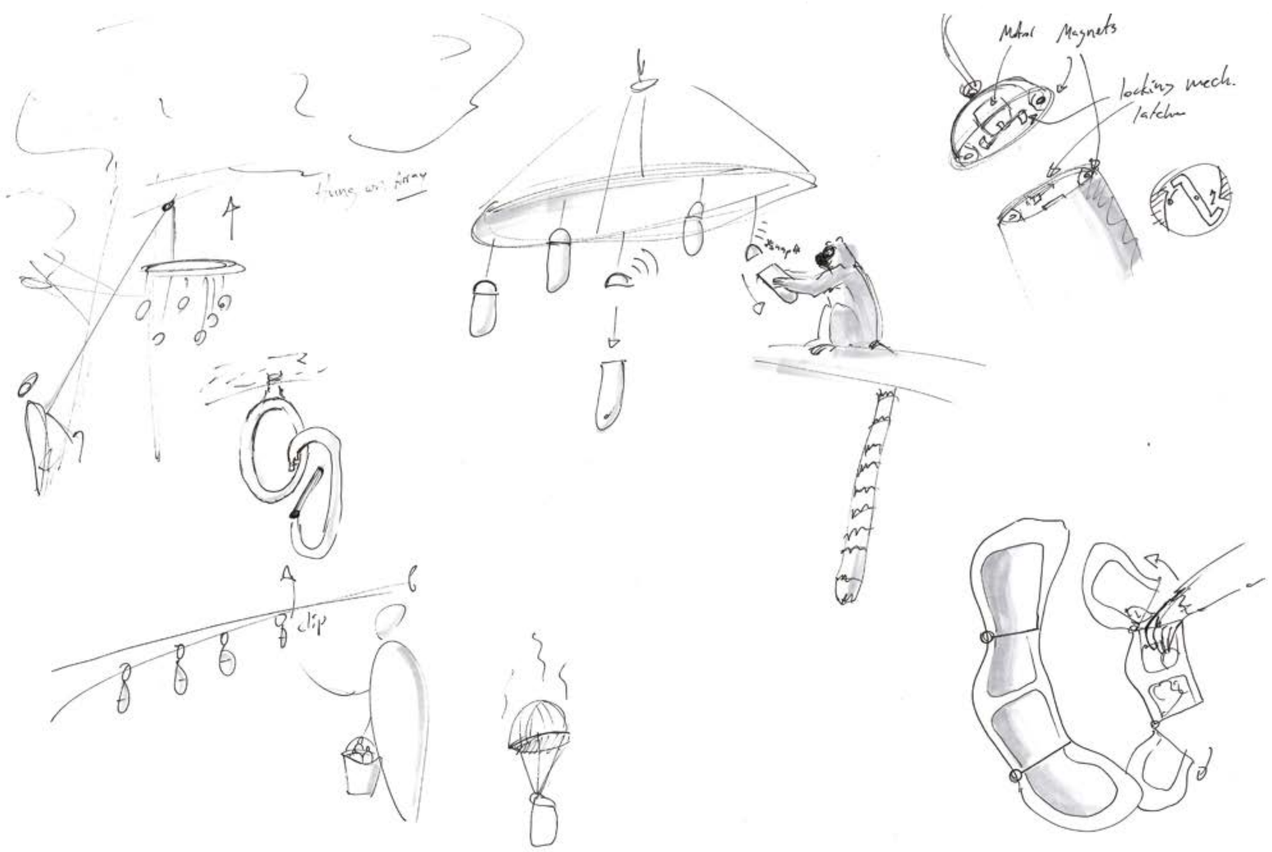


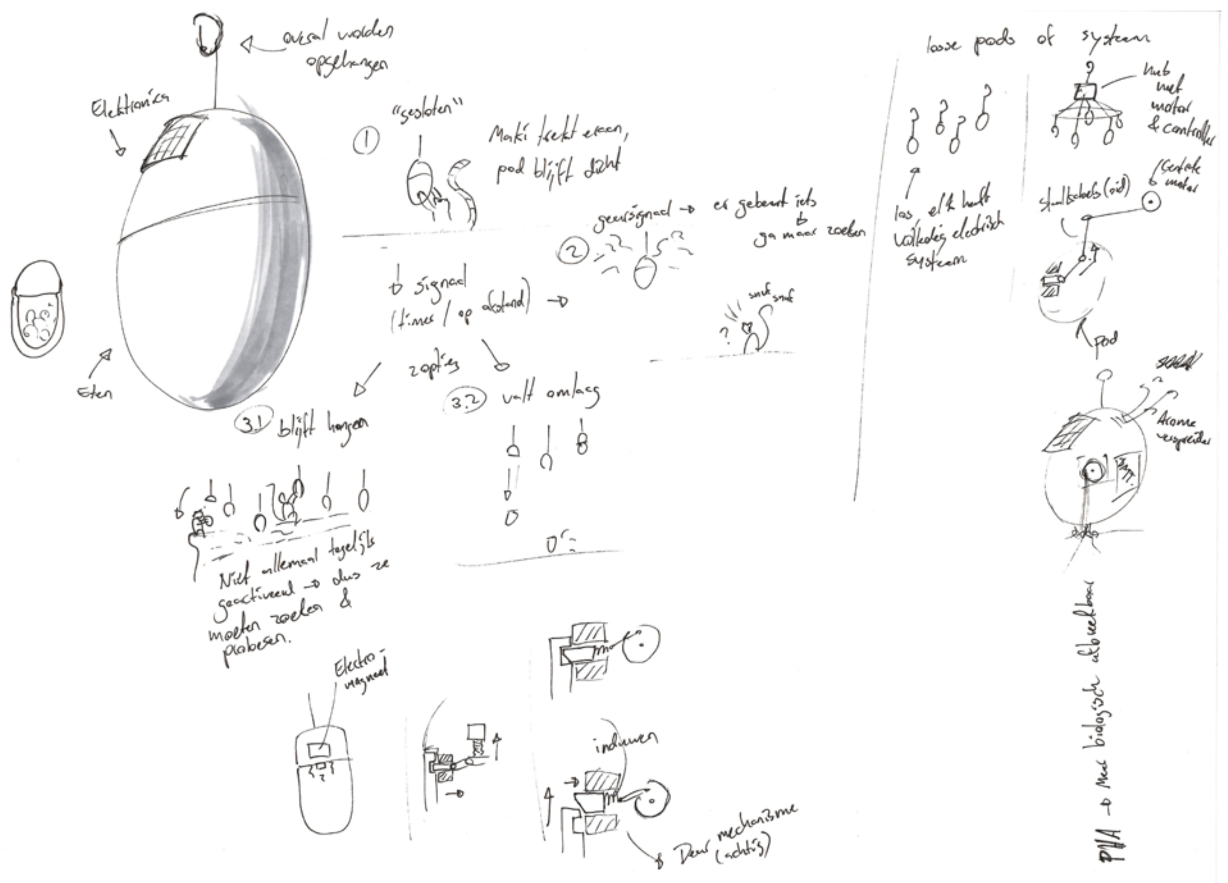


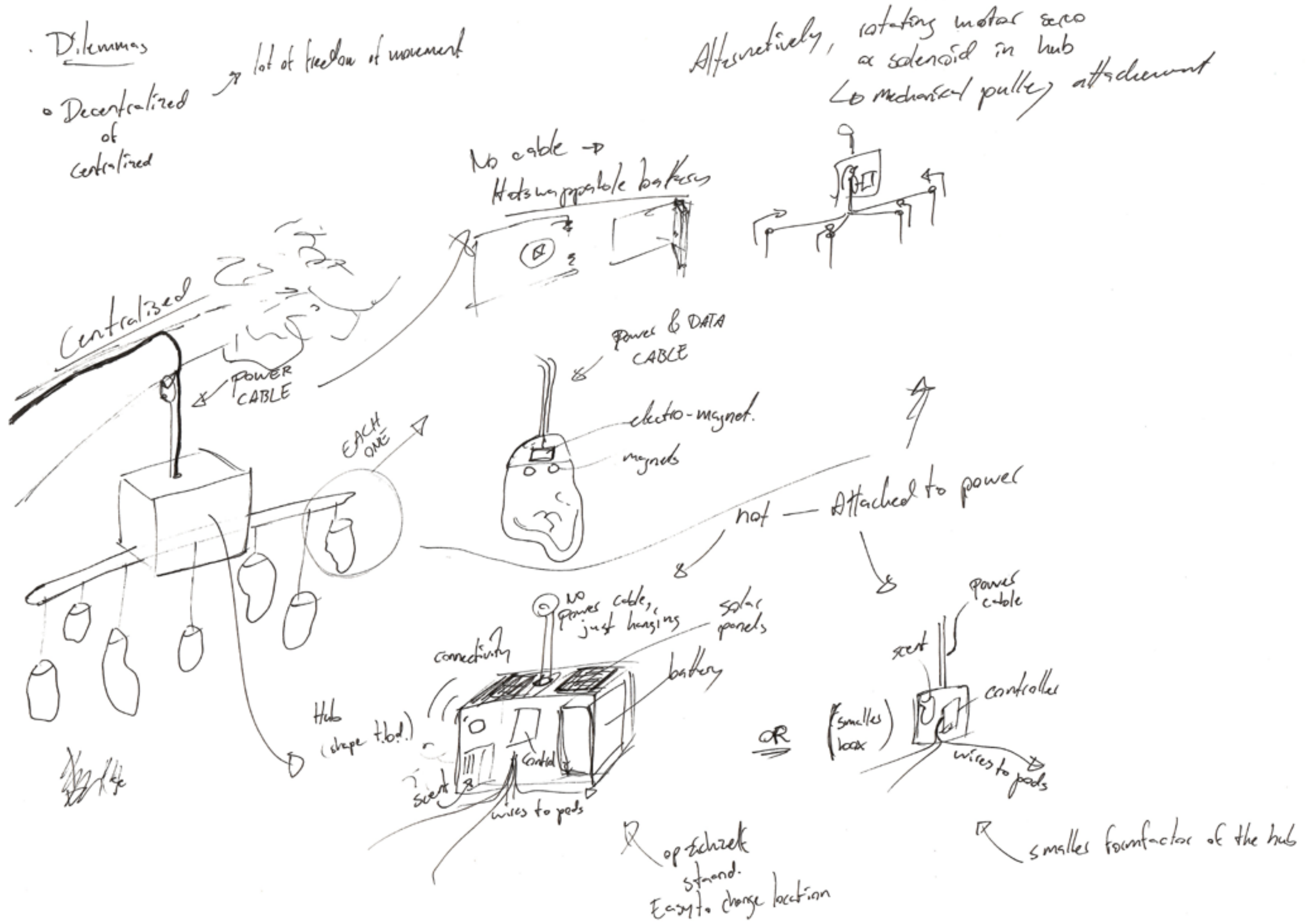
J.3.3 Additional sketches

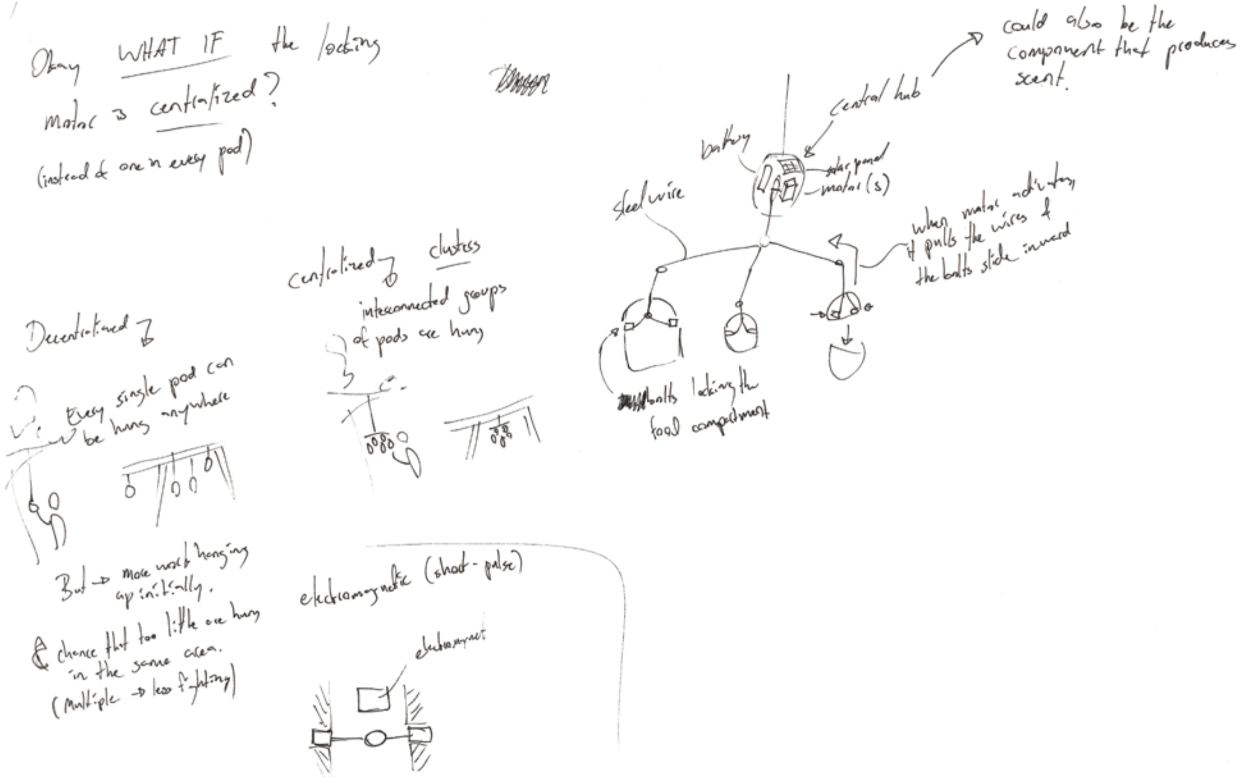
Below, additional sketches are shown which lead to the second round of morphological chart sketches. Of note is mainly the idea of using a **centralised** hub to power all the pods from one place, or a **decentralised** system in which each pod is fully independent. The latter was the premise of the main concepts I had come up with during the previous round of ideation.

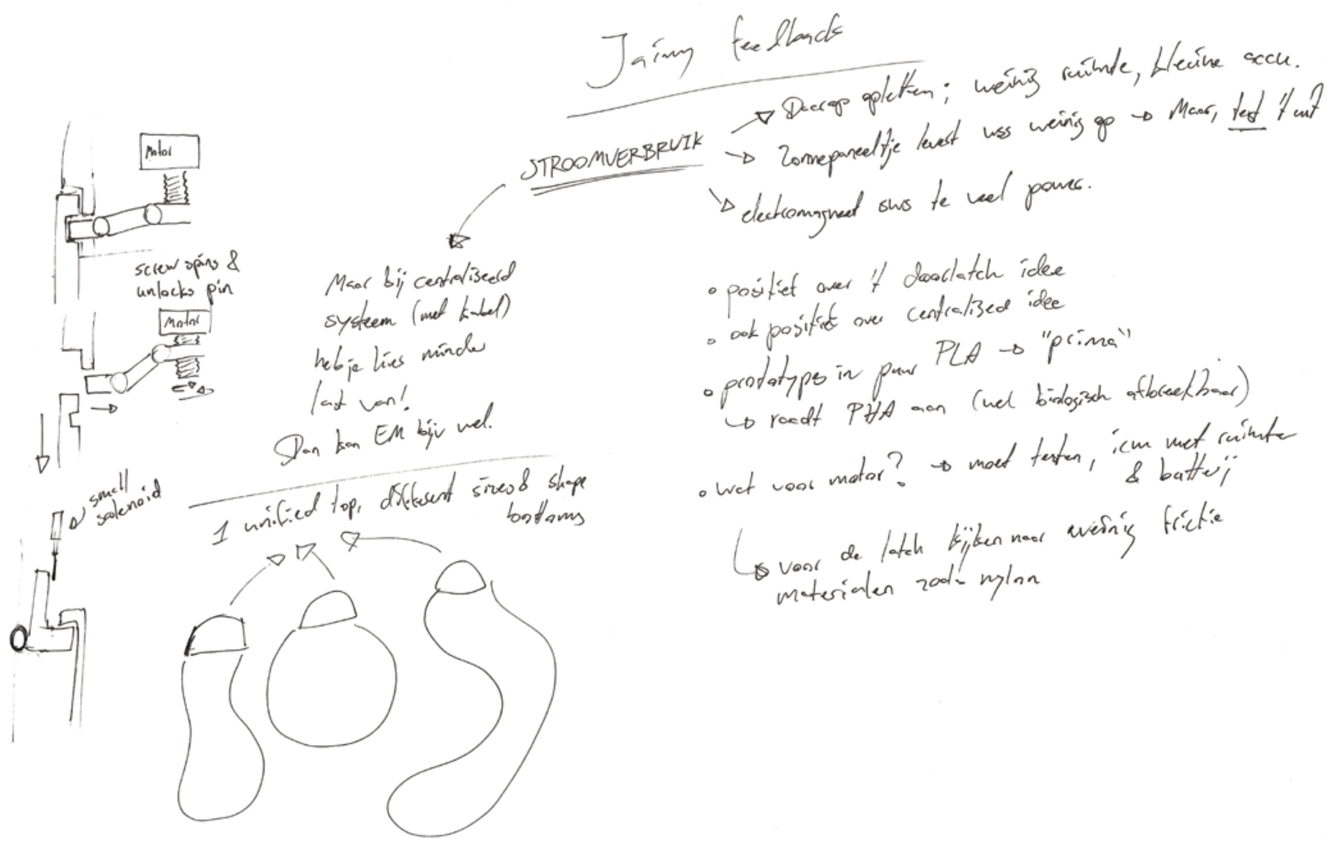





Elektronica
Eten
"gesloten"
2 opties
3.1 blijft hangen
3.2 valt omlaag
losse pods of systeem
Electro-magneet
PHA


Dilemmas
Decentralized of Centralized
lot of freedom of movement
Alternatively, rotating motor servo or solenoid in hub
Centralized
POWER CABLE
EACH ONE
No cable
power & DATA CABLE
electro-magnet
magnets
not
Attached to power
connectivity
solar panels
battery
scent
wires to pods
OR
power cable
controller
wires to pods
smaller formfactor of the hub


Okay WHAT IF the locking motor is centralized?
(instead of one in every pod)
Decentralized
Every single pod can be hung anywhere
centralized
clusters
interconnected groups of pods are hung
central hub
battery
solar panel
motor(s)
steel wire
could also be the component that produces scent.
when motor activates it pulls the wires & the bolts slide inward
bolts locking the food compartment

