MT-MA1 - Product Design and System Engineering

The FlowerGrower

Smart flower pot

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Abstract

For the EPFL course *Product Design and System Engineering*, we were given the task to develop from scratch a valid prototype of a microengineering innovative product.
The first weeks of the semester were spend brainstorming for a project that would suit the listed requirements. These demanded of the project to have microengineering content (both sensor, actuator and mechanical sections), to allow a prototype to be built in less than a semester with a fixed budget, and to have an innovative point. The two elected projects were a smart trash bin and a smart plant pot. Our group was assigned the latter.

During rest of the semester, we developed our own product, the FlowerGrower. It has a "water-elevator" concept, based on a compressible water chamber. This is something unseen on the market until now, and coupled with solar panels and a LED-based feedback system, enables very high energy autonomy.
We developed this working prototype from scratch and on a fixed budget, while using the knowledge gained during the lectures to manage our project. These managements tasks included for example intellectual property research, team organisation using the WBS method, and project planning using a Gantt chart.
In addition to this prototype, we also needed to make a pre-business plan in the event of the introduction of our product on the market later on. This includes more thorough market research, future team organisation, financing and planning.

Overall, this course and project were great sources of knowledge for us future engineers. It provided us with both the knowledge needed for us to become project managers, with the management points, and the general experience gained by working in groups on engineering points.

Contents

Introduction

The goal of this course was to design and manufacture a prototype from scratch. As a start, each team had to select their own best idea and present it to the class and to the teaching staff. The ideas presented were required to be possible to make at a prototyping stage during one semester, and present micro-engineering content, while being innovative.
For this year course, two products passed the teachers evaluations : a smart flower pot and a smart trash bin. Our group was assigned the first product: the smart flower pot.

This report presents the work done during the semester from the very beginning to our final prototype. The prototype was presented to the class on the 22nd of December. The goal of this report is to present the different elements studied by our group based on the lectures and our work. It contains a product concept presentation, the technical solutions we considered to lead to our prototype, as well as the management done on the project. In addition to that, it presents the work that would need to be done if going forward into production, including intellectual property search and pre-business plan.

1 Product concept

1.1 General description and main function

The main principle of our smart flower pot, the FlowerGrower, is to have a high autonomy in terms of energy. To implement this main idea the group had to design each part of the pot in a way such that the used energy is minimized. From the mechanical implementations to the coding of the micro-controller, each step had to be optimized. Moreover, our group wanted to create a pot which could be implemented for further industrial production. In order to be competitive, the pot has to be as cheap as possible while containing as many innovations as possible.
For these reasons, we designed the pot to use the weight of the plant itself to push the water up to the plant. This allows us to refrain from the otherwise necessary use of a pump and hence save energy. The coding of the micro-controller is also optimized to implement sleep cycles as the check of the humidity doesn't have to be processed very often.

The main functions of our smart flower pot are listed below.

- The FlowerGrower irrigates the plant autonomously and uses the weight of the plant and the energy stored in a spring to push the water up.
- LEDs on the pot give the user feedback on water and battery level, as well as valve state.
- The user can adjust the desired humidity in the pot with a knob on the exterior of the pot.
- Solar cells integrated in the pot charge the battery.
- A lever can be actuated by the user to lift up the piston once the water tank has been emptied and water can be refilled through a hole on top of the pot.

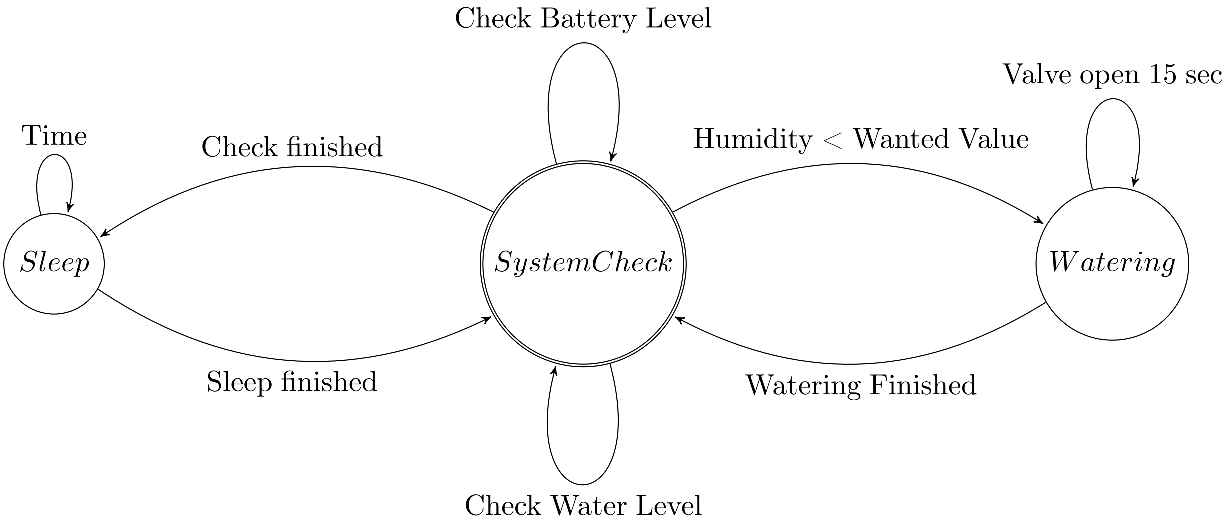


Figure 1.1: Simplified Finite State Machine of the FlowerGrower

1.2 Market analysis

1.2.1 Population classes

The main market of our smart flower pot is dynamic young adults in developed countries.The FlowerGrower is also suitable for other populations, for example elderly people with limited autonomy.

Many young adults have demanding jobs, and plants have a proven soothing effect. Our FlowerGrower addresses the needs of this part of the population allowing them to have a green interior while minimising time spent on plant care.
The young adults we target love technology and are most likely using it daily in their professional and their private life. However, for exactly that reason, they also wish to de-connect when at home. Recent trends lead users to "unplug" from technologies and clear up their interior. Our FlowerGrower is autonomous and does not bother the user with an smartphone application sending notifications, unlike most of our competitors. Instead it uses discrete LEDs to notify the user about critical water and battery status. The wooden exterior of the pot does not disrupt the aesthetics of a room, the pot could even be used as a decorative feature.

Our planter has an autonomy of one to two weeks, depending on the plant's requirements, allowing the user to enjoy their plant without worrying about its health. A "Holiday" mode would allow the plant to survive while extending water autonomy up to one month.

Our low retail price allows people to buy it as a gift for relatives, whether young or elderly. Active adults can be seduced by our concept for the reasons listed above, and it can also be a nice gift for children to teach them about botany for families without gardens.

Overall, we estimated our customer share to be approximately 60% young adults (24-35 years old), 20% adults (36-55 years old) and 20% for both the junior and senior populations (respectively under 23 and above 56 years old). A detailed market analysis by region and age groups can be found in section 4.1.