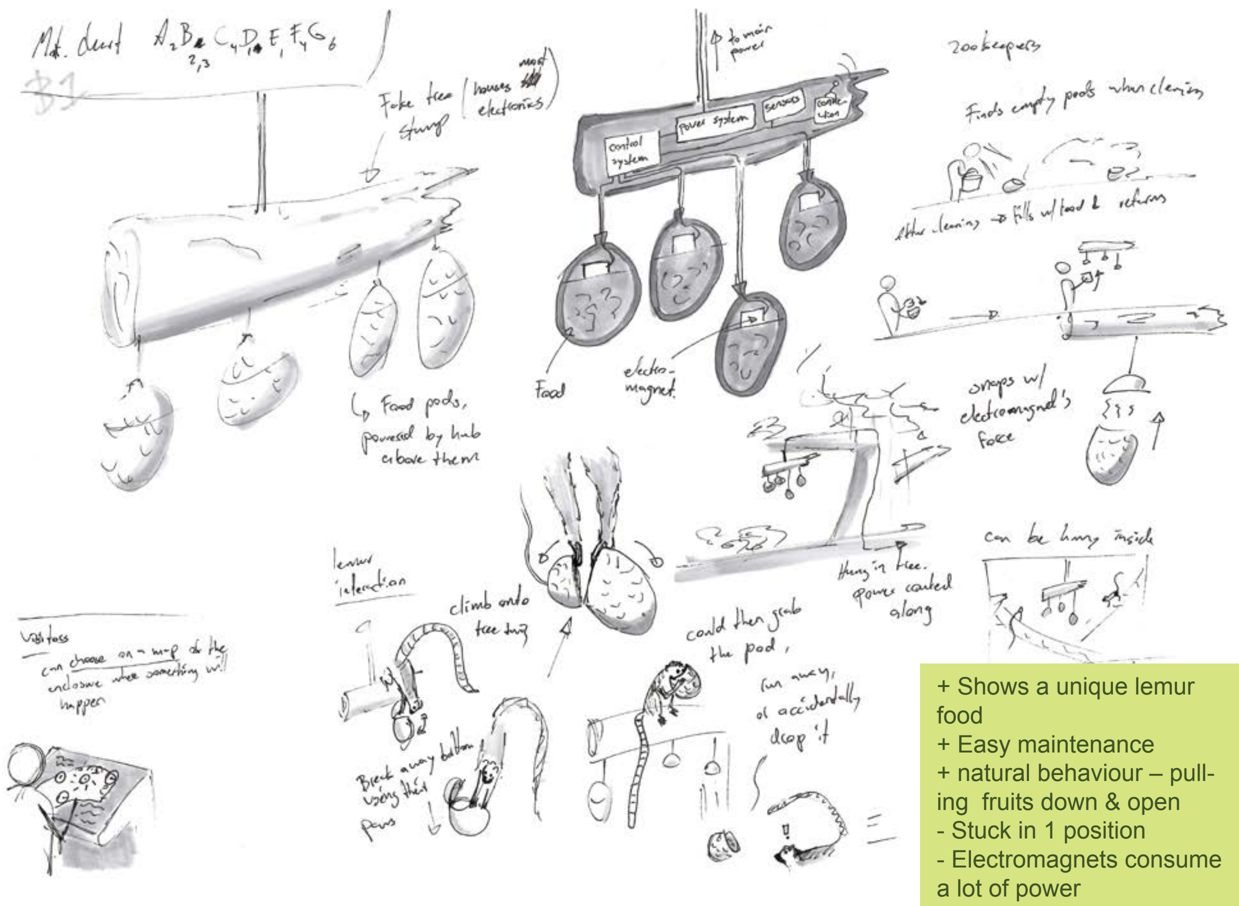

Motor
screw spins & unlocks pin
small solenoid
STROOMVERBRUIK
Meer bij centraliseerd systeem (met kabel)
Dan kan EM bijv wel.
1 unified top, different sized & shape bottoms
positief over het deadlatch idee
ook positief over centralised idee
prototype in puur PLA -> "prima"
wat voor motor? -> moet testen, icm met ruimte & batterij

J.4 Morphological Chart B

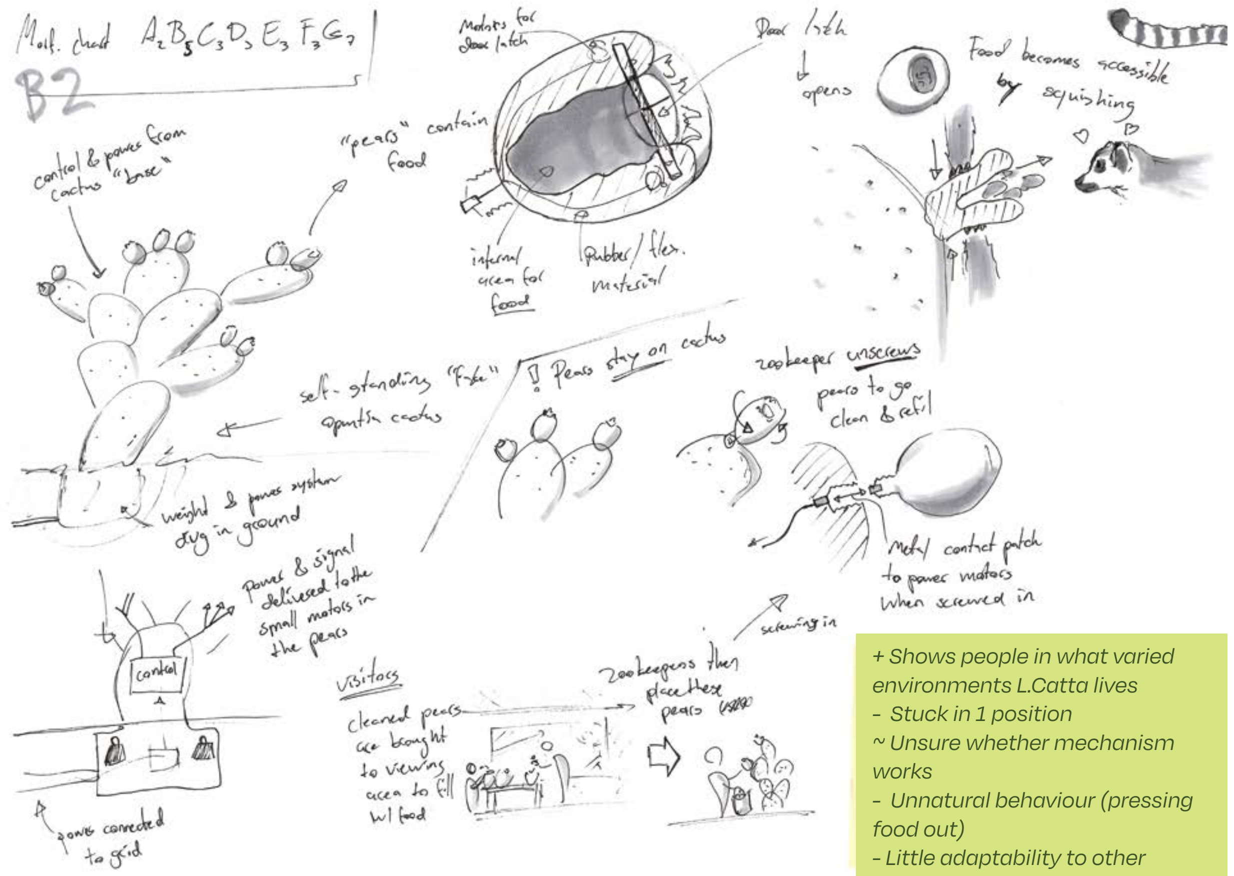
The second morphological chart (B) was created a bit after the first one. I felt the first chart missed some opportunities. The main addition was looking at how the pods are controlled: centralised or decentralised.

The main idea of the concept was a bit clearer through conversations and further research at this point, so aspects like aesthetics were more focused on.

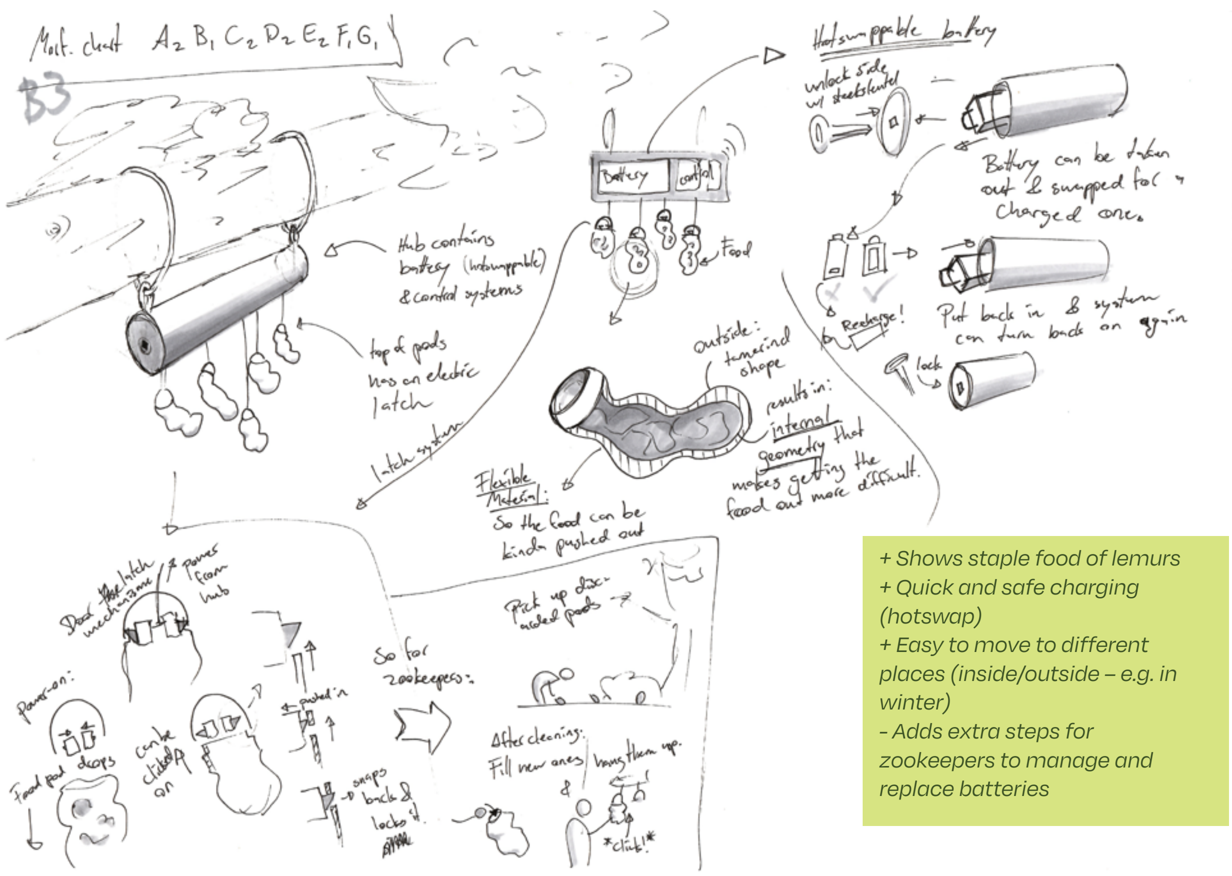
Continuing with ideation, a second morphological chart was created to look a bit more detailed into the concepts. Post-its highlight the concepts' plusses and minuses and this section ends with a short elaboration why concept B3 was chosen.



+ Shows a unique lemur food
+ Easy maintenance
+ natural behaviour – pulling fruits down & open
- Stuck in 1 position
- Electromagnets consume a lot of power



+ Shows people in what varied environments L.Catta lives
- Stuck in 1 position
~ Unsure whether mechanism works
- Unnatural behaviour (pressing food out)
- Little adaptability to other species



+ Shows staple food of lemurs
+ Quick and safe charging (hotswap)
+ Easy to move to different places (inside/outside – e.g. in winter)
- Adds extra steps for zookeepers to manage and replace batteries

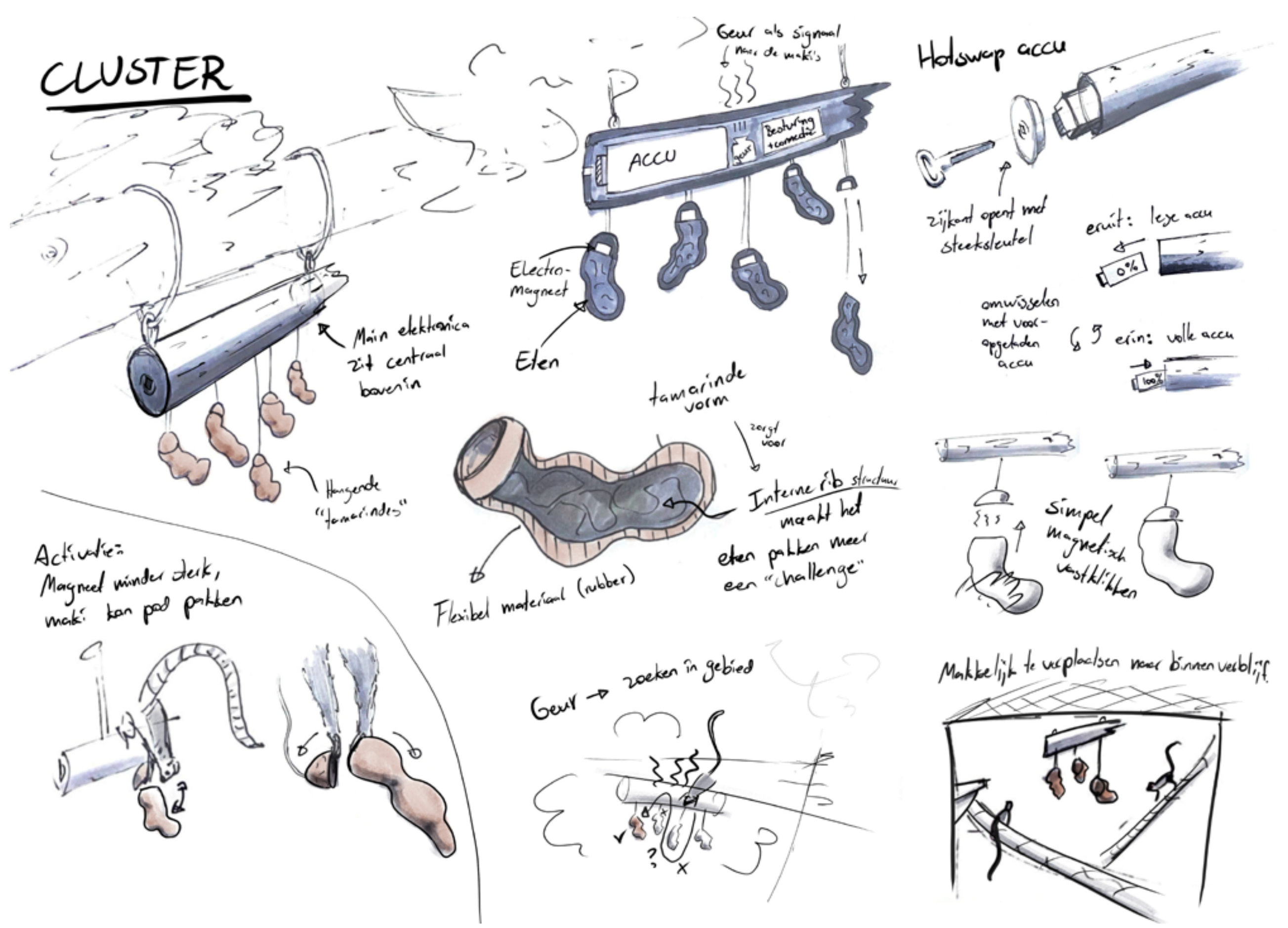
Concept choice

B3 was chosen as the concept to continue and compare against concept A3 due to it showing a staple food of the lemurs (the tamarind) and it being easy to move around. Compared to A3, it is way less of a hassle to change batteries and refill the scent reservoirs as it can be done for multiple fruits at once. Concept A3 evolved a bit more to be in the shape of a soursop like B1 and both of these concepts are elaborated on in the next section.

J.5 Two preliminary concepts

On the next page, the sketches of both preliminary concepts – one individual pod and one consisting of a group powered by one central component – that were discussed with stakeholders are shown. The texts on the posters explain the main points of the concept.

These concepts are both designed to be battery-powered so they can be easily moved around the enclosure and into the indoor spaces, while requiring minimal modifications to the existing setup and layout of all enclosures.



Appendix K. Ring-tailed lemurs and fruits

In this appendix, first a large list of fruits eaten by wild ring-tailed lemurs is given. In the second section these are put in a collage which is then visualised into how lemurs see the fruits. Finally a choice is made for the Soursop to use in this design.

K.1 List of fruits eaten by ring-tailed lemurs in Madagascar

This section gives a list with images of all fruits ring-tailed lemurs have been observed eating by Gabriel, 2013; Jolly, 1966a; Simmen et al., 2006.

Name food	Photo food	Additional notes
Tamarindus indica ~ Tamarind		If available, it is a huge part of the ring-tailed lemurs' diets - eating everything from the trees: leaves, fruits, flowers, buds, stems, and even wood (sometimes)
Celtis gomphophylla		-
Ficus Grevei ~ Fig tree		-
Tarenna Grevei		Grow in the south and west of Madagascar, where the lemurs live
Carica papaya ~ Papaya		-

Name food	Photo food	Additional notes
Cocos nucifera ~ Coconut		-
Opuntia vulgaris Mill. ~ xx		Invasive plant, introduced from the south
Barringtonia racemosa ~ Manandrondro		-
Capparis ~ Roy		-
Carissa spinarum ~ Fantsimbala		-

Name food	Photo food	Additional notes
Erythroxylum platycladum * ~ Menahihy		-
Albizia spp. ~ Sambalahy		-
Grewia ~ Sely		-
Harungana madagascariensis * ~ Tambihitse		-
Melia azedarach ~ Melia		-

Name food	Photo food	Additional notes
Passiflora incarnata ~ Passiflora		-
Psidium cattleianum ~ Guava		-
Solanum lycopersicum ~ Tomato		-
Turraea sericea * ~ Lafara		-
Anisophyllea fallax * ~ Hazomasy		-

Name food	Photo food	Additional notes
Aphloia theiformis ~ Voafotsy		-
Bremeria spp. * ~ Fatora		-
Diospyros spp. *		-
Mangifera indica ~ Mango		-
Mystroxylon aethiopicum ~ Vovona		-

Name food	Photo food	Additional notes
Tricalysia cryptocalyx * ~ Hazonkira		-
Poupartia minor * ~ Sakoa		-
Vepris elliottii * ~ Ampoly		-
Musa ~ Banana		-
Rinorea greveana *		-

Name food	Photo food	Additional notes
Cedrelopsis grevei *		-
Noronhia seyrigii *		-
Strychnos madagascariensis		Grows only in Madagascar and east africa coast
Hydnora esculenta *		Parasitic flowering plant
Flacourtia ramontchi *		-

Name food	Photo food	Additional notes
Annona L. ~ Soursop		Multiple species
Adansonia ~ Baobab		-

K.2 Collage & visualisation of how lemurs see food

On the next page, a representation is given of how these fruits are seen by the lemurs, showing that the colours of fruits do not matter as much to lemurs as they do to our human eyes. A contrast in brightness between the fruit and its environment seems more noticeable than a difference in hue. This also makes it clearer why lemurs rely more on scent to forage (as was explained by Cunningham et al., 2021; Jolly, 1964; Rushmore et al., 2012; Sauther et al., 1999)

Figure K1. A collage showing most of the fruits that Lemur Catta eats.

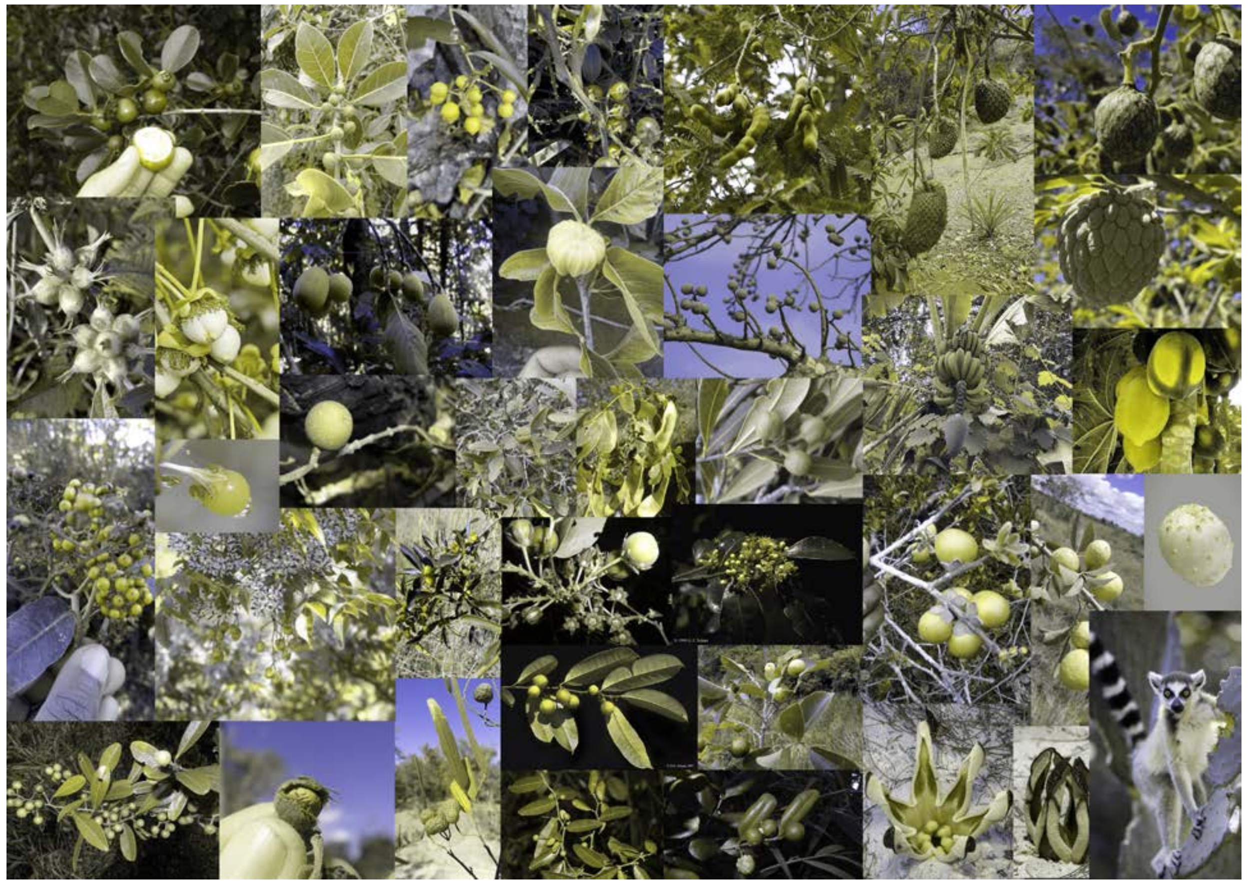


Figure K2. The same image adjusted to show how a ring-tailed lemur sees the fruits

K.3 Fruit inspiration for the preliminary concepts

Below an overview is given on what type of fruits were used in ideation for the preliminary concepts. The groups with the reason why they are interesting to look at are explained on the left.