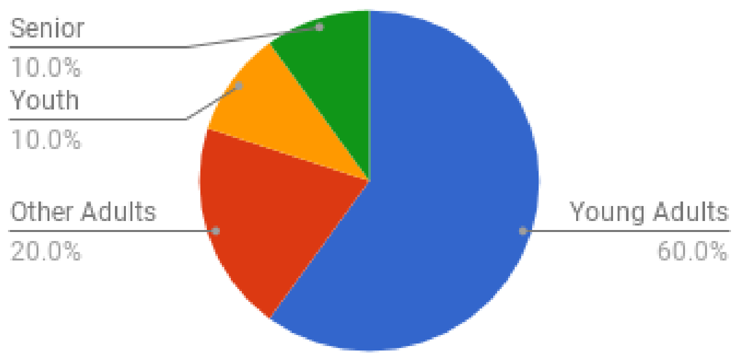


Figure 1.2: Estimated customer share for out product

1.2.2 Competition already on the market

Self-watering planters exist on the market in two forms: "passive" planters, using for example capillarity to suck up water from a water tank below the plant; and "smart" planters, using active monitoring of moisture to water the plant when necessary.

We focused our research on two main products representative of their segments: the Parrot Flower Power and the Lechuza planters.

Passive planters: Lechuza pots

Passive planters have a sub-irrigation system in which water stored underneath the plant is sucked up by the roots by capillarity. This simple principle allows lower retail price than smart planters but is not suitable for more sensitive plants such as orchids, which do not tolerate wet roots.

Passive watering planters, such as from the Lechuza[1] collection, are best suited for indoors or outdoors low maintenance decorative plants, for instance in commercial or office spaces. Manufacturers offer planters of various sizes, from tabletop to barrel-sized pots. They also offer a wide range of decorative outer pots to fit all types of interior design.

Smart planters: Parrot Flower Power

Smart planters are manufactured by Parrot[2], Meg Lab[3], Click and Grow[4] and more. They usually sell at around 200€ and are connected to specific smartphone applications.

Smart planters have moisture sensors and sometimes more sensors such as pH to monitor soil moisture and nutrient content. With continuous monitoring, manufacturers of smart planters promise healthy plants requiring very little care required from the user.

These high-end planters are best for high-maintenance or sensitive plants as well as for the tech-savvy user.

1.3 Unique selling point

Our unique selling point is providing **autonomous care for healthy plants**. The long autonomy of our product comes from its advanced functioning mechanism: indeed, using the pot as a weight pressing down on our water tank enables us to reduce the overall consumption of the FlowerGrower; its integrated solar panels pushes the autonomy ever further. In addition to that, the simple feedback system without a need to connect the pot to the WiFi or to a smartphone makes it unique on the market[1].

In the midterm presentations on the 27th of October, out of ten teams, our team was one of the very few using gravity to water the plant, and the other groups put the water tank above the plant. This demonstrates the uniqueness of our product.

2 Technical solution

The goal of this section is to show the technical work done during the semester, both from a mechanic and from an electronic point of view. It depicts what we did to arrive to our first product concept, until the final construction of our prototype. Finally, we also listed the important issues of our prototype that we will need to address before going into final production.

[1] from our research

2.1 Specifications

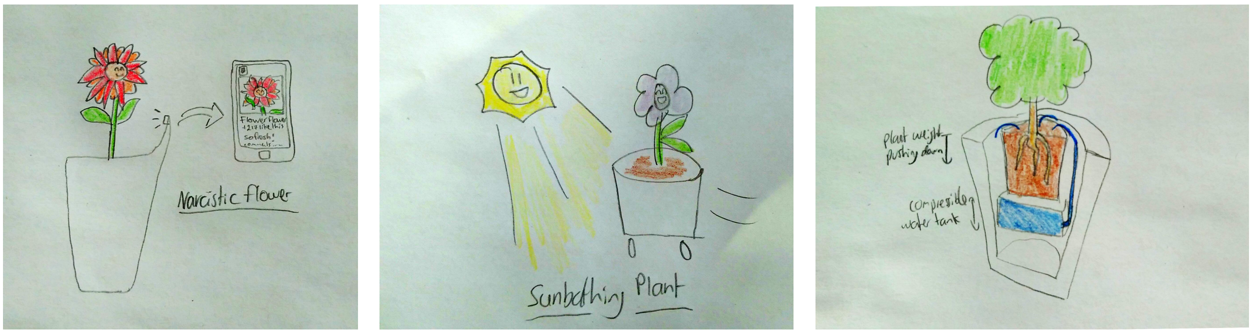
We first extracted the key requirements from the specifications given. To answer those, we needed to create a smart pot with both energy and water storage, and have a smart watering regulation, while keeping the weight and the price low. As for autonomy, we decided to use a minimum of one week for both water and battery.

Apart from these key requirements , we decided that it was important to have feedback for the end user, and agreed to have some kind of feedback mechanism, such as LEDs, a screen or a buzzer.
We also wanted to add something in our flower pot to separate it from the other solutions available on the market, and those in development by the other teams. This lead to a long brainstorming phase to decide what would make up the uniqueness of our project.

2.2 Design phase: solutions explored

We explored several possibilities to add to our project to separate it from the ones already present on the market, such as:

- adding a camera and WiFi capability and make the plant pot post pictures of its growth on an online feed (as illustrated in figure 2.1a)
- make the plant pot capable of movement with a wheeled base to optimize its solar exposition (sunbathing flower of figure 2.1b)
- using a "water-elevator" mechanism as sketched in figure 2.1c to remove the necessity of a pump, therefore reducing electrical consumption
- adding a presence sensor of some kind to detect if humans are present and initiate some interaction
- adding a pH sensor to measure the soil characteristics such as nutrient density



(a) Instagram Planter (b) Sunbathing Planter (c) Water-elevator

Figure 2.1: Sketches of our first main brainstorming ideas

From this initial brainstorming, we decide to use only the elevator design solution. This decision was made collectively by looking at which functionalities were essential and added a real gain over a simple plant pot. We concluded that most of our ideas, while interesting, didn't add any real plus to our product. We found the water-elevator concept very attractive, both from an engineering (moving piston), and from a consumer point of view (energy savings).

With this product concept and the base specifications, we concluded that we had enough material to begin working on the technical choices. As our product is complex in terms of engineering, we decided to all work on this part of the project for the first few weeks.

2.3 Technical choices made

2.3.1 Selected design

Our selected design had a compressible water chamber located underneath the plant pot. The weight of the plant would allow the water chamber to be compressed when a valve is open, and the water would flow to the top of the pot to water it at its base. The main technical challenges we identified in our design are listed below.

Water chamber:
We researched both flexible water tanks and a piston-based compressible chamber. For the sake of durability and reliability we decided to select the piston mechanism, although it created a need for strict tolerances for diameters and exotic materials in order to deal with friction issues.

Watering system:
The compressible water tank allows us to use a simple valve instead of an energy greedy pump. The main challenge was to find a valve that was compatible with an Arduino operation for our prototype, while being normally closed and of a sensible diameter.

Electronics:
As we did not have much time for prototyping and our prototype didn't need integration to a small-scale, we decided to prototype the electronics with Arduino for its ease of use and compatibility with many sensors and open-source libraries. To have a large autonomy, we decided to fit the electronics with a battery and solar panels to offer an extended battery autonomy.

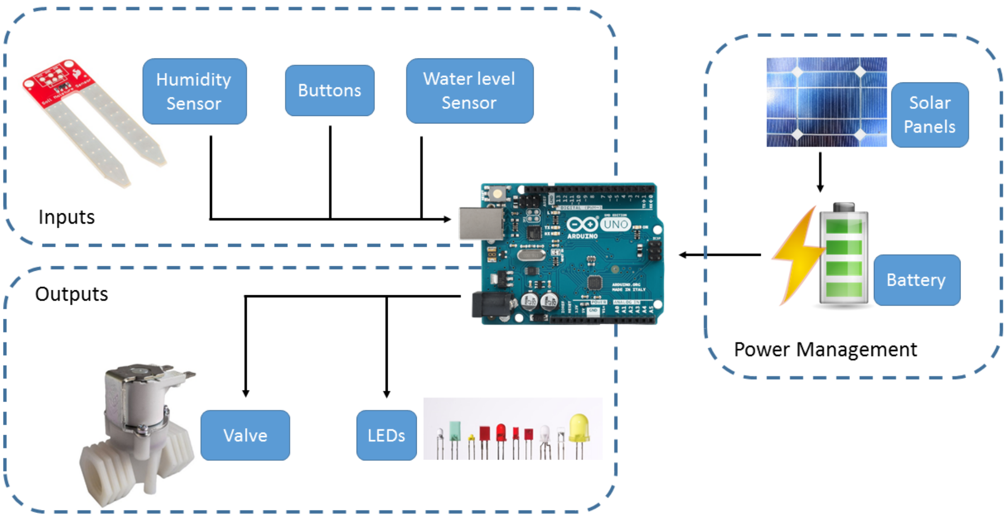


Figure 2.2: Simplified schematics of our selected design

2.3.2 Analysis and modelling of the key functions

The key functions that needed to be modelled were the pressure in the reservoir and the electrical circuits. The height and weight of the pot impose a minimum pressure to be present in the tank in order to have a working irrigation system. Rough initial calculations showed that either a tremendously heavy plant or some additional force would be needed and thus we added the spring to the system. The pressure and forces acting on the piston were calculated using simple analytical techniques (sum of forces, Bernoulli's equation). The electrical energy consumption was analysed using the manufacturer's normal specification for each of the components in our system. All the calculations in detail can be found in the annex.

With the components that we chose, the energy savings compared to a pump are unfortunately negligible. This comes down the choice in valve and Arduino board, which are both not the ideal parts for a low-consumption product, but allowed us to build a functional prototype as a proof of concept in the time available. With a low-consumption valve and a more minimalistic microprocessing unit energy savings would easily be possible. Nevertheless, the solar panels enable long autonomy and a sustainable solution which are both key selling points.

2.4 Manufacturing choices and proposals for production

2.4.1 Prototype fabrication

Cylinder main body:
The cylinder main body needed to be structurally stable and have a smooth surface for low friction between the piston seal and surface. A metal tube would be strong and smooth but expensive and hard to machine. Since the water pressure in the water tank is small, we decided to use a HDPE tube as a main body of the cylinder. Such standard pipes are cheap and available in normalized sizes in many hardware stores. We bought a pipe with 200mm external diameter and 6mm wall thickness from the locally based (Villars-Sainte-Croix) firm *Canplast*, directly cut to the correct length. A piston with the corresponding dimensions provides us with ample space to place a flower pot on top and sealing O-rings with the fitting dimensions are available. Furthermore, it is relatively easy to drill holes and cut out parts of a polymer tube, as opposed to a metal pipe.
One drawback of using this type of tube is the fabrication tolerances and roundness of the tube. Initially we thought this would not be much of a problem due to the stroke of the piston being relatively short (< 10 cm). However, the tubes indeed was not perfectly round and it was challenging improve on that because the walls were quite thick. Placing the bottom of the tank (piston bearer) in the tube applied stress onto the tube walls and it was eventually round enough to get proper sealing of the piston.

Piston:
The piston head requires precise machining to ensure proper sealing. At first, we considered to fabricate the piston head in a 3D printer but realized that it would be challenging to achieve the necessary precision and structural stability with the budget and equipment that we have available. We opted for PMMA (Plexiglas) instead due to its price and robustness. More importantly, we had access to a laser cutter thanks to the EPFL-LMTS, which allowed us to cut very precise parts from 3mm or 4mm PMMA sheets, which we bought from the ENAC workshops. The piston was made up of seven pieces with a thickness of 3mm or 4mm glued on top of each other. Hence, the grooves for the O-rings were created easily by cutting one of the circular layers of the piston to a smaller diameter, as shown on figure 2.3.
Since our design does not incorporate a separate guiding structure for the piston, it was necessary to seal the piston with two O-rings. The grooves for the two O-rings are separated by a certain distance in order to get better guiding and prevent blocking of the piston when an eccentric load is applied.

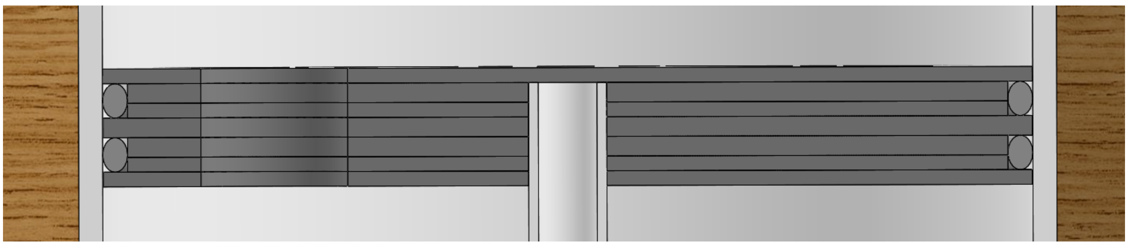


Figure 2.3: Layering of the piston

Piston bearer:
The piston bearer was also made from PMMA sheets with the same basic principle of stacking layers of PMMA. The piston guide rod passes through a hole in the middle that is sealed with two O-rings, similar to the piston. At first, we wanted the piston bearer to be supported by three supports machined from PMMA which are anchored in the PVC pipe. However, we overestimated the PMMA robustness, and some part broke during assembly. Hence we replaced these supports by wooden pillars. Most of the time, the supports need to withstand water pressure from above. Sporadically, during refills, the load on the supports is due to the compression of the spring only and therefore in the opposite direction of the water pressure. The original design was planned to support both directions of effort, but we did not see any problem with our much simpler solution. Due to the imperfect shape of the tube the piston bearer was in fact already blocked in place by static friction forces.