K.4 Final fruit choice

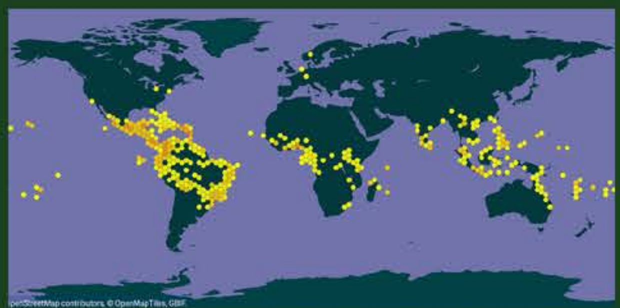
The design should look natural; thus, it was not feasible to make it look like the small berries or uniquely shaped endemic fruits without dramatically changing their size. From an educational perspective, it is preferred to showcase fruits they normally eat over something that is rarely eaten, as the latter could forge a skewed understanding of lemur life. Hard tamarind-like pods were also discussed in a stakeholder meeting and deemed not preferred. The lemurs are sometimes given real tamarind, in which case a bigger, fake tamarind would feel out of place. Besides, the longer and smaller shape would make putting food in and especially retrieving it for the lemurs too hard.

As a result, bigger fleshy fruits are preferred, so the soursop was deemed the best fruit to use, as this is something that ring-tailed lemurs eat (when available), and it has a very intriguing shape. This can make it very memorable to visitors and pique their interest. It is an introduced fruit, originally from southern America, which is an interesting fact to tell visitors in combination with educating them on that introduced plants can have on foreign ecosystems. Mangos have a similar foreign origin to Madagascar, yet them being so well-known would not interest visitors as much as the "weird" soursop. Everyone who has seen the sketches and images has reacted in a similar way, by being intrigued and consequently asking what kind of fruit it is.

Soursop

Annona Muricata

- Native to Southern America, introduced in Madagascar.
- Varying sizes from 10-35cm
- *Relatively unknown fruit with a unique and intriguing shape, which gives it the ability to intrigue and engage visitors*



African custard apple

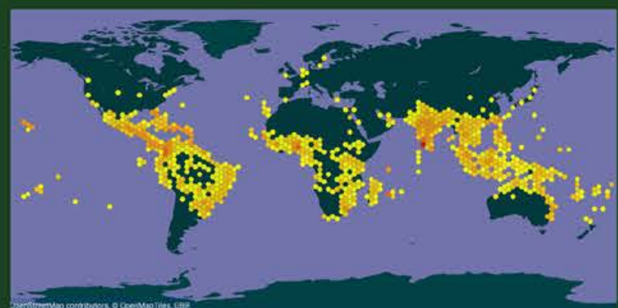
Annona Senegalensis

- African Annona variant, native to the continent & Madagascar
- Around the size of an apple (5-7cm)
- Relatively unknown fruit that stays under the radar

Mango

Mangifera Indica

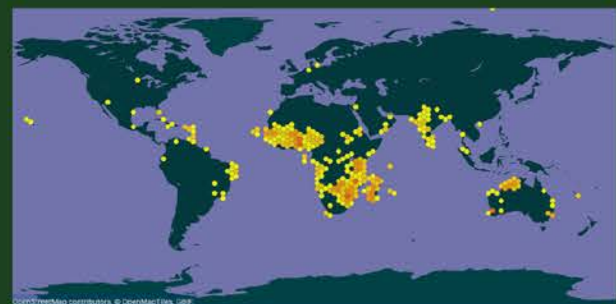
- A fruit originally from India and south-eastern Asia introduced all over the world in tropical regions.
- Around 10-15cm
- Very known fruit



Baobab

Adansonia

- Native african fruit which is very typical in the skylines of Madagascar
- Around 5-7cm
- *! There have been no observations of (ring-tailed) lemurs eating a Baobab fruit, probably due to the fruit having a very hard and thick husk*



Map data from Global Biodiversity Information Facility (n.d.)

Figure K3. Comparison final selection fruit

Appendix L. Reasoning behind the choice of the final concept

More reliable stationary solution

there was a clear consensus that moving away from a battery-powered system and thus hanging the pods on a powered fake tree would be best for reliability's sake. Fewer components would be needed in the animal enclosure, meaning fewer could break, and there would be no need for the zookeepers to keep managing battery percentages and swap them where needed. While optimising the mechanism for low power usage is now less needed, the doorlatch mechanism, where only power is used when locking and unlocking, is still preferred due to increased long-term reliability and heat generation.

Lemur locomotion

My initial focus on designing the concept to be easily movable to encourage the lemurs to travel to different spots was deemed unnecessary by the zookeepers, as they explained the lemurs would show similar behaviour with a non-movable system.

By placing the fully integrated non-movable system at the front of the enclosure near the open viewing area, the lemurs would, after feeding, move away to the back of the enclosure, where there is a lot more tree and shrub coverage. Activating the system again, then, would prompt the animals to return to the front of the enclosure, and after some time, they would again move to the back on their own accord.

Aesthetics

In terms of aesthetics, this was clearly also preferred over the movable options. The latter would result in a lot of hooks, carabiners, ropes, or tie wraps hanging in the enclosure, something which is preferred to be reduced.

An integrated system can be shaped to look like a tree, making the entire concept look more natural, improving the visitor experience – creating an eye-catcher. For this, three possibilities were explored as shown in Figure L1, L2 & L3. These have varying levels of costs. A full artificial tree is the most expensive as the foundation needs to be built, power needs to be dug underground and the entire thing needs to be designed and shaped. Artificial branches near the visitors windows are cheaper, as less material is needed and power connections can be gathered from inside the hut. The third and cheapest option is modifying the already existing Baobab tree

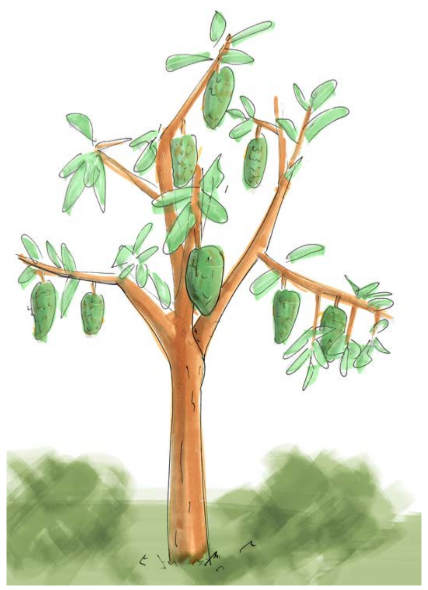


Figure L1. Sketch of Soursop pods hanging on an artificial tree

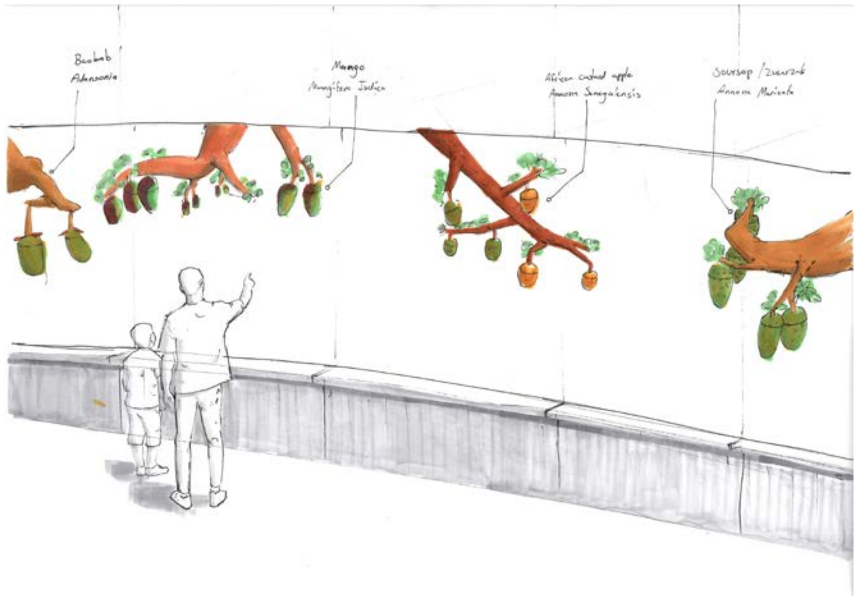


Figure L2. Sketch of the potential view from inside the visitor part of the exhibit, looking over the four final fruits. The fruits are hung from branches that start outside of the view of the visitors

Figure L3. Sketch of modification of the already existing Baobab tree in the ennclosure

in the enclosure. There is an existing power connection inside used for a heater which is underused by the lemurs. All three options result in the same outcome for the lemurs; so it is almost entirely an aesthetic choice. Within the budget available for the project (based on the cost analysis Appendix S, combined with an estimation of companies that would be building the branches) it was then decided to go for branches emerging from outside of the viewers' vision.

Fruit choice

Elaborated on in the previous Appendix K.

Scent

Emitting scent using some kind of diffuser and fluid from the pods was deemed unfeasible, as managing and maintaining each of these tanks inside of the enclosure & product would be too much of a hassle. So, the concept should use a preexisting scent machine. Rotterdam Zoo is starting a collaboration with RetroScent to create a custom solution for the polar bear exhibit. Using the same company or a similar company to implement a scent system standing outside of the enclosure, connected to the pods, is a better solution. This can be periodically refilled and put in the dominant wind direction. Also, the use of fluid is very little, as the scent machine is only active for short bursts of time. Due to this it will cost much less to operate than scent machines which are on the entire working day (which is more of the norm).

Visitor interaction

The ideas to create a kind of interactive game with the pods was deemed out of scope for this project and thus recommended as further research, as it entails much more research to be safely and successfully implementable. There are many difficulties in implementing a direct interaction at the volume of visitors Rotterdam Zoo gets in a day. With the example of an interactive quiz with buttons or something else where the visitors can directly influence what happens in the enclosure / with the pod, the difficulty highlighted is that quarrels could start between visitors wanting to be the ones to do the interaction and others feeling left out. This is not something easily fixed – I imagine it could be an entire graduation project of itself! – and thus deemed out-of-scope.

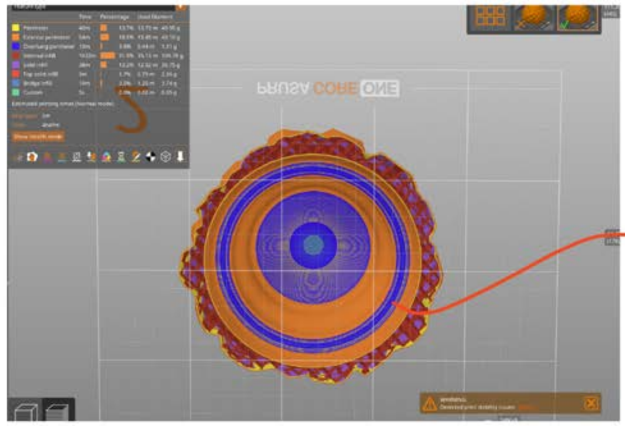
A poster/plaque in the visitor area can explain the story of the introduced soursop and how this enrichment design works and improves the lives of the ring-tailed lemurs. Placing a physical copy of the pod that visitors can touch makes it more engaging. This was discussed with the education staff about the entire lemur renovation project, but was deemed out of scope of this project as well.

Appendix M. 3D-print geometry optimisations

This Appendix shows the milestone steps in hollowing out the 3D model of the soursop fruit and creating ribs on the inside to hold the food that will be placed inside as well as the 3D-printing steps and main iterations.

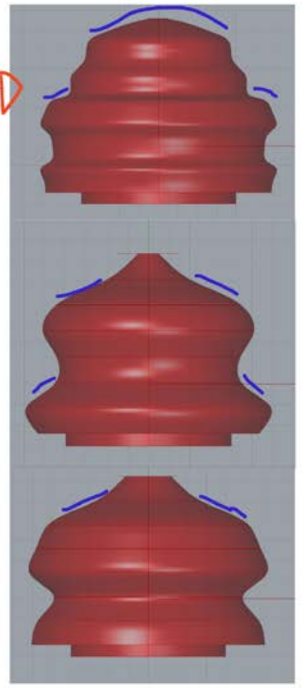
M.1 Internal geometry

As the prototypes are 3D-printed and TPU supports are horrible to remove, some effort went into shaping the internal geometry to be 3D-printable without need for supports. The fruit geometry is cut near the top so that we have a bottom part which is to be hollowed out, and a top part, from where the fruit can be hung and where the locking mechanism will be placed.



View from bottom → dark blue are too big overhangs. Especially the middle dark blue circle is almost printing in thin air.

Evolution of the internal geometry for the first prototypes

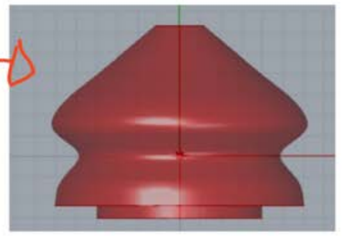


Angles too steep → print failed (printing circles in the air)

→

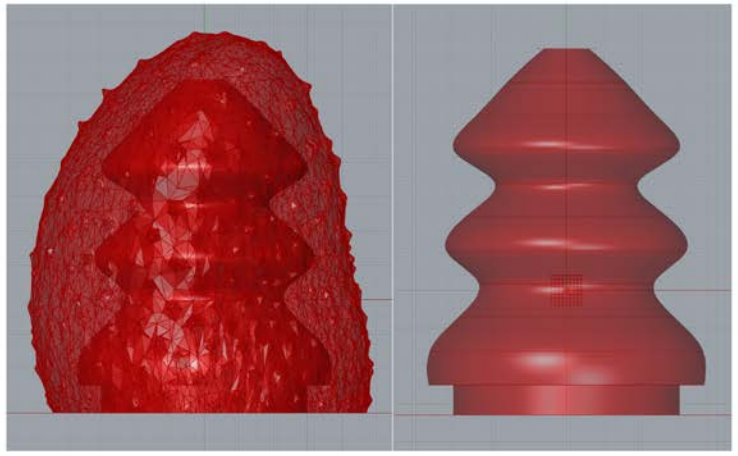
Design improvement: Less steep angles upward. Top 50° constant instead of increasing. Bigger flat spot in middle (for bridging; easier to print)

View from bottom → note there are no dark blue lines of angles that are too steep for the printer. The middle part is a lighter blue which means "bridging", where the printer will print straight lines in the air, something it can do easily over a couple of centimetres

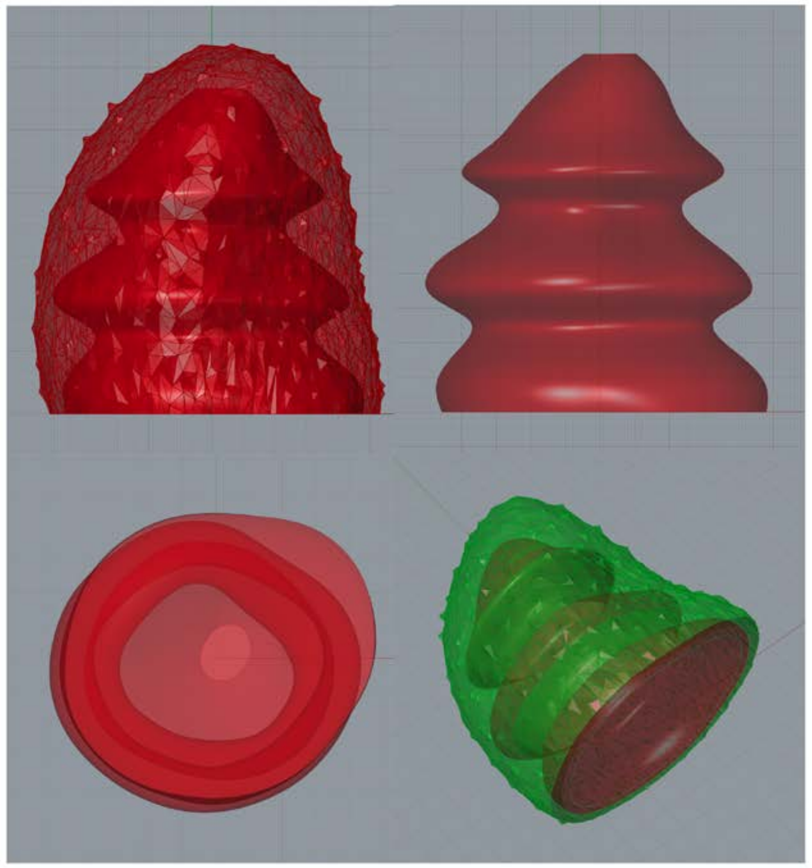


Sideprofile of the improved internal geometry

These findings were then used in the next iterations resulting in the prototype printed in TPU and tested in the animal enclosure



The following evolution of the internal shape follows the shape of the imported fruit's geometry and is then manually tweaked to be 3d-printable.



Using the geometry of the fruit to shape the inside is something that might make it more difficult for the lemurs to get the food out. This should also make the Rhino Grasshopper script easier adaptable for other (less round) fruits where a similar approach can be used.

M.2 3D printing material

The first prototypes (white) were printed using TPU (thermoplastic polyurethane) with a hardness of 95A, which is slightly compressible but quite hard. These prototypes held up well after a month of use but lemurs cannot hold them by biting the material as it is too hard.

The second batch of prototypes (green) are printed using TPU with a hardness of 85A, which is quite softer. Using 2 perimeters in the print settings resulted in a very soft pod, according to the zookeepers too soft as they do not expect this to hold up as well as the earlier prototypes. This, however, allows the lemurs to carry the fruit in their mouth by biting in it.

95A prototype squished

85A with 2 perimeters squished

85A with 3 perimeters squished. This prototype feels softer compared to 95A – it it place relatively in the middle of both options.

Lemur holding the 85A 2 perimeter prototype with its teeth.

Appendix N. Results prototype observation

This appendix gives an overview of the results of the 7 observations done with the first 2 magnetic prototypes.

Test	Version	Time & weather	Type of food	Time until pod dropped (after hanging it up)	Time until empty	Distance pod moved	Notes
1	A	12:00	Cherry tomatoes & lettuce	53 min	10 min	<1m	Little interest at first as the pod entered the enclosure closed. After opening and showing the lemurs the inside before closing it again, slight interest, but quickly given up and left alone. After all other food sources were empty and after a resting period, the pod was interacted with
	B	Low intensity rain		N.A.	N.A.	N.A.	
2	A	16:00	Carrot & kibble	>1.5h *	<16h *	x	* Dropped and eaten after the observation period, as the pod was empty next morning.
	B	Rain (increasing)		N.A.	N.A.	N.A.	
3	A	09:30	Chicory	37 min	9 min	1m	
	B	dry		N.A.	N.A.	N.A.	
4	A	16:00*	Broccoli	<1.5h *	Not empty	<1m	* I was not observing at the time of the pod dropping, however I observed it laying on the ground without interaction when I went home. Next morning the food was not eaten.
	B	dry		N.A.	N.A.	N.A.	
5	A	09:15	Lettuce & kibble	22 min	9 min	1m	* B was interesting directly after hanging it up. Just after setting up A, B was dropped.
	B	Dry		1 min *	15 min	1m	
6	A	11:58	Leek & kibble	<2.5h *	<2h *	1m	* Pod not dropped and eaten during the observation period, but it was empty before the following observation.
	B	Dry sunny		7 min	10 min	2m **	** Pod was moved by rolling and pushing, mainly with front paws
7	A	14:35	Celeriac & kibble *browse available	38 min	6 min	<1m	First they ate celeriac layed around, then spent some time feeding on browse hung in the enclosure and afterwards went to the pods.
	B	Dry sunny		29 min	6 min	<2m	

Appendix O. Locking mechanism prototypes

This appendix shows the prototyping steps of creating a working locking mechanism. It highlights the steps chronologically with the conclusions and lessons learned from testing and (accidentally) destroying components leading up to a working prototype safe enough to test in the lemur enclosure. Below, an overview is given of the goals for this mechanism.

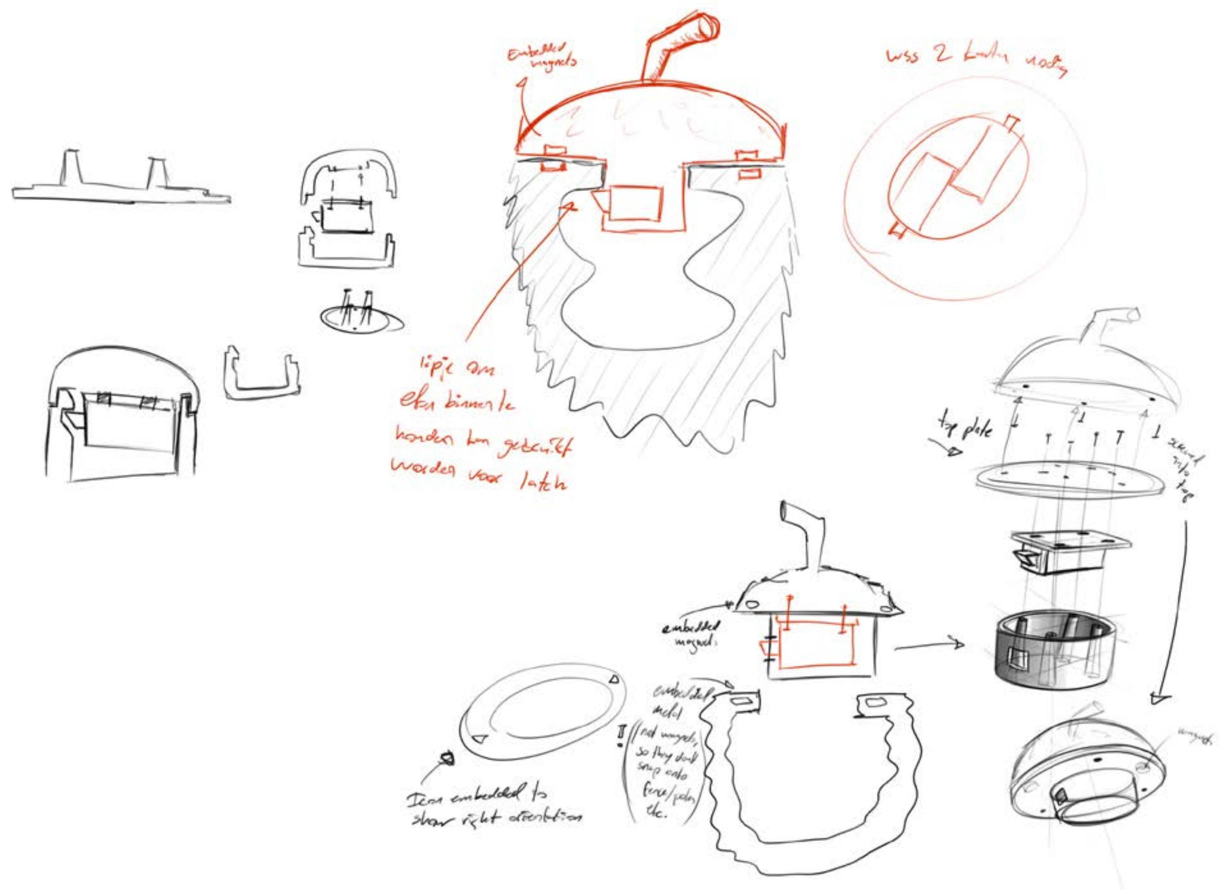
Lock prototype goals

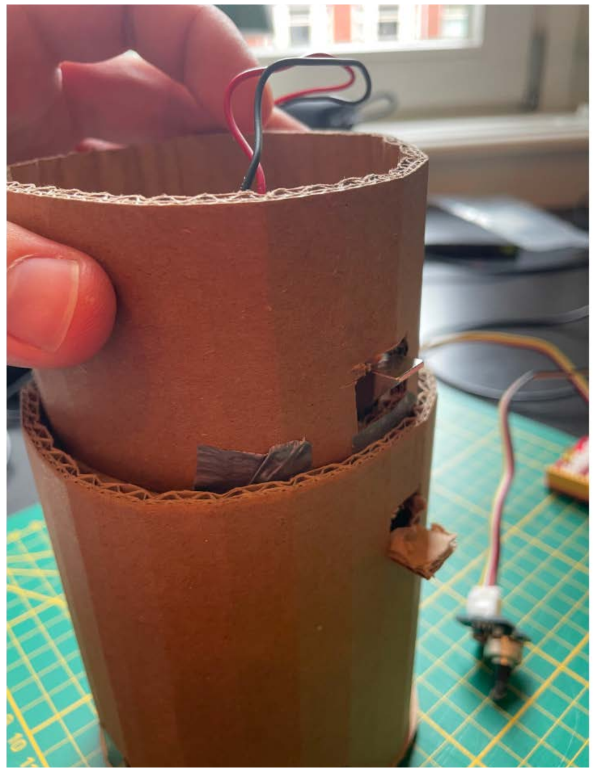
- Explore and find a reliable mechanism that lets the bottom part be clicked on after which it stays there.
- A reliable way for the pod to stay open for a long time (multiple hours)
- Optimise the size to fit in a [Soursop] fruit exterior

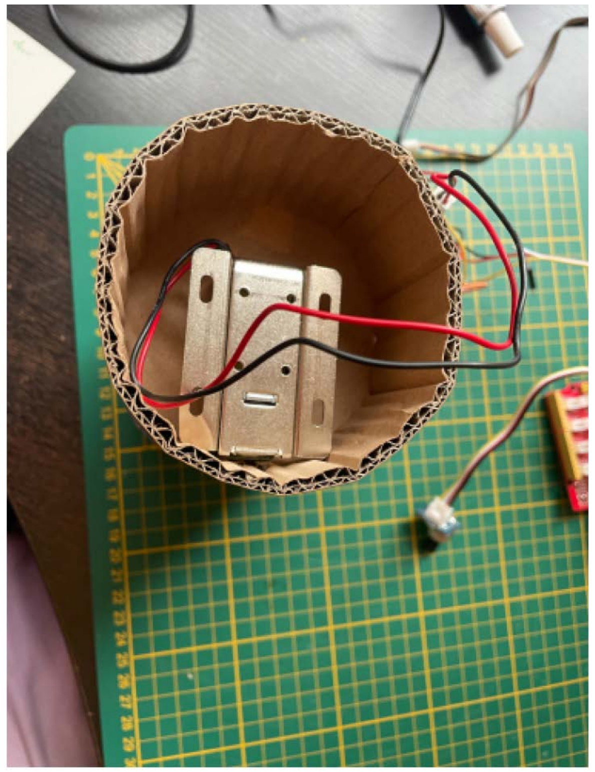
O.1 First version solenoid

O.1.1 Carboard prototype

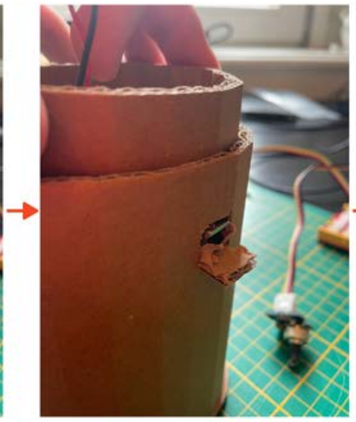
As a quick proof of concept, a solenoid door latch was programmed with Arduino to open and stay closed. The doorlatch mechanism of the solenoid allows the "pod" to be easily pushed onto the top part, clicking in place manually but being only unlocked electronically. This kind of mechanism allows the zookeepers to quickly and easily place all pod bottoms without needing to do interact with the electrical system at all.







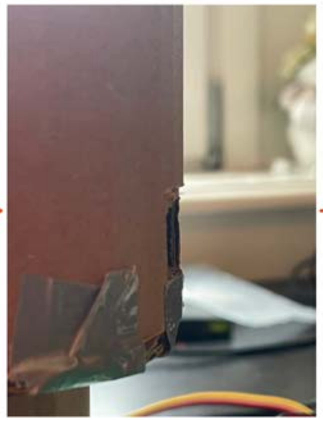
Click bottom onto top over the latch mechanism of the solenoid



Latch clicks out through the cutout in the bottom

Top and bottom now stay together

The latch sticking out holds the bottom



The solenoid turns on and the latch moves inward

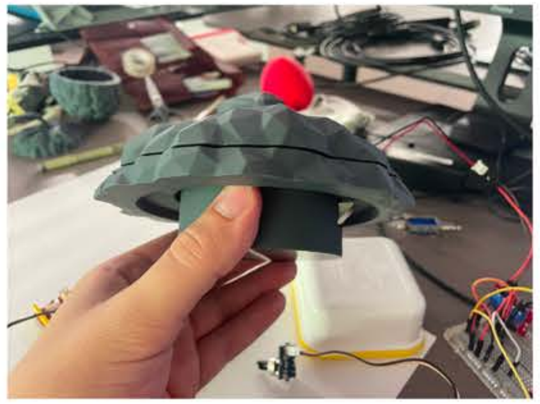
The bottom falls down

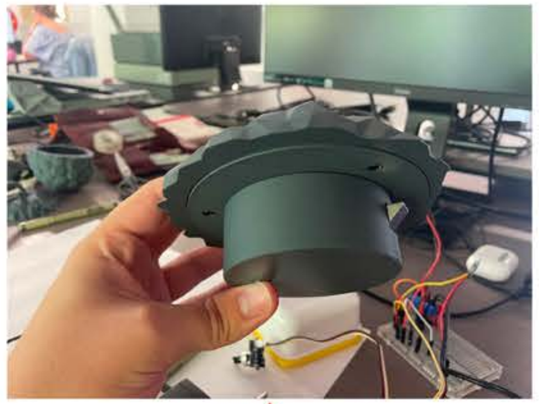
0.1.2 3D printed prototype

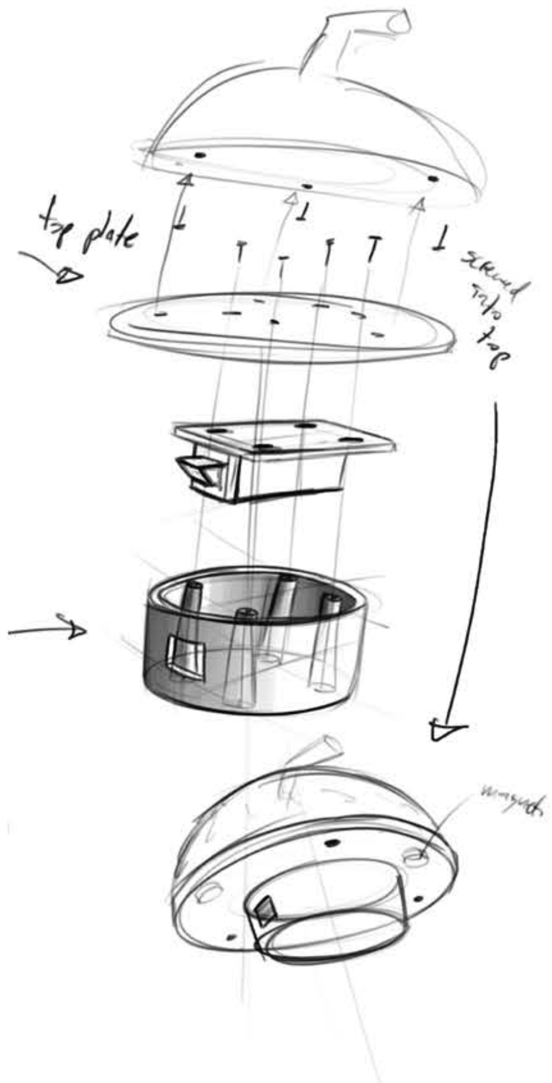
After the cardboard prototype seemed to work, a 3D-printed one was made in which the solenoid door latch could be screwed. The main principle did work. The "bottom" could easily be clicked onto the top part, and using Arduino, it would release. The negatives were that with a little bit of force hanging on the bottom part, the latch would not release. So with heavy food, it might not work. The doorlatch mechanism also takes up a lot of space and is quite heavy. This is especially a problem considering you would need at least 2 latches in one pod – otherwise the bottom will hang slanted.

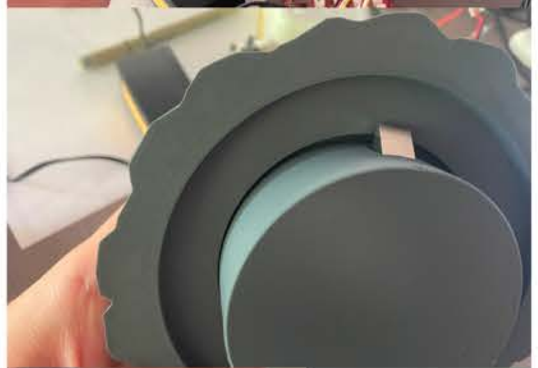
The biggest dealbreaker is due to how a how a solenoid functions. For the concept, it is important that the pod stays open after activation -> hanging on with magnets. This is so the lemurs have the choice to grab the pod any time after it activates. Keeping the solenoid doorlatch open, however, resulted in it getting burning hot after a few minutes, melting the PLA of the test print. Due to this it was concluded that it is not a suitable mechanism for this concept and something else needed to be tried.

Goals:
- test closing idea of top (see sketch)
- test working using internal rib for the latch
- test working filled bottom









Size of inside where the solenoids sits is very big...

Print failed, so filled bottom not tested.; only tested latch mechanism

Too much wiggle room between top & bottom → results in angled.

would need at least 2 solenoids.

Not ideal due to the bulk of just 1

CONCLUSIONS

Solenoid lock / unlock works well

Solenoid is stuck in well. Top part screwed in feels sturdy

With relative little weight put on, the solenoid does not open

Weighs quite a lot.

Gets hot after a few min.

X

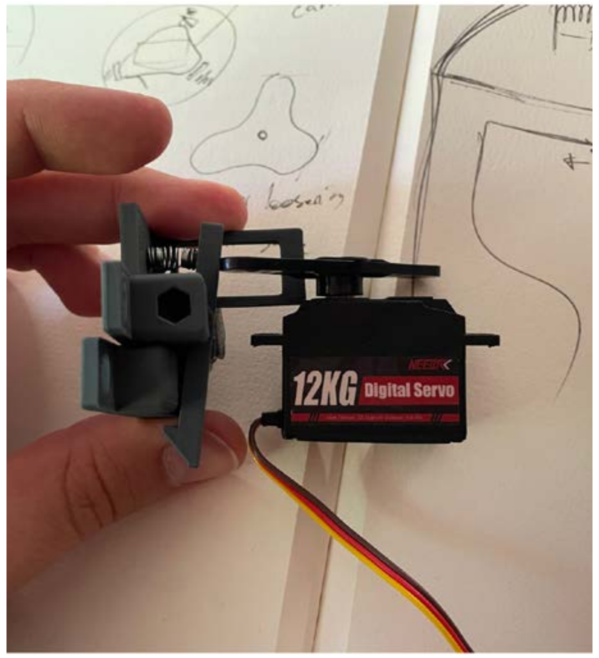
conclusion
Stop and look at other mechanisms

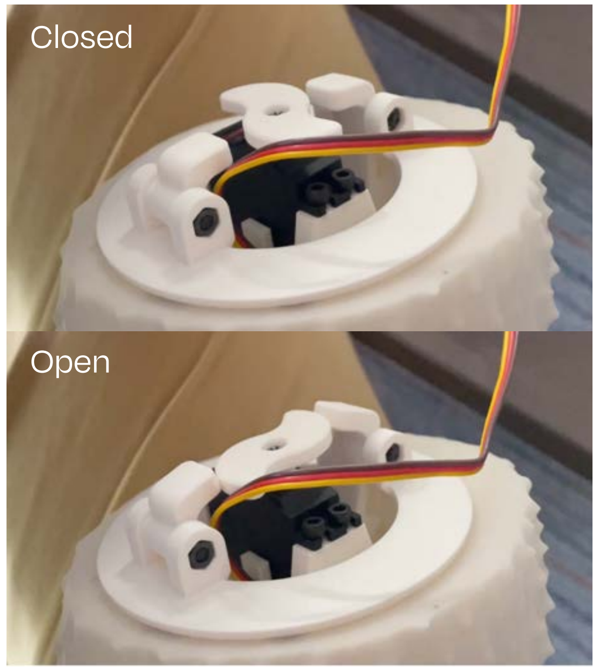
0.2 Servo prototype

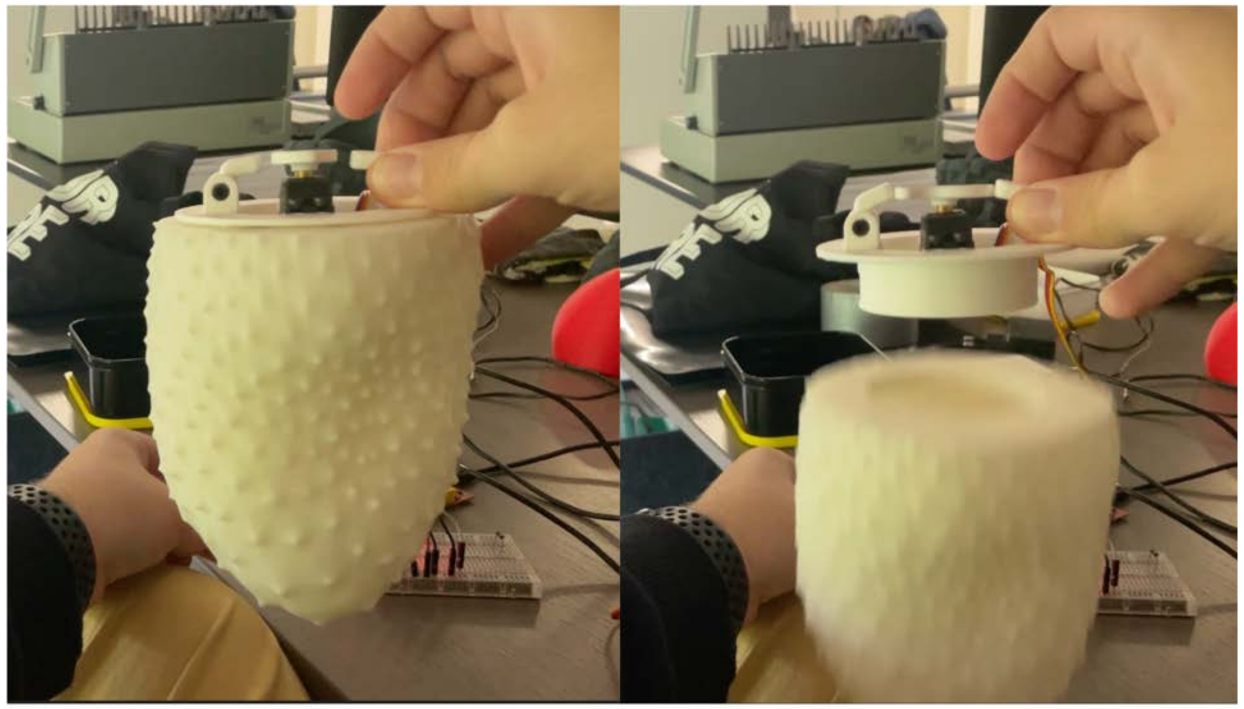
Since a solenoid overheated, the use of a servo to actuate the latching mechanism was explored.