Sealing solutions:

The main issue with sealing that we identified in the beginning was friction. Our system relies on water pressure to function properly. Friction forces between the piston and the seals decrease the maximum height that we can transport water to using pressure created by the weight and spring alone. In the worst case, the weight and spring force that are meant to compress the water are entirely balanced by the static friction forces, so the piston would not move at all. The majority of cheap commercial seals are made out of nitrile rubber and are mostly meant for static applications. Nitrile rubber has a high friction coefficient and we estimated that it would be impossible to seal our water tank with nitrile rubber O-rings while having acceptable friction forces. Therefore, we decided to use PTFE O-rings. Among many other outstanding properties, PTFE has an extremely low friction coefficient and exhibits minimal stick-slip behaviour. PTFE O-rings are expensive but they solve our initial problem perfectly. Additionally, the low friction makes the piston less prone to block, so a separate guiding structure is not necessary.
When the PTFE O-rings were delivered, we realised that we underestimated their high rigidity. We obtained a flexible seal by adding smaller, soft rubber o-rings in series with the PTFE o-ring. These pushed the PTFE o-rings slightly outwards and allowed them to move in the groove, which was needed to conform to the imperfect roundness of the tube. This solution resembles to seals commonly used in pneumatic pistons where a rectangular PTFE glide ring rests on a compressed o-ring which allows for a tight seal with a low friction coefficient.

Spring:

The spring compresses the water tank in addition to the weight of the plant. Initial calculations (shown in annex B.1) showed that it would not be possible to get sufficient pressure with the plant alone. The spring mounted in compression enables to reduce greatly the weight required for the pot. It is guided by the piston shaft. We were provided the necessary spring from the locally based *Ressorts du Léman.*
In order to protect our PMMA plates, we reinforced them in the contact area with an aluminium plate.

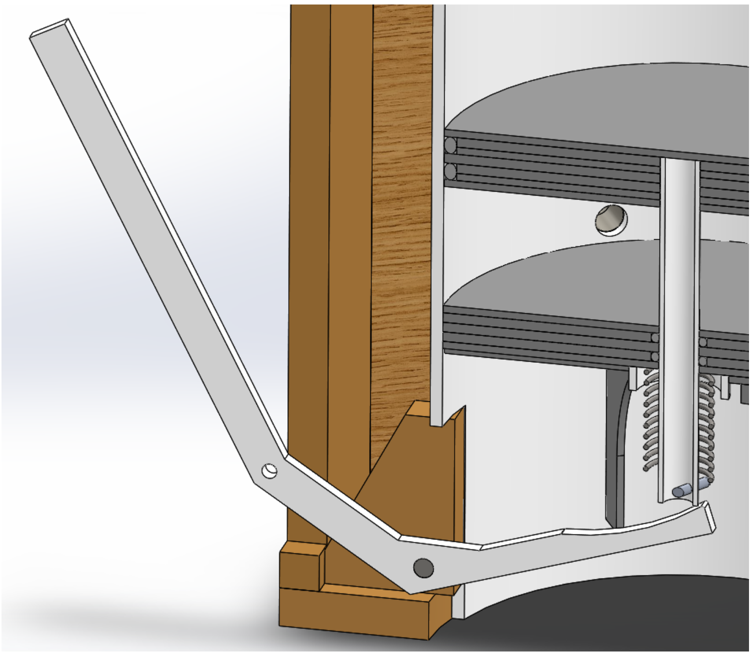


Figure 2.4: Pedal mechanism

Refill system:

To enable refill of the water tank, the piston has to be moved upwards. An integrated lever (shown in figure 2.4 above) in the flower pot can be pulled out to push the piston upwards, creating space in the water tank. Once the water tank is extended to full capacity, the lever can be blocked with a pin. After removing the plug, the user is able to refill the water tank by pouring water through a hole at the top of the flower pot. This refill system minimizes the interaction

required from the end-user as much as possible.
The pedal is one of the weak points of our system, and our initial solution (two PMMA sheets) was estimated too brittle for the load it will need to support. We hence reinforced it with wood and aluminium. The lowest end of the pedal is made so that a pin inside of the piston rod can freely slide on it with minimum friction when pushed upwards.

Wooden structure:
Apart from the inside tube used to support all mechanical components, our product has a wooden exterior structure to support and integrate all electronic components. We decided to make it much larger than the tube to keep the inside space easily accessible for optimisations and improvements. In addition to that, we needed the space to fit our prototyping board. However, the outer design would be a point that would be significantly improved for a final product.
The exterior structure is made from 16mm thick pressed wood, as it was both inexpensive and relatively easy to machine. We chose one with a nice exterior plating. The structure is based on a clever system using wooden pins to lock the side panels into place, inspired by Ikea's simple assembly methods. Three of the six side panels are fixed from the top and bottom using these pins, and the other three are easily removable, as they are only positioned into place with the bottom plate using the pins, and locked with a single screw into the top plate. This system makes it possible to avoid the use of screws as much as possible, which is a great point for aesthetics and assembly time. Only one of the three locking screws is visible, the other two being hidden by the solar panels.

Electronics, parts chosen:
This project was not as challenging from an electronic perspective as from a mechanical point of view. As mentioned previously, we made the choice to use an Arduino board and a prototyping board. This removed the necessity to make a PCB, one of the big challenges that would need to be addressed before going into final production.
What we did for this prototype was to connect each element of the circuit together with the Arduino. These elements are listed below:

- An Arduino Uno, chosen for its ease of use and for the compatibility with upgrade shields. We were aware of its relatively high consumption, but decided that at the prototyping stage, the pros outweighed the cons.
- The soil moisture sensor *Gravity SEN0193* to detect the moisture of our plant's soil. It can also be connected directly to an Arduino shield. Even though we won't use it for this project, we decided that if we wanted to try to upgrade our product with multiple sensors (light or pH for example), the shield will be an easier solution than direct connection.
- The magnetic proximity sensor *Gravity DFR0033*, used to detect when the piston is low, hence when the water level is low. We decided to go with a magnetic sensor because it was very easy to include a small magnet in our piston, and the one we chose has a digital measure capability and was available from the same retailer as our moisture sensor.
- Solar panels and battery pack linked to the Arduino through a shield that connects directly to the Arduino Uno. Both the battery and the solar panels were dimensioned according to the estimation of the current draw of our prototype, as shown in the calculations of annex B.2.
- The solenoid valve is used to control watering of the plant. The two key requirements for our solenoid valve were that it needed to be normally-closed and direct-operating. Normally-closed means that when no voltage is applied, the valve is closed, and open otherwise. The reasoning behind this was that this would reduce the consumption as our valve is closed most of the time. Direct-acting means that there is no minimal pressure difference needed for it to work, ideal in our case where the pressure is small. The valve also needs to be powered on 12VDC, obtainable with the Arduino via a 12V step-up booster.

Electronics, interactions:
The interactions we want for our components are described below. They are also the same as shown in the finite state machine of figure 1.1.

- The moisture sensor is checked every X period of time and compared with a value set by the

user through the use of a potentiometer. For device testing, X is chosen to be 16[2] seconds for prototyping, but will be much longer in the final product for energy saving. The exact value will need to be estimated for the final product. We think that a value such as one or two hour could be good in term of energy saving, while staying high enough so that the plant doesn't go for too long without water.
- The base value for moisture is obtained from average soil moisture requirement adjusted by the user with the use of a potentiometer. For final commercialisation, we will make available a user guide to help the end-user determine the need of their plant depending on its species and the environment it will be in. A "holiday" mode would also be possible to give the plant its most basic requirements to survive while increasing the autonomy of the watering system.
- If the moisture sensor detects a low level of moisture, the valve is opened for a certain duration, determined by knowing the output flow rate of our system. This duration has been set to 15sec.
- The magnetic proximity sensor detects when the water tank is below a certain level of filling, which is fixed by the range of the sensor. If the water level is low, a LED switches on and indicates to the user that a refill is necessary.
- Another LED lights up when the battery level reaches a critical level defined at 20% (note that this scenario should not occur except if the FlowerGrower is badly positioned or if the sun exposure is very low). The user can charge it with a standard USB cable.