0.2.1 First prototype principle & working explanation

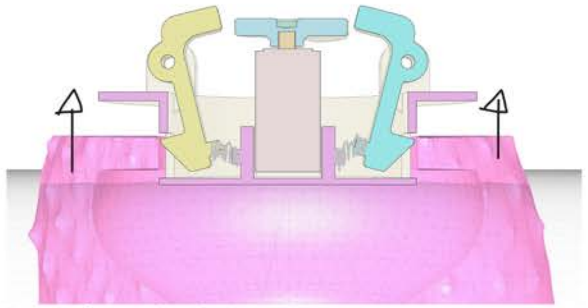
Here, the first working prototype of the locking mechanism is shown. The first image is a mechanism that was used as inspiration. The photos show it locking and holding the bottom of the pod as well as unlocking and dropping it. A section cut overview shows what each step looks like and entails



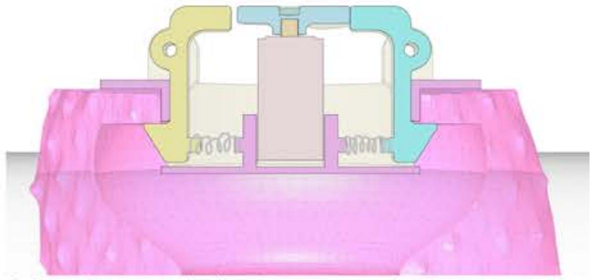




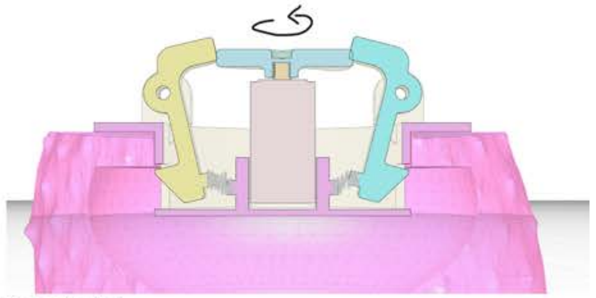
Working principle



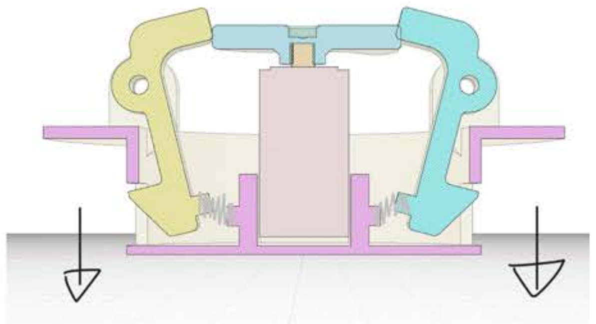
Bottom of the pod is clicked onto the top.
Springs compress to allow the bottom to be placed



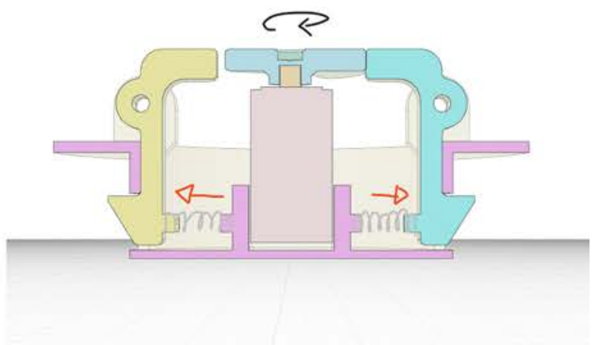
Springs decompress, locking the bottom onto the top component



Pod activates:
Servo turns to open the latches



Bottom drops / is taken off by a lemur



Servo returns to locked position
Springs uncompress and push the latches back out

0.2.2 Problem

In a longterm (5 minutes) test I burned through a motor while keeping the mechanism in its open state. This is due to the cam being angled against the latches, thus the motor keeps pushing to reach its goal angle but it cannot reach it as the latches are already maximally extended.

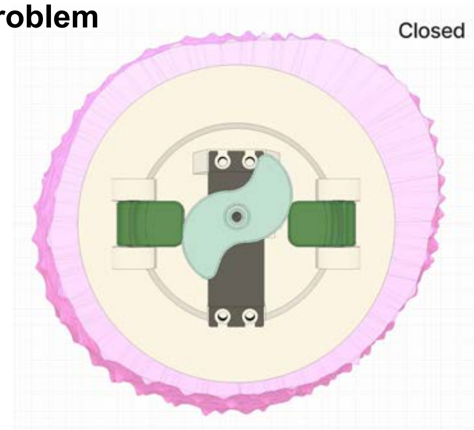
The solution: The cam needs to have plateaus at the open state for the motor to rest.

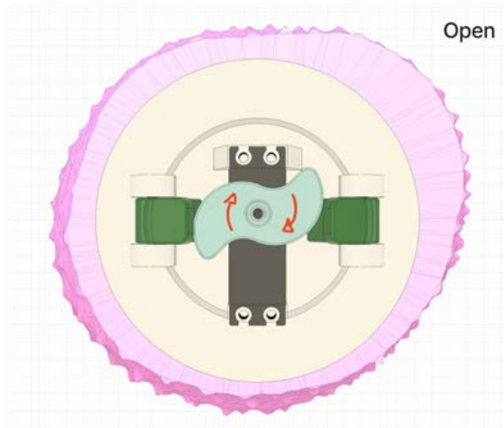
The motor used in the final prototypes and design is also bigger dan the one used before, this results in another problem: the axis of the cam is not centred between the latches.

The solution: calculate the offset using cam motion curves, in this case the formula for Simple Harmonic Motion, explained in

$$s = \frac{1}{2}H\left(1 - \cos\left(\frac{\pi\theta}{\beta}\right)\right)$$

Problem



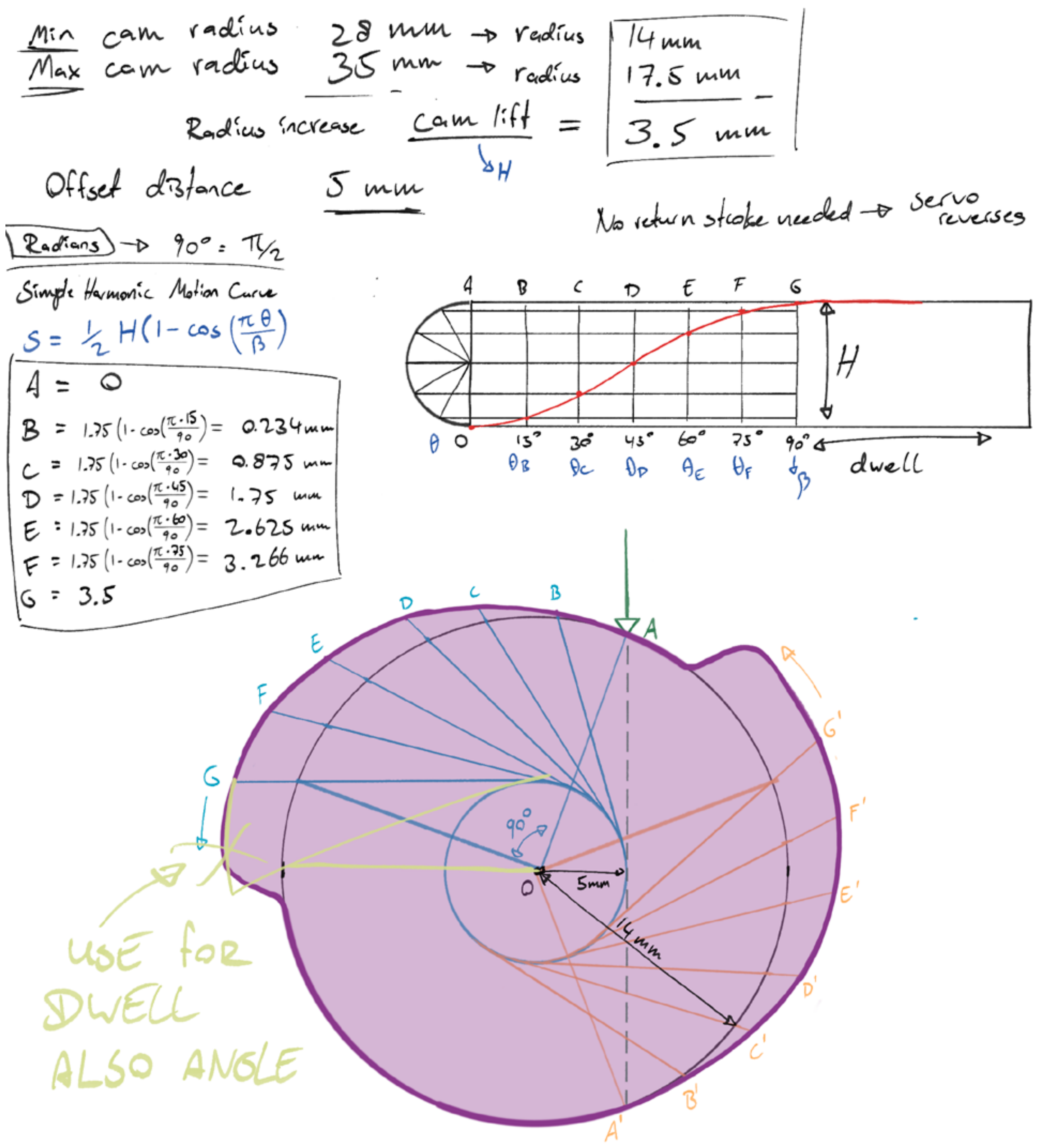


Motor keeps trying to rotate further, while the latches push in the opposite direction

O.3 Cam and Follower design - Simple Harmonic motion

O.3.1 Calculation

Below, the calculation and sketch of this cam is shown. This shape was then parametrically modelled in Autodesk Fusion which resulted in multiple prototypes to find the perfect size.



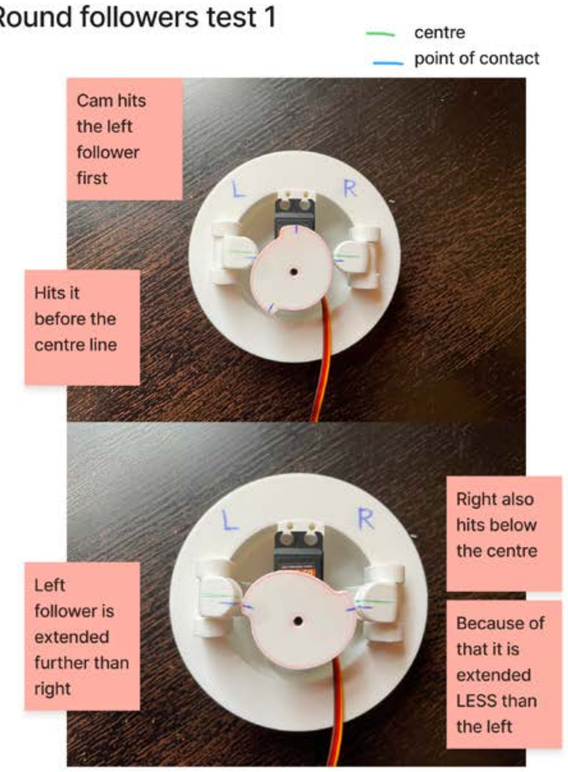
O.3.2 Initial tests and follower design

Testing this with the same latches (hereafter called "followers") of the earlier cam design resulted in one side being actuated earlier and further than the other. This is due to the calculation using the centre of these followers, and these earlier ones being square.

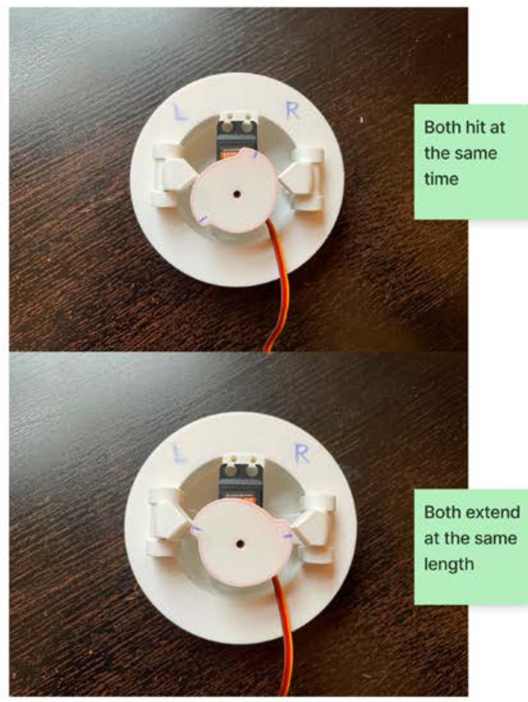
So two tests were done to create a better follower design using a pointy and a circular follower. The pointy circular follower did not engage at the same point on both sides, the pointy one did. However, I expected a pointy follower to wear down quicker than a circular one, thus the next evolution is a compromise between the two; a small ball as a point.

This ball point follower was consequently modelled and deemed to be working well, so it is used in the final prototypes.

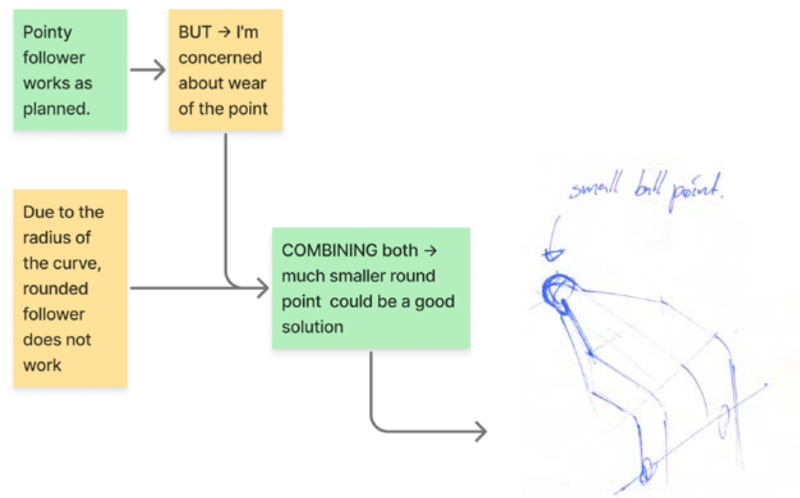
Round followers test 1



pointy followers test 1

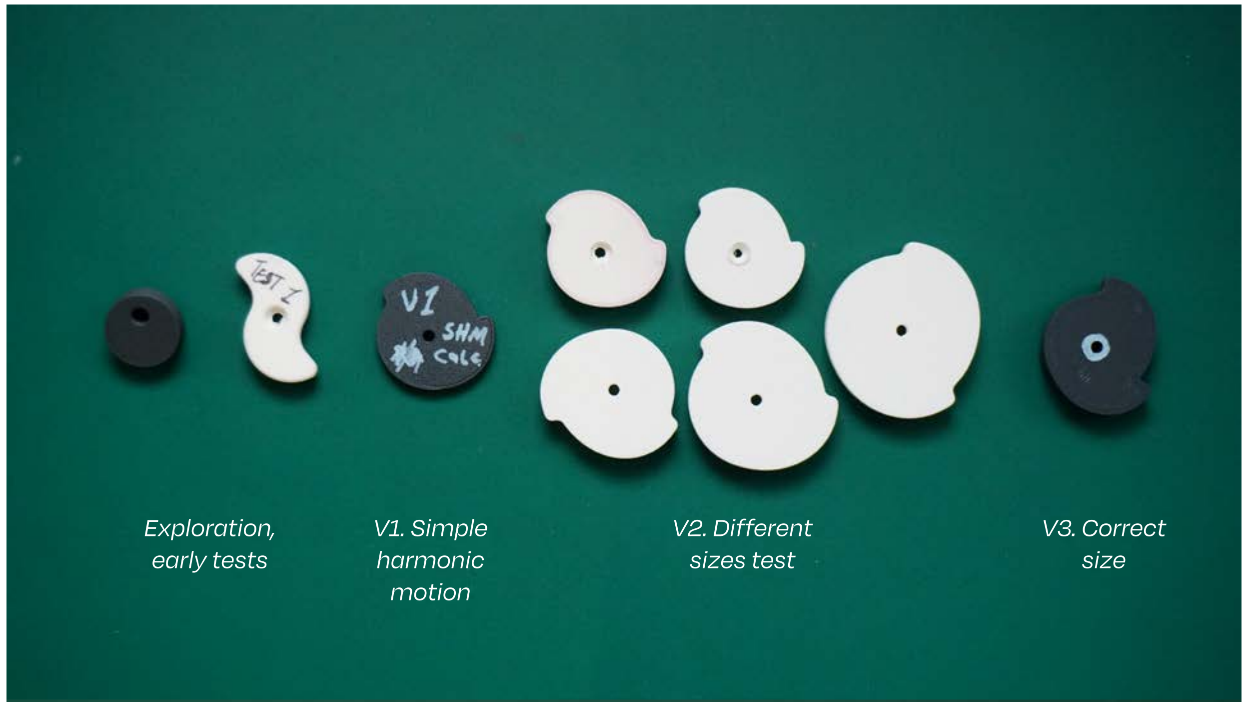


Conclusions



O.3.3 Cam iterations

While the calculation yielded a well-working shape, practically testing different sizes to see what actuated the latches best was needed to find the perfect size and actuation distance. A photo overview of the different versions is shown below.



Exploration, early tests — V1. Simple harmonic motion — V2. Different sizes test — V3. Correct size

V4. Test working prototype — V5. Optimising printability — V6.Testing size final prototype — V7. Final cam design

O.4 Main body iterations

O.3.1 Calculation

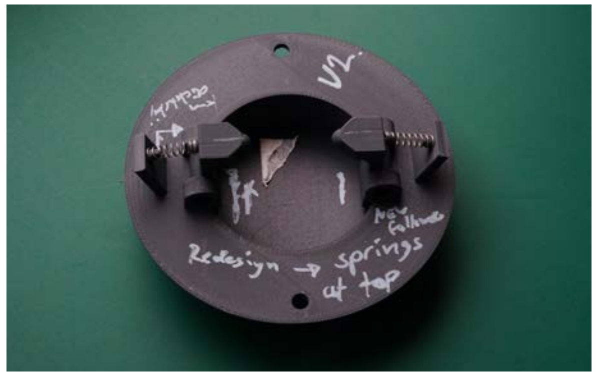
Below, the iterations of the main body are shown. Through iterative prototyping, each step improved on the last one. All faults per iteration were written on the part itself after which a new one was created, fixing this mistake.

Version one used a smaller servo and was meant to prove the working of the concept. Here I found out that placing the springs at the bottom was very difficult to assemble, and this also kickstarted the follower iterations shown earlier.

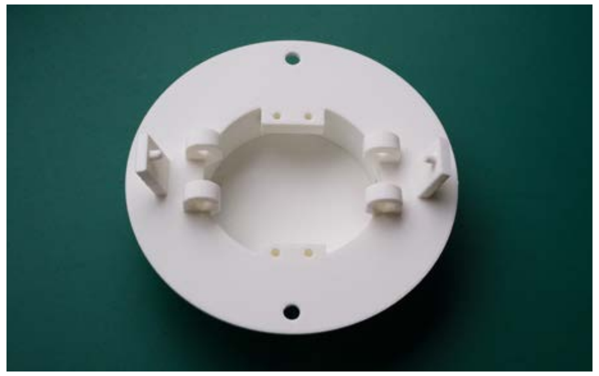
Later prototypes proved springs at the top worked better and then focused on, first, mounting the servo motor, and then adding magnets for the pod bottom to hang onto. These were used in the first working prototype with a power bank on the top.

Then, iterations were focused on printability and ease of assembling of the entire assembly, splitting parts and adding ways to screw them together. The final iterations were printed to make sure everything fits into the top part of the soursop and can be connected to the power and controller.