For a further understanding of the electronic system and of the way the components interacts with each other, please refer to both the electronic schematics and the Arduino code joined respectively in annex D and E.

2.4.2 Further optimization of product for commercialization

Naturally, the purpose of our prototype is to prove the functioning of the concept that makes it an innovative product with great potential. It goes without saying that for the realization of a complete and mass producible product, some parts must be redefined or optimized.

Piston:
Regarding the realization of the piston, a single piece will be preferable to a stack of several layers. We will invest towards injection machining of the entire piece to make it mass producible and simplify its construction. The accuracy of this part is crucial for the tightness of the system and must be made with care and precision as well as the cylinder in which it slides.
As for materials, ABS could be considered for its toughness and ease of machining, POM for its great fatigue resistance and other mechanical properties or polyethylene for its low cost and moisture resistance properties, but it is subject to stress cracking.

Electronic circuit:
The use of an Arduino allowed us to save time on the creation of the electrical system and was well suited for the design of a prototype, but in order to fulfil our promise of a minimum energy consumption, the final product will have to be equipped with a a custom PCB created for this application. The system will last longer and take up less space which will allow us to leave more space for the water tank. In addition to that, it will also integrate the battery management, as we used a solar panel shield until now. The number of solar panels used was voluntarily higher than needed for our project. Once the system has an optimized energy consumption, their number and sizing could be reduced to allow some improvements in aesthetics.

Valve:
Regarding the valve, the current system still consumes a lot of energy and is maybe not perfectly appropriate for our system. A simpler mechanism to block the exit of the water will have to be imagined in order to limit this consumption. The construction of a dedicated valve or the use of a two-post engine could potentially mitigate this issue.

Lifting system:
The current piston lift system, the pedal, is the biggest weak point of our system. While it is

[2] needed to be a multiple of 8

functional on the prototype, it gave us nevertheless a lot of problems during its manufacturing and the rising the piston has to be done carefully. A different mechanical system will have to be created to facilitate its use for the customer. A pushing movement instead of traction will make its use easier.

Filling system:
Note that the tank filler hose slightly rubs during the movement of the piston which could be a problem. Implementing a button to manually open the valve in case of low tank level will allow the consumer to use the same pipe (which would then have a increased diameter) to fill the tank, simplifying our system. A detachable, tuned diffusion nozzle will be fitted to the end of the tube to reduce the flow for irrigating. The user can then remove the nozzle and use a funnel for refills.

Aesthetics:
Finally, an improvement on the aesthetics of the product will also be taken into account. The wood design gives a very pleasant appearance but can be redesigned during the design of the final product. Indeed, pressed wood was cheap and easy to manufacture for our prototype, but using timber wood would greatly improve the aesthetics of our product while reducing harmful chemicals contained in condensed wood boards. The outer pot of our prototype is also much larger than what it could be, which leads to a bulky prototype. For final production, the use of a custom PCB will greatly reduce the space used, and will lead to a sleek design. Another upgrade we could implement is to offer the consumer a way to choose between different design or patterns which could be printed on the boards to make the product more personalized.

With all these improvements, we expect our product to be well optimized to please the user. Indeed, thanks to the improvement of these points, its mass production should be easily implementable and its price will thus be reduced.

2.4.3 Final product

As a start-up, we wouldn't have much initial funds available for buying production warehouse space and equipment. As such, the fabrication of most elements would have to be subcontracted, we would only keep in internal production what makes our product's specificity: the compressible water tank and the product assembly.

Figures 2.5 to 2.7 present all estimated costs for the planter's elements, taking into account a redesign of most elements. While our prototype was optimised for fast production and proof-of-concept, the final version of the product will be developed to optimise function, durability, costs, as well as design for assembly.
Most electronic parts can be bought on the market and mass production costs are significantly lower than for prototyping. A custom PCB lowers our costs and improves the reliability of the system.

Our total estimated costs would be around 45CHF, with about one half of the costs coming from mechanical elements and the other half from electronic elements.

Element	Part	Material	Method	Production	Quantity	Est. cost CHF
Assembly						
Assembly	Outer pot	-	Manual	Internal	2	2
	Water Tank	-	Manual	Internal	1.5	1.5
	Electronics	-	Manual	Internal	1	1
					Total	4.5

Figure 2.5: Assembly estimated costs

Element	Part	Material	Method	Production	Quantity	Est. cost CHF
Mchanical parts						
Outer pot	Outer pot	Wood	Saw cuting + sanding	Subcontracted		5
Pedal	Pedal	Wood + Plastic	Saw cutting + Injection	Subcontracted		1
	Pedal support	Plastic	Injection moulding	Subcontracted		1
Water Tank	Cylindre	Plastic	Injection moulding	Internal		2
	Piston	Plastic	Injection moulding	Internal		3
Tubes	Watering 4mm	Plastic	Catalogue	Bought		0.1
	Filling 1/2"	Plastic	Catalogue	Bought		0.1
Spring	Spring	Stainless Steel	Catalogue	Bought		1
O-rings	Internal O-ring	PTFE	Catalogue	Bought	2	2
	External O-ring 190mn	PTFE	Catalogue	Bought	2	3
Small elements	Screws, pins, etc		Catalogue	Bought		2
					Total	**20.2**

Figure 2.6: Mechanical elements estimated costs

Element	Part	Material	Method	Production	Quantity	Est. cost CHF
Electronique						
PCB	PCB		Subcontracted	Subcontracted		3
	Resistors, transistors, etc		Catalogue	Bought		1
	Microcontroller		Catalogue	Bought		0.5
Battery	Battery		Catalogue	Bought		5
	Solar Cells		Catalogue	Bought	3	2
UX	LED		Catalogue	Bought		0.5
Watering system	Valve solenoide		Catalogue	Bought		2
Sensors	Potentiometre		Catalogue	Bought		0.5
	Soil Moisture		Catalogue	Bought		4
	Magnetic Prox		Catalogue	Bought		0.5
Small electronics	Cables etc		Catalogue	Bought		2
					Total	**21**

Figure 2.7: Electronical elements estimated costs

Manufacturing

If we were to manufacture our product from scratch, as a start-up, our final choice for production would depend on our funding and investors. If we decided to buy an injection machine, this would cost approximately 500'000CHF, and additionally we would need custom moulds for our parts costing between 15'000 and 50'000 CHF each depending on the complexity of the part. These parts produced internally would be at least the compressible water tank elements, but structural elements could also be produced from an injection machine.

For the electronics, it is easy and reliable to subcontract entirely soldered custom PCBs from professional companies either in Switzerland or in Asia. The same goes for the wood elements and plastic elements if subcontracted.