V1. Proof of concept

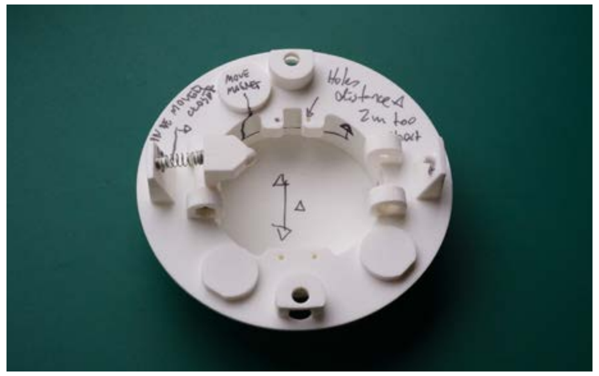


V2. Springs top and follower test



V3. Servo attachment (did not fit)

V4. Adding magnets (failed print), servo did not fit

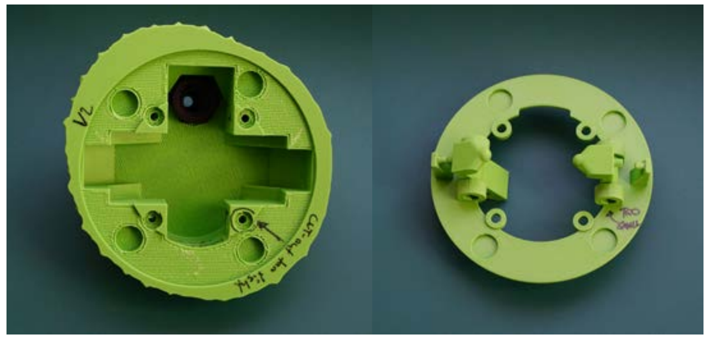


V5. Adding magnets

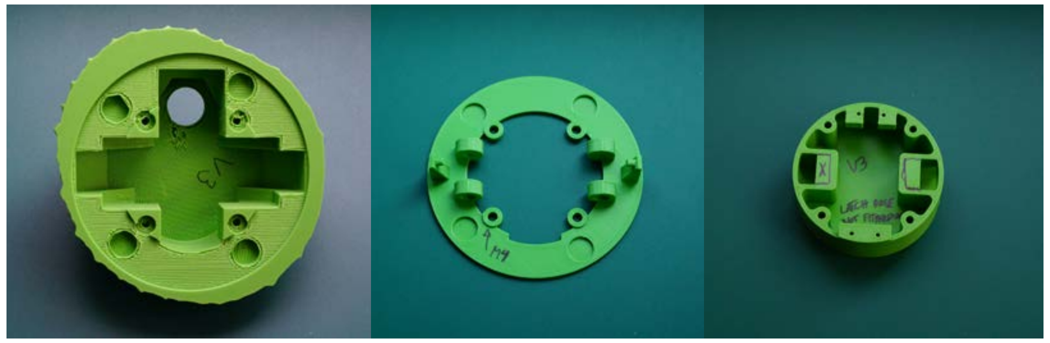
V6. Prototype used in first locking mechanism tests

V6. Loose components for printability

V7. Putting mechanism in soursop top



V8. Bottom waterproofing test, but latches did not fit. Top used nuts that fell out



V9. Using square M3 nuts slotted into the part; holes too big, they fell out

V10. Print orientation & small fitting optimisations

V11. Final design

Appendix P. Wireless control system

This appendix shows the wiring, results, and code of the testing prototypes.

P.1 Testing prototype - powerbank

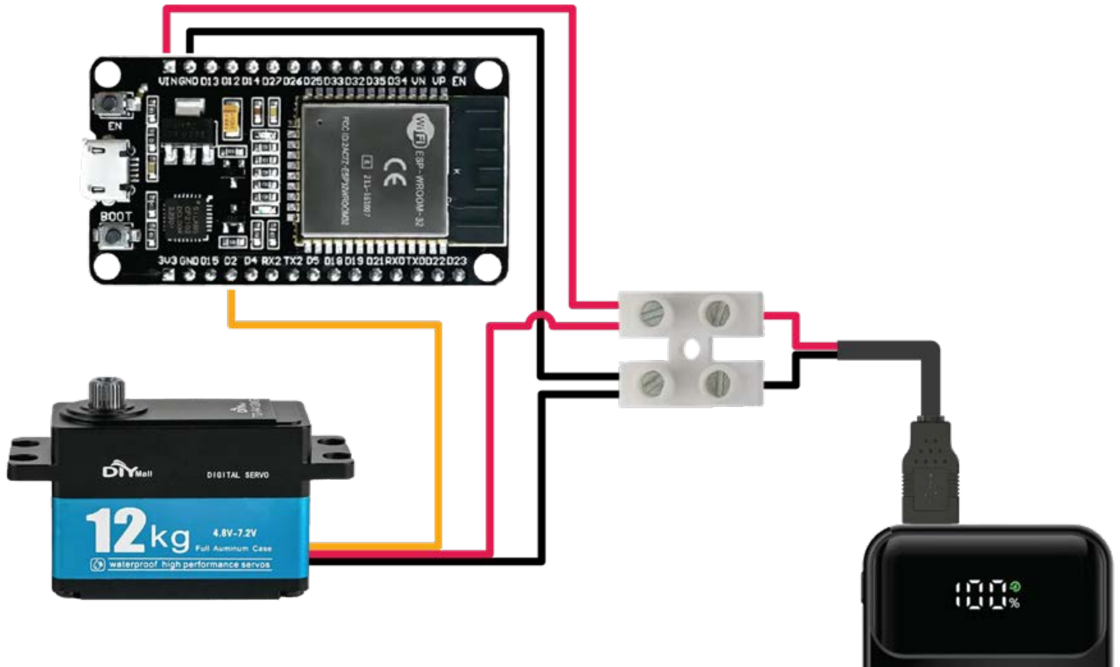
For tests with the automatic opening-and-closing system it was essential to have a prototype that can be controlled remotely, as standing directly next to it with a wired button in my hand would have influenced the lemurs' reactions much more than standing further away.

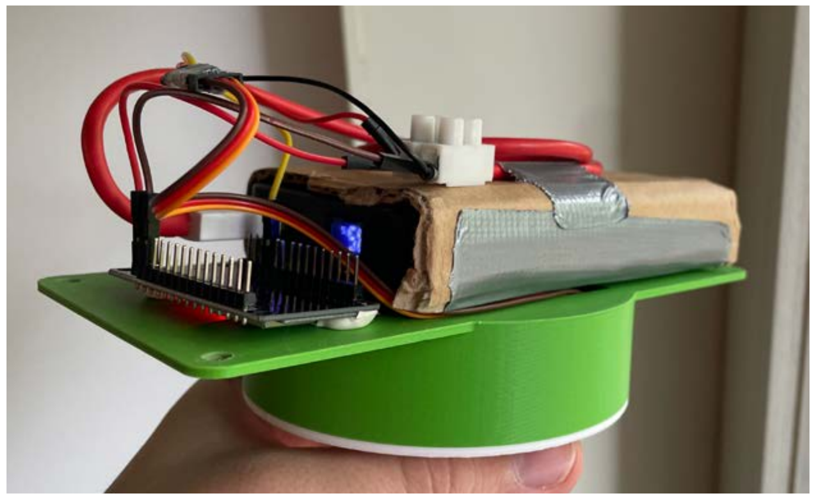
To achieve this, the prototype is controlled by an ESP-32 microcontroller and powered by a power bank capable of giving 3A at 5V (needed for the servo to move optimally). The wiring diagram is given below.

The microcontroller is connected to my phone over a WIFI hotspot which allows it to communicate with the online service / app Blynk. Through this, it is possible to flip a digital switch and rotate the servo to the locked and unlocked position from my phone.

P.1.1 Results

In general, the use of the system worked as intended. The mechanism locks and unlocks when instructed to.





Connectivity issues

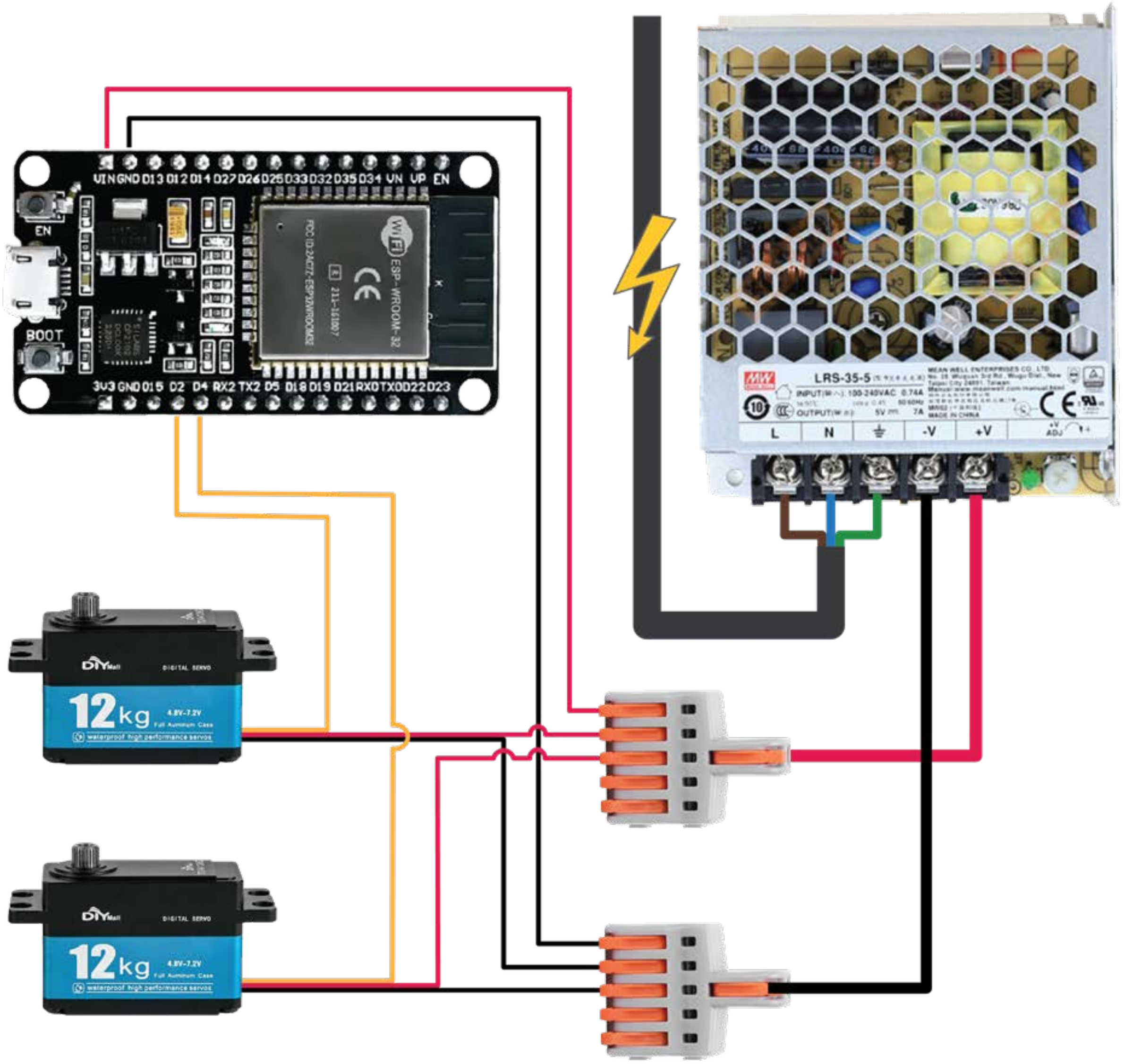
Walking too far away from the pod & microcontroller (more than 10 metres), the mobile hotspot would disconnect after which it did not automatically reconnect and then the only solution was to restart the system. Connecting to a stationary and local network would make this more reliable and implementing some sort of code through which the microcontroller would periodically check and reconnect with the network would fix this problem.

Optimising how often the controller checks for updates is also needed to improve power efficiency, as after staying connected to the 10,000 mAh power bank for around 24 hours, it was completely drained.

P.2 Testing prototype – wired

In the second prototype, the aim was to check if it works to control multiple (in this case 2) locking mechanisms from one servo and one power supply.

After learning first-hand the importance of grounding everything correctly, a working prototype was created with a backup power supply supplying 5V 10A. The wiring diagram is shown below.



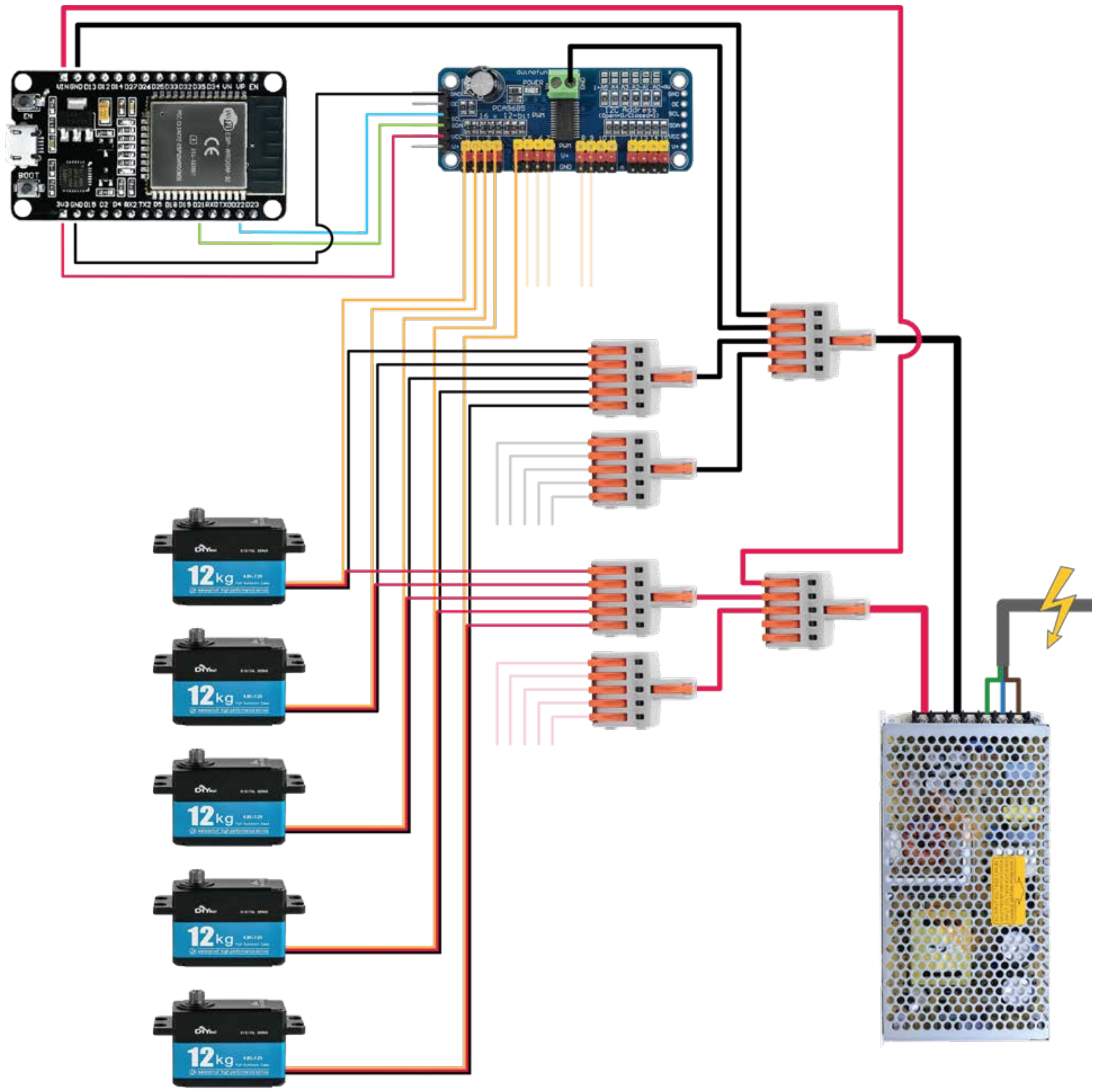
P.2.1 Results

As expected, two locking mechanisms can be controlled individually using a web interface/app with an ESP32 and a power supply. Increasing the amount of servos is possible by using a bigger power supply rated for a higher current. As an ESP32 has 16 PWM channels (which are needed to communicate with the servo's), a maximum of 16 servo's can be used in this way.

P.3 Scaling the setup

To better scale the setup, and to increase reliability it is recommended to use a PWM driver (such as the PCA9685) which allows 16 servo's to be controlled and to which another PWM driver can be connected to increase the amount of servo's controlled by one ESP.

This would result in the following wiring diagram.



P.4 Servo control & Blynk connection code

Using the Blynk.io website client, 2 switches are made which output an angle of 50° and 150° in the on/off position (after which the cam was screwed on the servo . The code below is then loaded on the ESP-32 to connect with the phone's hotspot and Blynks servers. It takes the input on the Blynk app/website and sends this to the PWN pin (written in the code below) where the servo is attached.

The use of Blynk was ideal for prototyping, as it is relatively easy to use with little coding experience. For actual use of the system, a custom codes solution connected to a local network is preferred for stability.

```
//Control Servo Motor Blynk 2.0

#define BLYNK_TEMPLATE_ID "TMPL4-_b5wTkh"
#define BLYNK_TEMPLATE_NAME "Quickstart Template"
#define BLYNK_AUTH_TOKEN "[XXX]]" // Blynk authetnication token is added here

#define BLYNK_PRINT Serial
#include <WiFi.h>
#include <BlynkSimpleEsp32.h>
#include <ESP32Servo.h>

char auth[] = BLYNK_AUTH_TOKEN; // Blynk authentication token
char ssid[] = "[XXX]]"; // Your WiFi SSID
char pass[] = "[XXX]]"; // Your WiFi password

Servo servo1;
Servo servo2;

void setup()
{
  Serial.begin(115200);
  Blynk.begin(auth, ssid, pass);
  servo1.attach(2); // Attach servo 1 to GPIO 2
  servo2.attach(4); // Attach servo 2 to GPIO 4
}

void loop()
{
  Blynk.run();
}

BLYNK_WRITE(V0) // Slider Widget for Servo 1 on V0
{
  int pos1 = param.asInt(); // Get value from slider
  servo1.write(pos1); // Set servo 1 position
  Blynk.virtualWrite(V2, pos1);
}

BLYNK_WRITE(V1) // Slider Widget for Servo 2 on V1
{
  int pos2 = param.asInt(); // Get value from slider
  servo2.write(pos2); // Set servo 2 position
  Blynk.virtualWrite(V3, pos2);
}
```

This fragment of code is based on the template by Tech-Trends-Shameer (n.d.) on Github

Appendix Q. Final design

Q.1 Materialisation

The top parts of the design are printed in ASA plastic, which one of the stronger commonly available FDM printing materials and can withstand rain, the heat of the sun, and lemurs pulling on it.

The lower fruit pod is then made of silicone rubber, which can be cast into a 3D-printed mould. The volume of one pod is around 0.46L (thus the amount of silicone rubber needed for 1 pod).

3D-printing and casting are vastly different production methods. A casted product is entirely filled with materials, whereas a 3D-printed one is mostly hollow on the inside. Due to this 3D-printed rubbers and casted rubbers behave relatively different which makes it difficult to say what shore hardness of silicone rubber is ideal based on the 3D-printed prototypes. It is thus recommended to test different hardnesses but recommended to use a relatively hard one, so it withstands many falls and lemur bites – shore 40.

This choice for a relatively hard rubber is mostly based on experiences by the zoo staff. Between the harder TPU prototype (shore 95A) and the softer ones (shore 85A), everyone mentioned that the harder one would be preferred. A softer material does not work great in a zoo, as it gets damaged much quicker when being used roughly by both animal and carers.

Q.2 3D-printing optimisations

It was decided early in the process to FDM 3D-print the top and all the components due to the low volume of products needed and so Rotterdam Zoo can manufacture them in-house. All prototypes used PLA (Polylactic Acid) and the final design will use ASA (Acrylonitrile Styrene Acrylate) which is much more capable at withstanding everything the weather throws at it than PLA.

Quite some thought and iterations went into how the design could be optimised for 3D-printing using multiple different methods which this appendix highlights.

Q.2.1 Sandwich structure

Earlier prototypes had a large overhang where the rubber bottom part would connect. When printing this, a lot of support material was generated which needed to be broken away (green in Figure Q1). A time-consuming, and material consuming task (25% of the material used for this component was supports) that resulted in a relatively ugly finish (Figure Q2).