2.5 Quality control

We implemented a quality control procedure to determine whether our flower pot was marketable. This procedure is based on two different points: a first pass/fail for each of the specifications, and a second more detailed study based on certain metrics.

The requirements listed in section 2.1 should be entirely fulfilled to pass the first quality test. All the key specifications are listed below:

1. the flower pot correctly waters the plant
2. it is autonomous from an energy perspective
3. it has both a feedback and a user input hub

4. it is suitable for indoor operation (operation temperature range of 10-35°C)
5. it has an inventive aspect to differentiate itself from the rest of the market

These can simply be checked at a glance for most of them. The fifth item will be further explain in the intellectual property search of section 3.

In addition to these functions, it also matches the weight and price requirements. The total weight of the prototype (with water tank empty) is 5.2 kg without the plant, and it cost us a total of 320 CHF to produce, with not all elements included in the final prototype. In fact, we bought components that we did not use in the end due to change of plans. For example, we bought a LCD screen to test whether it was feasible for our product, but preferred the LED approach in the end.

The second part of our study was to create a procedure to test different characteristics of our product. The points to check are listed below:

1. the flower pot can last at least one week without being filled in water, or recharged in battery
2. it can sustain a maximum number of watering cycles. We can test our product with 10'000 cycles for example, corresponding to 5 years of use with 3 watering every day, with a safety factor of x2

These point are much harder to test than the first, more straightforward ones.

For the first criteria, we can use it for one week with settings adapted to the plant and its environment (temperature and humidity) and check the water level left at the end of the week. Unfortunately, we couldn't test this due to the fact that we gave our prototypes after the presentation, and that we didn't have time to check it before for extended period of time.

For the second one, we need to design a procedure that will test our product in an accelerated manner from what would happen in real life, and extrapolate the results. For example, if we see from experimentation that the flower pot usually water the plant every two hours, we can set it to water every 20 seconds. That way, we have an acceleration ratio of 360. If after one full day of testing the mechanism still work, it should be able to function for at least 360 days. However, in our case, the segment of interest of our product is its mechanical system. Indeed, the electronic circuit will be done in a completely different manner for the commercial product, so testing the prototype isn't necessary. Moreover, all the components are designed to be used the way they are in our project, so they are not the main liability of our product.
The element we need to test is the mechanical system. To test that, one thing we could do is set the valve to "always open" and refill it whenever the tank is empty. However, this solution requires constant supervision, so testing it on a long period of time is not doable. A second solution would be to move just the piston repetitively in its chamber, and check if they are any more leaks at the end compared to the beginning. The problem with this solution is that we need to design a specific testing machine, which is not possible to do in the span of this project.

In a final prototyping/product stage, the reliability of our product will have to be tested more thoroughly. For the first criteria, additional to theoretical validation, the planter could be tested in "extreme" conditions in a room monitored in terms of temperature and humidity. The conditions would be set to very dry and hot (within operating ranges) with a delicate plant usually withstanding these conditions. The autonomy of the water tank can be verified in such extreme conditions which usually won't be found in a typical user's home.
The second criteria, mechanical endurance, will have to be tested on a custom test bench. If as said above we want to test it through 10'000 cycles, our watering system would be set on a bench doing constant accelerated repetitions of the refill-watering cycles: refill, open valve, water, close valve, repeat. These repetitions would be performed automatically on a set of units coming out of production. The maximum endurance could also be tested during prototyping and production to calculate if our system is fragile and might break during its lifetime or not.

3 Intellectual property analysis

Intellectual property is an essential task of product development. It is necessary as the law condemns the usage of protected ideas and concepts. Were we to use a protected property, the fine that would follow would be very handicapping for our would-be company. Therefore we need to carefully study the already existing legal protections.

3.1 Prior art search methodology

A quick research shows that smart flower pots are already available on the market. This can be confirmed further with an intellectual property research, done in our case on the platform *EspaceNet*, worldwide patent database. The goal of this search is to look for possible patents that could become problematic during our product development.

We tried to find patent related to our system using different keywords, such as the following:

- *autonomous* or *automatic*, as well as *smart*, to filter for the self-regulating plant pots that don't require (frequent) actions from the user
- *moisture*, the main item to monitor
- *valve*, one of the key electronic components of our project
- *compressible chamber*, our main mechanical complexity, and the term most liable to filter the results to only our system. Apart from this keyword, we also tried with *flexible tank*, *piston* and *syringe*
- *spring*, *weight* and *gravity*, the means of compression of our chamber

We also used the patent classification system to filter our search to only certain classes. The classes applicable to our product are *A01G27/00*, relating to *Self-acting watering devices, e.g. for flower-pots*, and *A01G9/00* relating to *Cultivation of flowers, vegetables or rice in receptacles, forcing-frames or greenhouses.*

We then divided our search in two sections, electronic and mechanical. In the first search, we will try to determine whether our concept is already patented from an electronics point of view, and if we need to change some things in our product. We already know that smart planters exists, so this search will be very broad. The second one will be much more specific, being based on a system that we haven't seen on the market. In the case of a proved uniqueness, we will then try to create a main claim for a possible patent filing.

To decide which patents are relevant or not, we first looked at their titles. If the title seems relevant, we read through the abstract to see which claims could be said for our product as well. The huge number of patents returned by each search makes it impossible to read all of them, so we decided to reject patents when an element made it irrelevant. Reading the different abstracts also enabled us to better understand the relevancy of some keywords, which we then took into consideration for the next searches.

3.2 Patent search results

We did a first research using only the first two keywords and the classification to find patents related to our project in general, and not specifically to the mechanical system used in the FlowerGrower. This research returns a lot on different systems, some of which are closely related to our project.

For example, we found a first one from 1991 on *Automatic and autonomous device for watering pot plants*, relating to "a device consisting of a small sized pump moved by an electric motor capable of pumping a nutrient liquid from a reserve to bring it into contact with the roots of the plant according to a watering period and a watering sequence frequency which are determined by a programmer connected to the device" [10]. While corresponding to our product for most of the content, the mention of a pump excludes it from our search. Moreover, as the patent is now quite old, we expect that it will not be a problem for us.
More recently in 2016, a patent was filed for a *Pot with a water reserve for a plant* [11] by the company Parrot for their Flower Power, one of our direct competitors. It concerns an autonomous plant watering device, but it doesn't affect directly our IP research as once again the

patent abstract mentions a “pumping means” [11], which our product doesn’t use.

This same research also returned a patent applicable to us. This is the case of the patent called: *Watering method matching potted plant soil moisture level and smart potted plant water-spraying system* [12], filed in 2017. It has a similar system to ours in the sense that it monitors the moisture level and compare it to a pre-set level and water the plant if it is needed. They also describe the means of watering as a “water-spraying system”, which could also be said about our product. This patent may cause conflicts were it accepted during the span of our product development. However, for now it is not a direct threat.

The second stage of our search included all keywords in various combinations, sometimes omitting certain specific keywords such as *valve*. The goal of this second search was to look for a mechanic system close to ours.

We found one result that corresponds slightly to our project, apart from the compressible chamber part: a 1977 patent called *Automatic plant pot or garden plant watering container - has water inflow and outflow connections with return pipe and absorbent pot lining* [13]. It contains the same general concept as ours in the form of a water-containing chamber with input and output valve/entry inlet. However, from its publication date, the patent is now obsolete and changed to a public domain patent. As a result, this system cannot be patented again in the same form, so this aspect of our project is secure.

Globally, where the systems put into sight by our research are similar to ours in term of usage, they always differ by the watering system, often using a pump, or by the connectivity/embedded electronics level, sometimes completely passive. On a mechanical perspective, we haven’t found any patent describing our compressible chamber system.

We will then continue the development of our system while taking into consideration the patent conflict found during the first search. However, before going further into final commercialisation, doing a more thorough study, potentially outsourced to a specialised company or lawyer, may be a smart idea in order to avoid conflicts in our commercialisation. While it will be expensive, we believe that the investment for not having to worry about intellectual property on our end is enough to justify it.

3.3 Discussion on IP strategy

From the researches we did, no patent were found to depict our mechanical system enough to raise concern on the commercialisation from this side. From its uniqueness, we think that filing a patent will be a smart move as our product may be copied by other firms. The main aspect of our product to protect is its ingenious way to push the water upwards, as the rest of the plant pot is already present in some way in other patents. Moreover, this system is not an obvious one, in the sense that it is not something so ordinary so that anyone could have thought of, so protecting it is a good idea.

As such, we wrote points for a possible main claim on the mechanism as found below. A name we could choose for the patent claim is *Watering system for a plant without the use of a pump; using passive actuation instead*, and would be filed in class *A01G27/00*.

- Our invention is a pot designed to contain a plant.
- Via a set of sensors, the system will detect when the plant is in need of attention, be it from a water perspective or any other element that the plant may require such as nutrients, light or fungicides.
- The different parameters for the plant requirements can be set through buttons, potentiometers or other actuation methods.
- The water is contained inside of a compressible chamber.
- The chamber is compressed via a passive force that can be created for example by the weight of the soil container itself, by a spring or by a combination of both.
- The compression causes the water to flow upwards to the plant to regulate its water requirements.

- When, according to the sensors input, the plant doesn't require watering, a valve closes the water circuit so that the plant doesn't go above its requirements.
- A lever system makes it possible to easily refill the water while lifting the plant pot.
- Diverse feedback mechanisms (LEDs, buzzer, LCD screen...) can be used to communicate the plant's state to the end-user.
- An electronic circuit links the different electronics components together (user feedback hub, user settings hub and valve) powered by a battery pack.

4 Pre-business plan

This section describes the work that needs to be done where we to decide to launch the production of our product. This pre-business plan would allow us to be prepared to the different aspects that we would be exposed to.

4.1 Market

Market trends: Approximately 50% of the European population have indoor plants[9]. This market is expanding: multiple recent trends focus on clearing up one's interior while bringing more life into it. Trends such as Konmari, Hygge, wellbeing and cocooning advise enthusiasts to create a cozy interior by surrounding themselves with little decoration, and focus on things they love. People like having house plants for their proven soothing effect.

Moreover, our society is slowly evolving to adopt a more natural lifestyle promoting contact with nature. This trend directly impacts the interior plants market which has grown by 5% over the past 5 years.
However, adepts of these trends are often busy people who do not have much time to take care of their plants, travel often for work or leisure, and might consider themselves unable to care for plants. These people would welcome a smart aid into their homes to make it more liveable while being easy to manage.

Western countries are faced with an ageing population and elder people often find themselves lonely at home, and losing their autonomy. A smart planter might allow this segment of the population to enjoy interior house plants while not having to burden themselves with too much necessary care.

Market segments: As described in figure 1.2, our main target population would be young active adults. We also consider sales as gifts for elder relatives or younger users.

We would mainly target Europe and North America for our sales as their market behaviour and consumer habits are similar to Swiss ones. For France, Germany and the UK, approximately 10 million of people aged 25 to 40 years old having indoor plants. If we target 1% of them, that is 100'000 clients market potential for 3 countries, which is already big.
The total European market for garden and plants amounts to approximately 88 billion euros[8]. On average, 5% of spendings are on indoor plants and 10% on equipment.
In 2016, in France, consumers have spent 380 million euros on indoor plants, with an average of 6 indoor plants bought per home and per year, with a 70€ of annual budget[7]. Furthermore, 760 million euros have been spent on gardening and plant care equipment, that is twice as much as for the plants themselves.

Main competition: Our main competitor is the Parrot Flower Power, which is between 1.5 to 2 times more expensive than our product. It also requires more user involvement as the pot has to be connected to the internet and a phone app. It uses 4AA non-rechargeable batteries, which might be a concern for some users.

The Parrot Flower Power alloys us to estimate our sales potential: according to their 2016 Reference Document [5], the Flower Power was launched during 2016's last quarter and they sold for 2.1 million euros an estimated 40'000 devices per year, which is a growing figure.

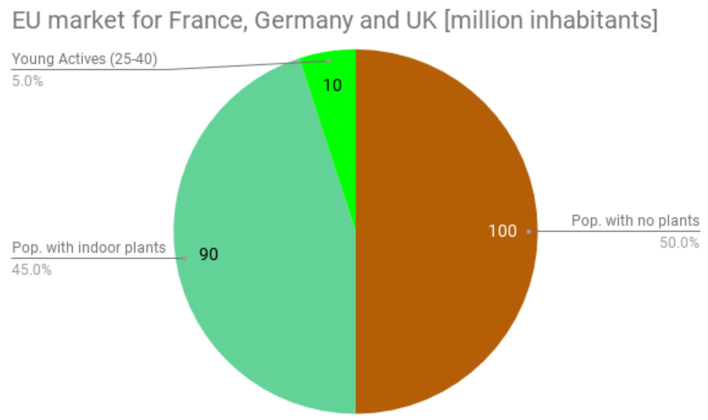


Figure 4.1: Target market size for France, Germany and the UK

We would compete with Parrot, but also target the less tech-savvy users who wouldn't want too much of a high tech flower pot. Having a lower price range, we can also reach a larger customer basis.

4.2 Strategy towards commercialisation

We identified two main strategies towards commercialisation: either going through well-known retailers, incurring a higher sale price due to margins, or selling it directly through our website, for a lower cost but also having less visibility.

Retailers:
Partnerships could be tied with retailers such as *Nature et Découvertes*, *Fnac* or *Botanic*. These could either be exclusive or we could try to get as many retailers as possible. Such retailers have a wide population among their clients, which are often recurring customers. People who regularly buy plants tend to trust more retailers and specialised plant retailers[6]. Our product would get a high visibility through these retailers and we could expect to have good sales. However, the retail price would have to be higher as the retailers would take a margin.
Retailers could also chose to sell our product in packages with wellness plants such as medicinal or depolluting plants for increased attractiveness...