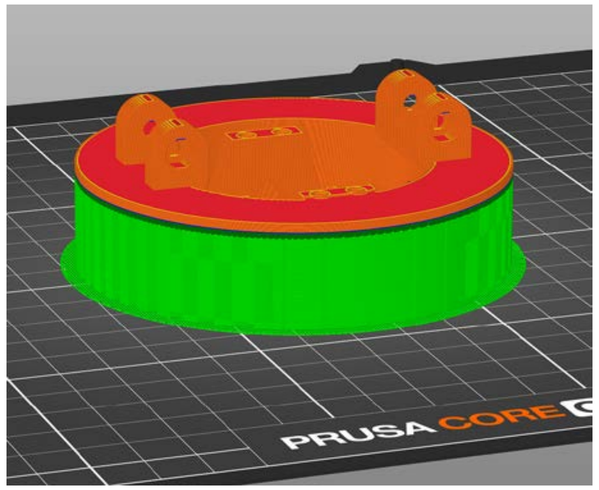


Figure Q1. Lot of support on prototype

Figure Q2. Rough surface finish

To stop the need for these supports, the final design uses a sandwich structure; breaking this main housing into two parts that can be printed flat and then are screwed into the top exterior part (see Figure Q3).
Note the opening only on one side, this makes sure the components only fit together in the correct orientation. Due to the different spacing of the magnets (used to help make sure the pod and top are oriented correctly) it is needed that they are placed in the correct orientation.

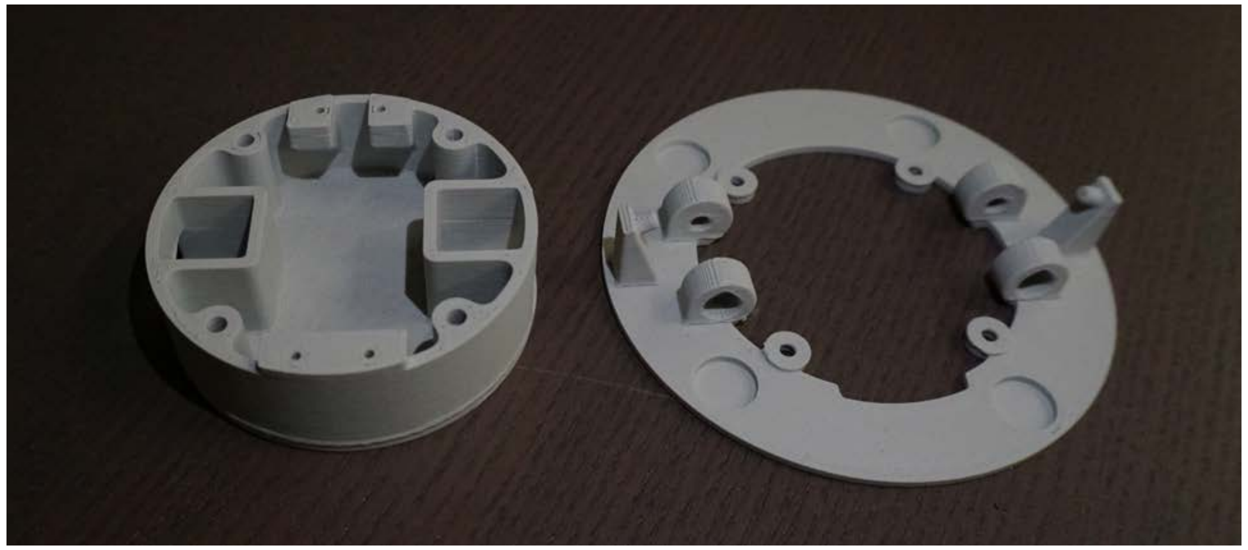


Figure Q3. Sandwich structure

Q.2.2 Printing angles and a teardrop shape

Due to the way 3D-printers go layer by layer, they can struggle with too steep of an angle or straight over nothing. When no support structures are used, these things can result in the material sagging in those places.

This can be mitigated by ensuring there are less of these overhangs. So, on this top circle, there are holes to put a bolt through and tightened to connect the latches. By giving the circular entrance an upward teardrop shape, the printer can print it without need for supports (see Figure Q4). On the other side where the nut is inserted, this is also positioned in a way so there is an upward angle.

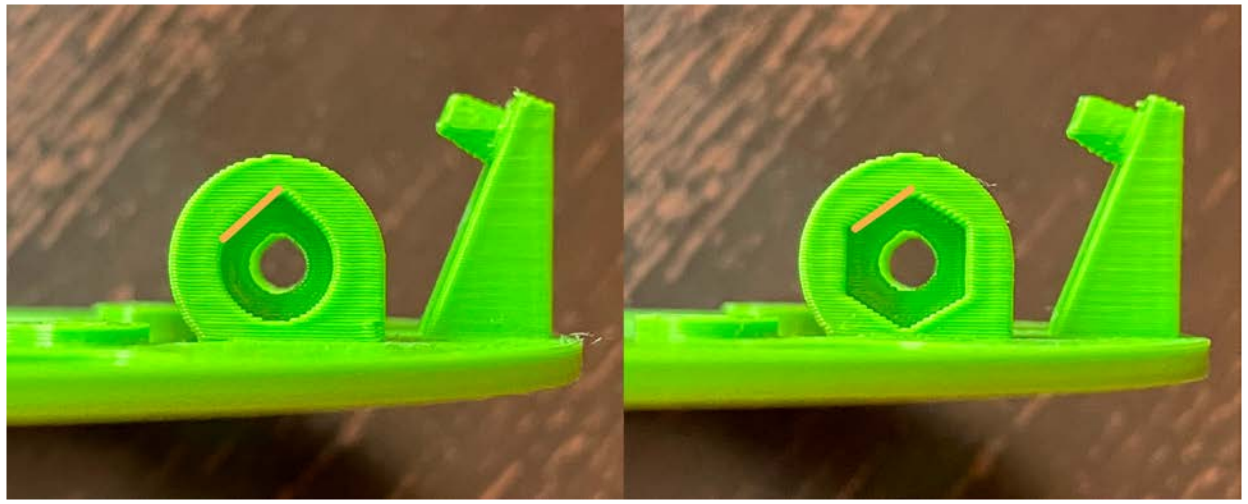


Figure Q4. Teardrop shape and angled top of the nut insert for supportless printability

Q.2.3 Follower

To limit the need for breakaway support structures on the follower, a constant angle (highlighted in yellow in Figure Q5) was added to support the ballpoint in the geometry. This angle is place on the opposite side as to where the cam is coming from and does not interfere with the working.

Q.2.4 Latch – print orientation

The latch is printed on its side. This ensures the part sticking out, on which the fruit pod hangs, is as strong as it can be due to the orientation of the layer lines.

Q.2.5 Top part – print orientation

Orientation of a part on the print bed can also play a significant role in how to optimally 3D-print components. Angling it 45 degrees and using tree supports (Figure Q6) allows the printer to print most of the part without support structures. This uses 5% less material for supports compared to laying it flat, but also gives a much cleaner finish, and increases strength in the z-direction (which is the direction the screws used to fit everything together pull on).

Difference in the internal areas between printing horizontally with supports (Figure Q7, left) and angled with tree supports (Figure Q7, right). Note especially how the circle areas where the magnets are placed don't connect as well to bottom layer and how these lines are not connected as smoothly, as they are deemed bridging lines by the printer. Also, since this supported area is just a few millimetres thick, this made it very difficult to remove the supports; something which is not a problem when printing at an angle.

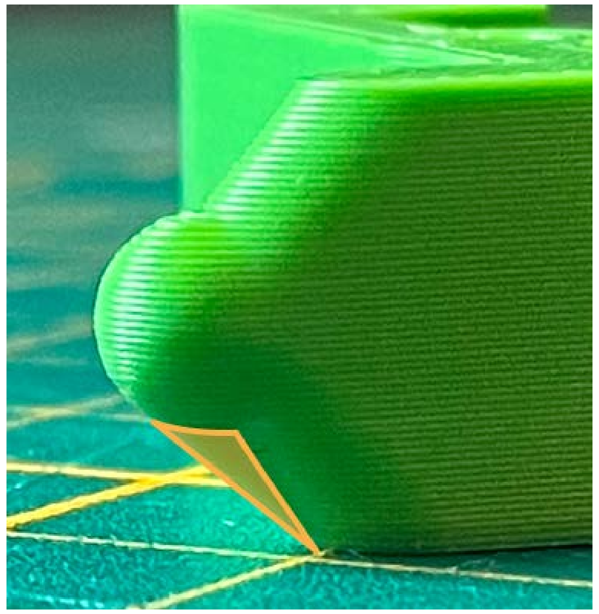


Figure Q5. Limiting need for support by adding a constant angle

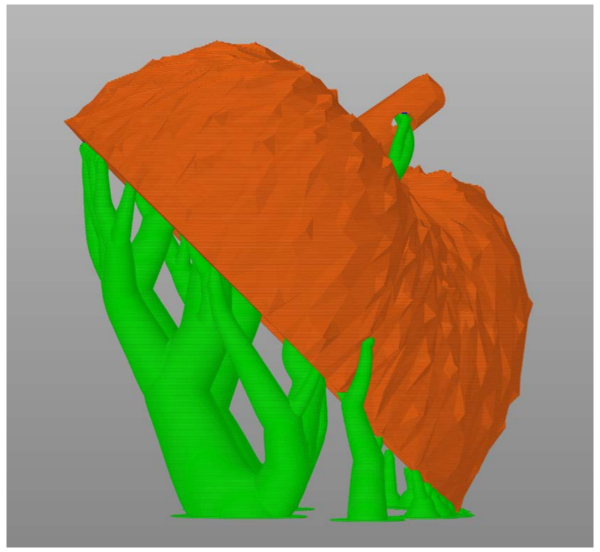


Figure Q6. Tree supports on 45 degree angled part

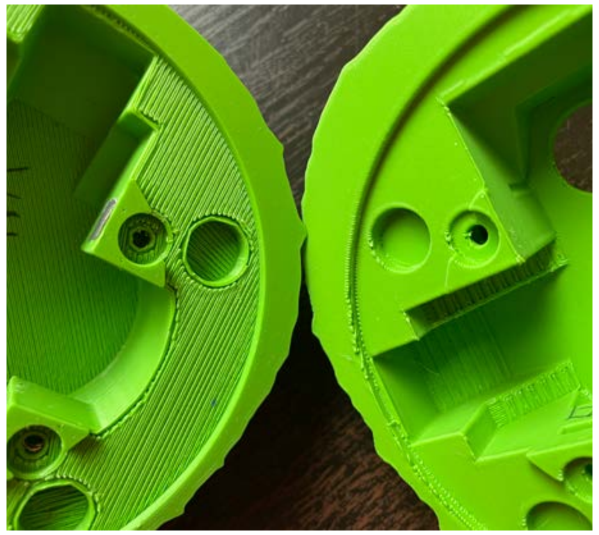


Figure Q7. Differences printing flat with supports (left) or 45 degrees angled with tree supports

Q.2.6 Bridging to support a circular hole – cam

The cam is attached to the servo using a screw. Due to the thickness of the cam (needed to actuate the followers fully), the head of this screw needs to be embedded. This would result in a smaller hole that is printed in the air (when using no supports) as there are no edges for the material to attach to. To stop this from happening, 2 bridging layers are modelled into the part (see Figure Q8). These make the printer print a square over the hole using only straight lines connected to the sides of the big circle, after which the smaller circle can be printed atop of this square (Figure Q9).

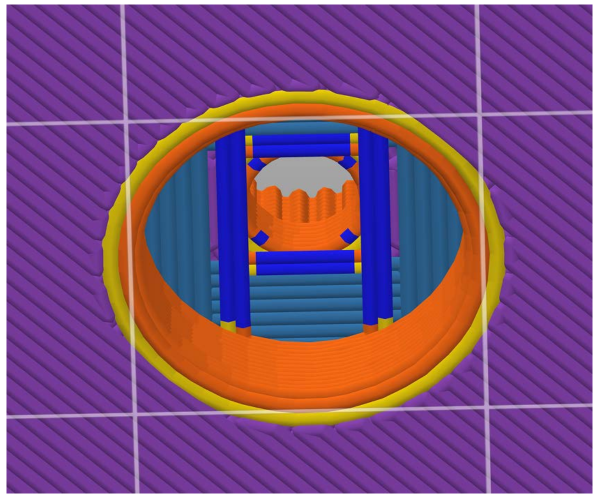
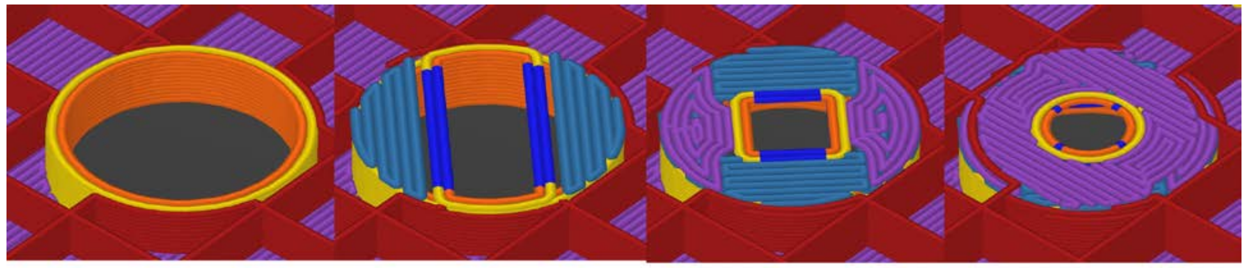


Figure Q8. Two bridging layers



Starting point: wide open hole	First bridging direction is printed by connecting the edges of the circle in one direction*(blue lines)*	Second bridging direction is printed by connecting the edges of the previous layer's bridged; creating a small square *(blue lines)*	On this square, a almost fully supported circle is printed. As it has enough touch points with the previous layers, small parts can be printed as bridges safely

Figure Q9. Steps of the bridging process

Appendix R. Assembly manual

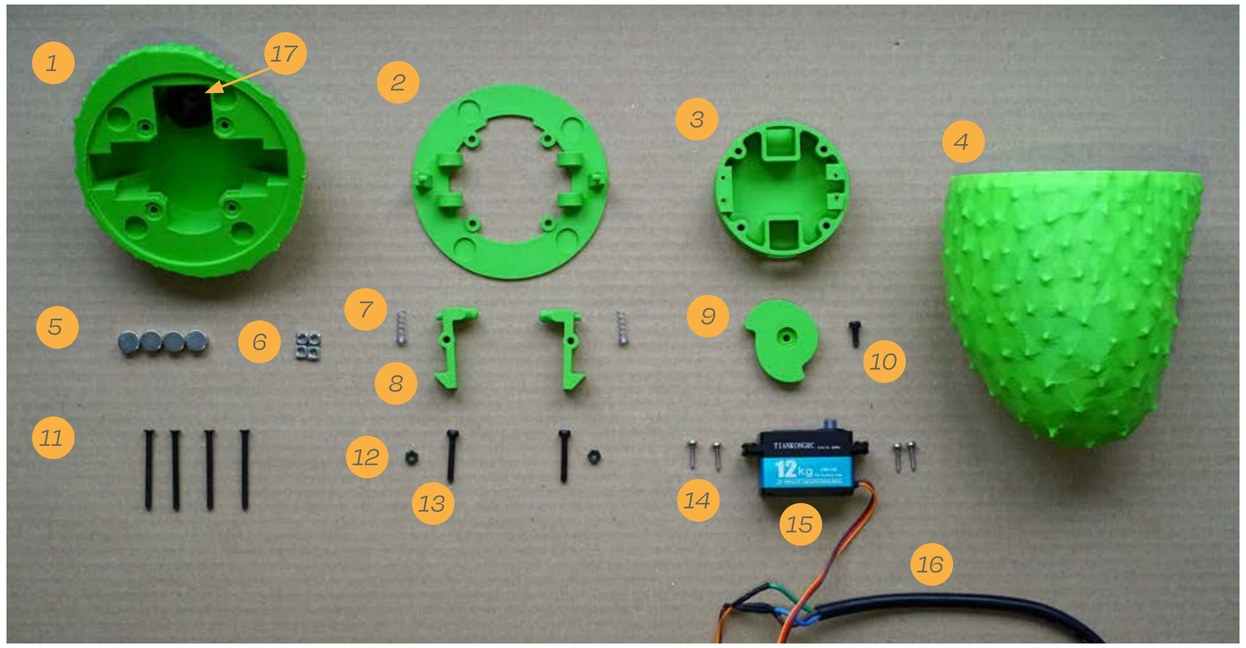
R.1 List of components

This list shows all components needed for 1 pod that are not manufactured in-house.

The rubber body of the fruit is cast using around 0,46L silicone rubber and the components for the top part and mechanism are 3D-printed using ASA for which some guidelines are given in R.2.

List of components

Type	Description	Amount	Used for
Fasteners	M3x35 flathead countersunk screw	4	Attaching entire top assembly
	M3 square nut	4	
	M2.2x13 self-tapping screw (included in servo package)	4	Attaching servo to the main body housing
	M3x5 machine screw (included in servo package)	1	Attaching cam to the servo
	M3x20 socket head machine screw	2	Attach latches & as pivot point
	M3 nut	2	
	PG-9 cable gland	1	Inserting the power & connection cable into the mechanism pod (waterproof)
	3-core cable	1	To connect servo to power & signal
Magnets	10x3 neodymium magnet	4	Slotted in holes in top assembly
	10x3 neodymium magnet	4	Embedded into rubber bottom pod
Springs	15mm x 4mm diameter spring	2	Actuating the latches closed
Servo	Waterproof servo (12kg*cm)	1	Actuating latchen to open



List of parts

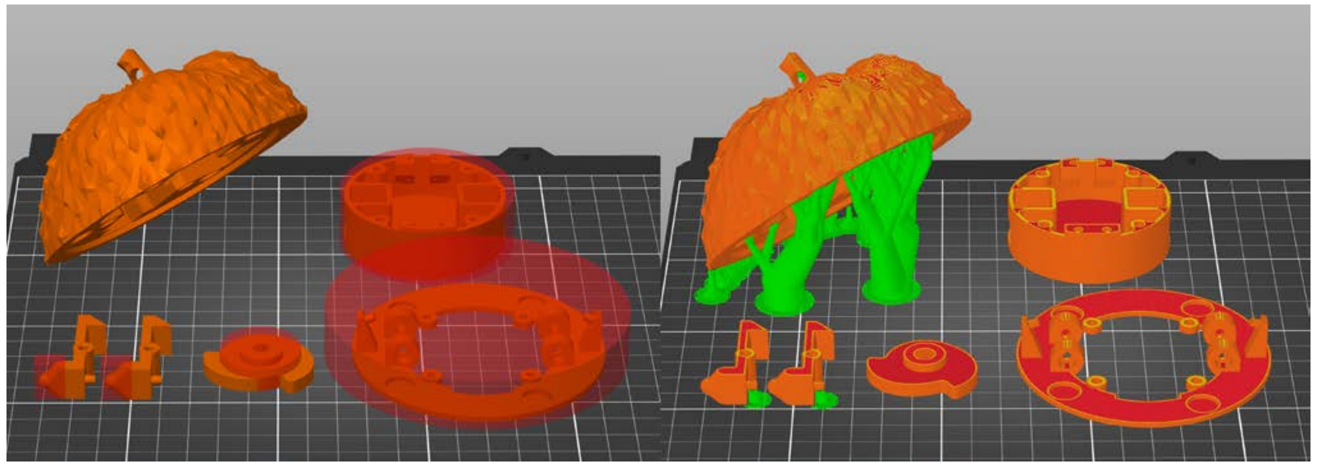
1	Top soursop part	7	Springs	13	M3x20 screw
2	Top circle	8	Latches	14	M3x5 screw
3	Main housing	9	Cam	15	Magnets
4	Bottom soursop part	10	M3x5 screw	16	3 core cable
5	Magnets	11	M3x35 screw	17	Cable gland
6	Squared nuts	12	M3 nut		

R.2 3D-printing guidelines

As explained in Appendix Q, most parts are optimised to be printed without supports, thus supports should only be used on the spring attachment of the latches and the soursop top. All but one part can be printed flat. It is recommended to print the load bearing parts (cam + latches) with 4 perimeters for strength.

The soursop top should be angled 45° upward and supported by organic/tree supports. Before angling the part, make sure that the inside lines are horizontal to the print bed. In my case, I had to rotate the part by 35° to ensure this.

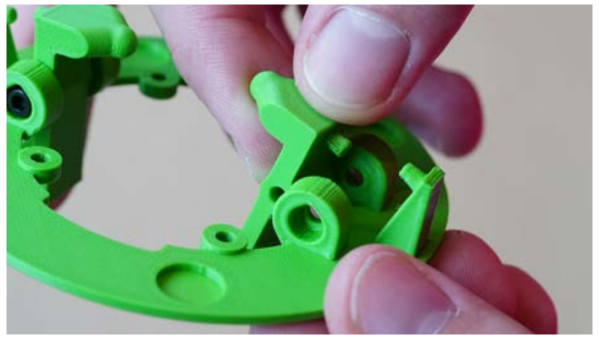
This all should result in a print bed as shown below (where the red boxes are support blockers). Orange and red are the parts extruded; green are supports.



R.3 Assembly steps

Here, the step-by-step process of assembling one soursop pod is shown. Connecting this to the controller and power is then done in the way shown in the wiring diagram in Appendix R.4.

Step 1. Insert and screw the latches to the top circle



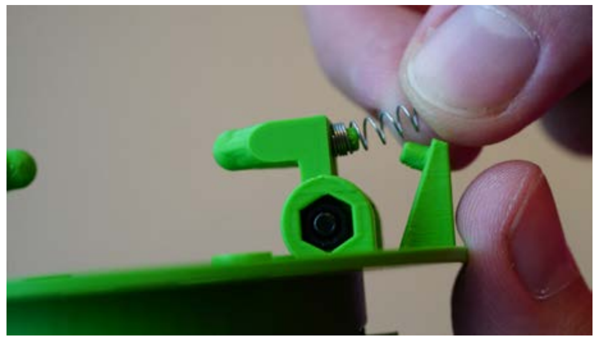
Insert the latch on the top circle

Insert the M3x20 screw

Attach a M3 nut to the other side

Screw the latch in place, repeat for the other latch at the other side of the top circle. Make sure not to screw it too tight as the latch needs to move freely.

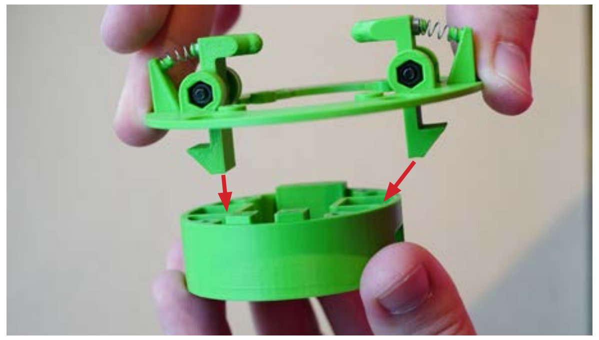
Step 2. Attach springs to the latches



Attach the spring as shown between the latch and top circle

Repeat for the other latch

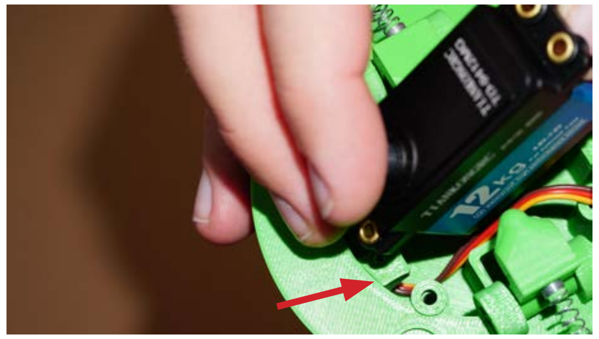
Step 3. Place top circle assembly in the main housing



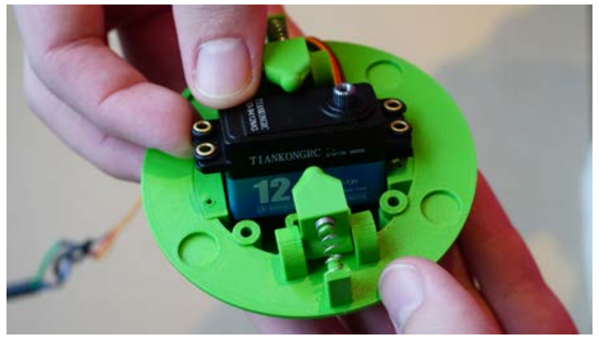
Click the top circle assembly in place in the main housing, by placing the latches in the designated holes.

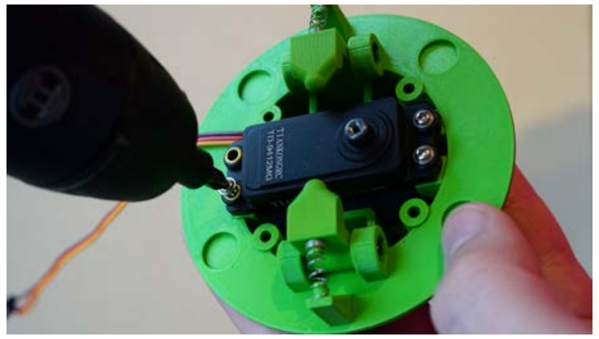
Due to the geometry of the top circle it fits in one way.

Step 4. Place servo and screw in place



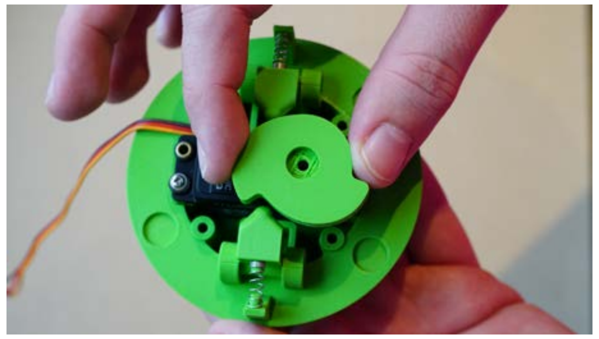
Place the servo in the main body. Make sure to guide the wire under the protrusion in the main body and along the servo length

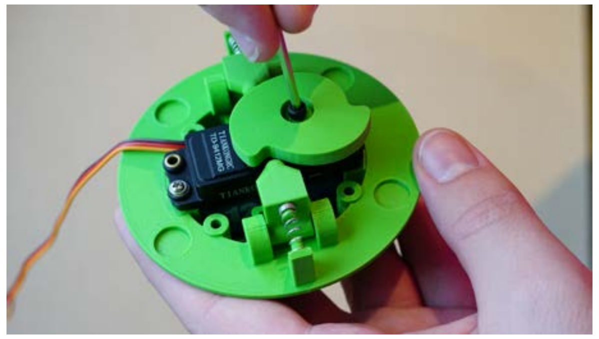




Screw the servo in place using four M2.2x13 screws

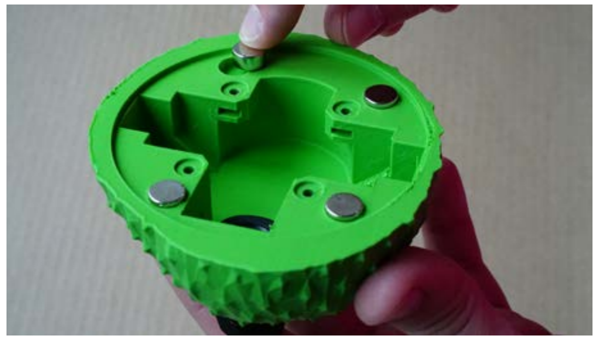
Step 5. Place cam on servo & screw in place





Before placing the Cam, connect the servo to the esp32 and rotate the servo 50 degrees. After that, place the cam on the servo as shown and screw in place using the M3x5 screw

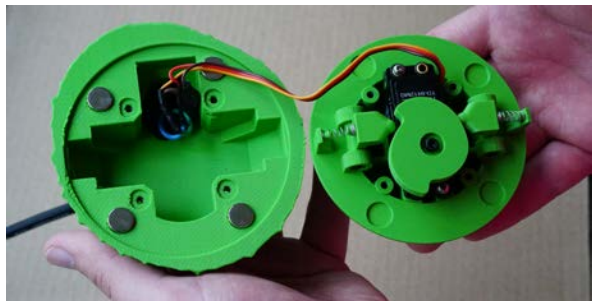
Step 6. Insert square nuts and magnets



Insert four square nuts in the designated slots in the top soursop part, it is adviced to push them in by using, for example, a small allen key.

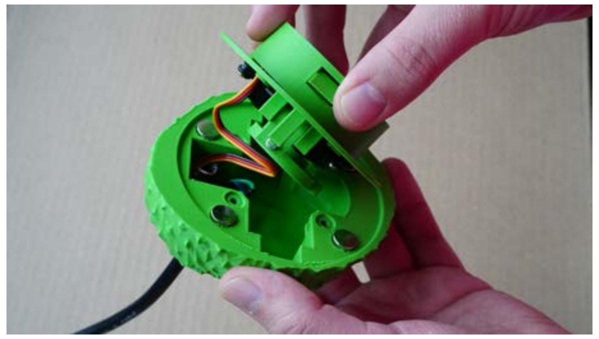
Place four magnets in the big holes in the top soursop part, the orientation of the magnet should correspond with the bottom soursop part (so they attach to each other).

Step 7. Attach cable gland, push wire through the cable gland



Attach the cable gland to the top soursop part using pliers. Then push the wire through the cable gland and tighten the cable gland to achieve waterproofness

Step 8. Close the electronic housing and screw close



When slotting the assembly into the top soursop part, the cam must be hooked behind the holes where the square nuts are located at the circular side of the top. When closing the assembly, make sure the cables are not interfering with the cam.

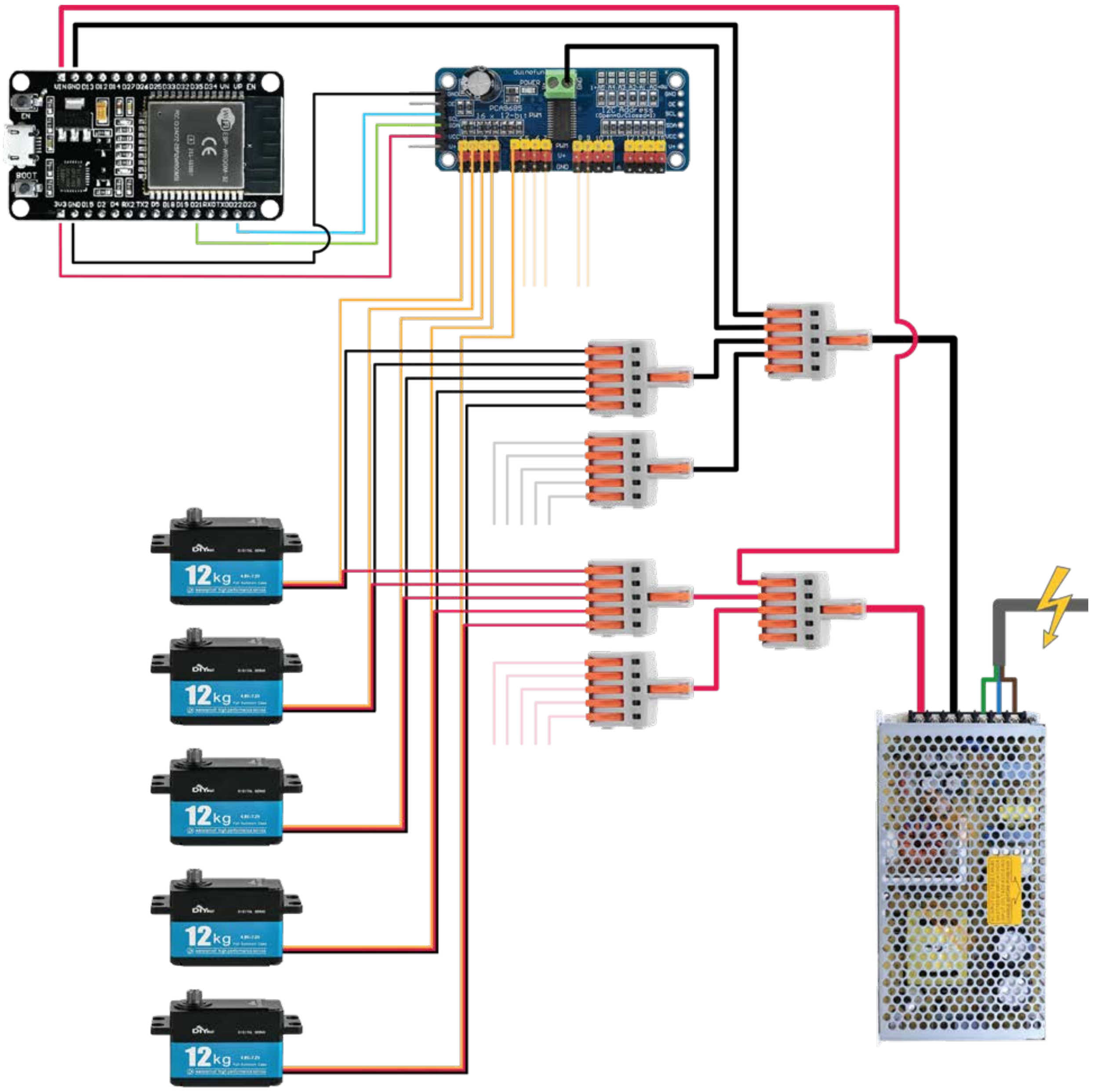
Screw housing in place using four M3x35 screws

Attach the bottom soursop part using the magnets and attach a rope to the soursop's stem to hang it in the animal enclosure

R.4 Wiring diagram

One ESP-32 controller is connected to a PWM- servo controller. To this PWM controller, another one can be chained to create as much connections as needed. The ESP-32 is connected to a power supply and the ground of the PWM controller should also be connected to this.

The servos of the locking mechanism in the pods are connected to the signal pin of the PWM controller. They are powered directly from the power supply. Each servo runs on 5V 2.7A at peak. When in use to feed, a maximum of 4 pods is unlocked at the same time (using 10A of current). However, when all servos are reset t0 their locked position before new pods are clicked on, they all need power at the same time and for this a big power supply is needed. A smaller power supply can be used when programming the pods to lock one after another – limiting the current draw.



R.5 Recommended improvements to produce the design

Below the things that are recommended to improve to the presented design parts are listed

- Add holes at the bottom of the main housing to allow water that gets inside to flow out
- Test what strength and size magnet is ideal and implement these in the final components
- Create a sturdy attachment to where it is hung, using a steel cable that bears the load, and the power cable is hung around it.
- Look into how to connect the servo wires to the system in a sturdy or repairable way
- Wire and program the scent dispensing machine to the ESP control system
- Wire and program a timing screen at the visitors area, showing how long until the next batch of pods is unlocked.

Appendix S. Cost overview

In this appendix, an estimation of the cost per pod is given as well as the price of the system using 2 sets of 10 active pods, with for each 10 extra rubber ones in storage plus 4 extra in case of loss of pods.

Price per pod

Name	Additional info	amount	Price	Price total	Notes	Link
Bottom fruit pod	Bulk price of 20L used	0,023	€ 429,99	**€ 9,89**	*0,46L silicone rubber is needed, so around 40 can be made using 20L*	shore 25 (slightly flexible) https://polyestershoppen.nl/siliconenrubber/siliconen-gietrubber-1-1-shore-25-599.html or shore 40 (hard) https://polyestershoppen.nl/siliconenrubber/siliconen-gietrubber-1-1-shore-40-594.html
Magnet	Neodymium	8	€ 0,20	**€ 1,60**		https://nl.aliexpress.com/item/1005009232659095.html?spm=a2g0o.order_list.order_list_main.50.2d5d1802E7xIXs&gatewayAdapt=glo2nld
Top printed parts	ASA	1	€ 3,50	**€ 3,50**		*custom*
Servo		1	€ 11,00	**€ 11,00**		https://www.tinytronics.nl/nl/mechanica-en-actuatoren/motoren/servomotoren/td-9412mg-waterbestendige-digitale-servo-12kg
Spring		2	€ 0,05	**€ 0,10**		
Screws	M3x35 sunk	4	€ 0,18	**€ 0,72**	*assuming order of 50+, 18c per unit*	https://www.amazon.nl/gp/product/B0CN3DK4J4?smid=A8WH3ZK3N54U4&th=1
	M3x20 socket head	2	€ 0,10	**€ 0,20**		https://www.123-3d.nl/123-3D-Metaalschroef-inbus-M3x20-mm-cilinderkop-verzinkt-50-stuks-i1175-t3122.html
Nuts	square insert M3	4	€ 0,07	**€ 0,28**		https://www.amazon.nl/gp/product/B07D28BQ2B?smid=A2LZADUCQG7RBO&psc=1
	M3 hex nut	2	€ 0,16	**€ 0,32**		https://www.rvspaleis.nl/moeren/zeskant-moeren/din-439/din-439-[-]-a4/din-439-[-]-a4-[-]-m3/439-4-3_1
Connection wire (to ESP/raspberry)	copper + insulation	2	€ 1,33	**€ 2,66**	*price depends on length - estimated 2m per pod*	https://www.elektramat.nl/ymvk-kabel-3x2-5-per-meter/?channable=0141ac6964003631363393856&bg_source=ga&bg_campaign=22916978387&bg_kw=-mi-9214030-pi-401169442-ppi-&bg_source_id=
cable to servo connection		1	€ 0,30	**€ 0,30**	*cable connectors or materials used to solder & waterproof connection*	
printer costs	*rough estimation*	1	€ 4,00	**€ 4,00**	*electricity + expected maintenance (est. 1 euro power consumption, 3 euro wear&tear)*	
Total one pod				**€ 34,57**		

Name	Additional info	amount	Price	Price total	Notes
Amount of pods	*(max 16)*	**10**		€ 345,70	*Max of 10 depends on the power supply used and. Bigger powersupply > higher maximum*
Additional rubber pods to switch each day		**10**	€ 10,69	€ 106,90	*Material cost of 10 additional rubber pods, so they can be rotated each day while the other set of 10 is being washed and dried*
Extra pods (40% more)		**4**		€ 42,76	*Backup in case some are lost*
Amount of sets		**2**			
Total one set				€ 495,35	*Total = 10 upper mechanism parts, 24 rubber bottom parts*
Total individual section				**€ 990,71**	

One time purchase – *based on amount of sets*

Name	Additional info	amount	Price	Price total	Notes	Link
Controller (ESP-32/raspberry pi pico w)	One total	1	€ 9,00	**€ 9,00**	*One ESP connected over wifi can control multiple PWM controllers*	https://www.tinytronics.nl/en/development-boards/microcontroller-boards/with-wi-fi/esp32-wifi-and-bluetooth-board-cp2102
PWM-servo controller	One per 16, so for ease of calculation 1 per set	2	€ 6,00	**€ 12,00**	*One controller can control 16 servo's individually.*	https://www.tinytronics.nl/nl/mechanica-en-actuatoren/motoraansturingen-en-drivers/servo-motoraansturingen/16-kanaals-i2c-pwm-servo-aansturing-pca9685-1
Power supply 5V 26A	c.a. one per set of pods	2	€ 31,25	**€ 62,50**	*Depends on how much pods connected (3A per pod - but not all are using power at the same time). Expected: Around 10 pods per one PSU. The used cable connectors can handle max. 32A – so larger PSU would need different connectors (&cables)*	https://www.tinytronics.nl/nl/power/voedingen/5v/mean-well-voeding-5v-26a-switching-power-supply-rs-150-5
Cable connections	6 needed for 10 pods	12	€ 1,23	**€ 14,75**		https://www.amazon.nl/dp/B0BF9411SV?ref=ppx_yo2ov_dt_b_fed_asin_title
Tablet		1	€ 150,00	**€ 150,00**	*For zookeepers to program the times - rough estimation*	
Scent machine		1	€ 350,00	**€ 350,00**	*Same device used for other animal exhibits*	*Pricing based on confidential quote*
Dishwasher		0	€ 1.000,00	€ 0,00	*Optional but wanted*	
Glaswasher (Glazenspoeler)		1	€ 100,00	**€ 100,00**	*cheaper alternative*	https://www.ggmgastro.com/nl-nl-eur/glazenspoeler-met-lekbak-g3-8-gl239
Glaswasher placement & installation	*rough estimation*	1	€ 100,00	**€ 100,00**	*Table like structure & attachment pipes – rough estimation*	
Hanging branches system	*very rough estimation*	1	€ 5.000,00	**€ 5.000,00**	*Includes the mechanical hanging system and the aesthetics of shaping it to look natural*	
Total one time				**€ 5.798,25**		

Recurring costs

Name	Additional info	amount	Price	Price total	Notes	Link
Scent (per Liter)	Price per liter	2	€ 145,00	**€ 290,00**	*per day around 30-60 min of on-time for scent machine. Estimation 1L per half year.*	*Pricing based on confidential quote*
Total recurring				**€ 290,00**		

Final expected costs

Total individual section	**€ 990,71**	
Total one time	**€ 5.798,25**	
Total recurring *(per year)*	**€ 290,00**	
TOTAAL	**€ 7.078,96**	*(inc first year of scent fluid)*