Webshop exclusivity:
By selling our product exclusively through our website, we could guarantee a lower price to our customers. However, especially in the beginning, if we don't have a strong brand positioning and our product is not well known it might be hard to get sales to go up. If we have a good marketing strategy and communication, we can create a strong online presence and target social media users who prefer shopping on the internet. A digital strategy would allow us to boost our sales.

4.3 Team organisation

Our potential future company would be divided in three main subgroups working closely together: mechanical/design, electronics and management. We would prioritize the recruitment of creative, hands-on and open-minded people to join the team.

The electrical team would be composed of a small group of skilled engineer, working on the development of the low energy consumption of the system. Therefore, their tasks would be for example to find a valve adequate for our system, dimension all the electronic components (such as the solar panels or the battery) to limit costs, as well as create the PCB design to be sent to subcontracted firms. This team should be in our estimations one to three people strong. Indeed, the work to be done is not extensive as compared to the other sections.

The mechanical team could use a specialist in industry to provide guidance during the prototyping phase in order to have a final product more adapted to mass production at low costs. This person could potentially be external to the company. During the development stage, it is also important to have an industrial designer in order to get an appealing final product. In addition to these two key employees, we would need some to rethink our system globally in order to optimize it mechanically. Overall, the mechanical team should be somewhere between two to five people.

On the managerial branch, we would need a marketing and communication team in order to make our product known, which is essential for the tasks listed below in section 4.4. This person or group of person will be in charge of marketing, digital strategies and social media communications, which nowadays are the keys to a successful product launch. If we judge it necessary, seeking an external advice from an IP specialist could be a good idea, even if expensive. This group will also be in charge of the general budget and time-frame management. This means deciding where to allocate money (factories, sourcing materials...), when to do each tasks in order to be on the time-frame decided in the beginning of the project. This group will also be responsible of the human resource component of the project, therefore salaries and employment. We estimated that two or three motivated employees would be sufficient.

Globally, our final team could be anywhere between five and a dozen full-time employees, with additional specialized persons. Working with even less people could be doable, but the quality of the product will probably decrease while the lead would decrease. Working with more would be inefficient considering the price of qualified labour.

4.4 Financing of the project

The financing for our project could be found in multiple places. As our company will be quite small, crowdfunding could be a good solution. Indeed, we won't have the size needed for a stock introduction, and the use of our product is too specific to hope for public subventions, as well as being a *gadget* object, not necessary useful for everyday life.

Crowdfunding is often considered a very good solution for small sized firms to check the market without taking too much risks. For our crowdfunding campaign to be successful, we will need to create an attractive marketing campaign. This campaign could be emphasized on social media, as they are one of the key vector of communication of our target market (young adults). Our ideal scenario would be to *go viral*, even if we need to not rely on it, as social media have a lot of fluctuation. Early adopters could be a powerful way of advertising our product in social media, it could be interesting to target these people and offer them a special treatment to keep their interest high. In addition to that, online exposition on social media doesn't cost as much as magazines and other classic marketing vectors.

If we decide to go for a more **classic financing**, we will need to look for investors willing to put money in our product. These can be big firms that are close to our market, such as *Nature & Découvertes*, who already commercialise a lot of gadgets (some related to plants), or more from a plant perspective *Botanic*, who sell plant pots, and may be interested in a more technologically advanced product. These companies could invest in our start-up for exclusivity or even buy our budding company to make it bigger within their own structure.
As our product is at the border between plant and gadget, the idea would be to go to firms specialized in the two domains to try to seduce a larger audience.

As a start-up, we could also participate in competitions and accelerator programs to secure capital and coaching which would be very helpful for our growth. **Business angels and other investors** would be very important as they could invest in our company while guiding it in a market-secure direction.

A **loan** will probably be necessary in any case, as we begin our project with nothing more than a first working prototype. We will need a certain sum of money to begin the final product development. As we will launch our product as a start-up, we will first need a small office to rent, and later during the development process also a manufacturing place. Any loan would have to be taken up with much precaution as we have to be certain it will be paid back. This is to be avoided in early steps of development, and more preferable towards market launch when we can expect an influx of money.

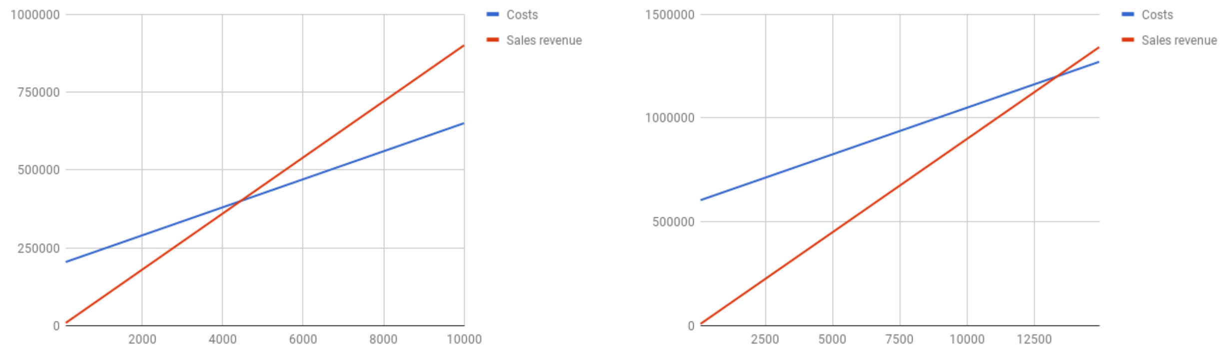
4.5 Planning

We will consider here two scenarios: one where the fabrication of every element is subcontracted (Fig. 4.2a), and one where we buy our own injection machine, costing 500'000CHF (Fig. 4.2b).

We can see that in the first case, break-even is attained at around 4'500 units sold. In the second case, break-even is around 13'000 units sold. Considering the scenarios presented in sections 4.2 and 4.4, different approaches can be considered.

In a big company, if we were bought by a retailer or a large company, the best strategy would be to buy the necessary equipment and keep all crucial manufacturing in house. As the company would have sufficient funds to provide a warehouse, machines, operators, etc. it would be cheaper, safer and more effective to proceed this was. As seen in section 4.1, for only 3 countries our estimated market potential was around 100'000 clients so it is safe to assume break-even can be reached through these means.

As a start-up, funds will be less available and all investments have to be strategically thought up. The 4'500 units target shown in 4.2a seems like a reachable objective through crowdfunding, which would allow our start-up to confirm our product and market position. With the buzz created through the campaign, we would be able to attract new investors and launch a second production round, this time perfecting the design and bringing back the crucial production elements in house.



(a) Break-even with development costs of 200'000CHF

(b) Break-even with development costs of 600'000CHF

Figure 4.2: Break-even scenarios for our product, at a cost of 45CHF and retail price of 90CHF (to client or retailer)

4.6 SWOT analysis

The purpose of the SWOT analysis is to study the factors that could impact the development of the company, both external and internal, positive and negative. Regrouping those factors in 2x2 matrix allows us to have a quick overview of the current strategic position of the project. It also allows to prepare the strategic options, the risks and problems to solve before going further. The SWOT analysis helps balancing the positive with the negative and can avoid making costly managerial mistakes.

For our product, it can be found in figure 4.3 below.

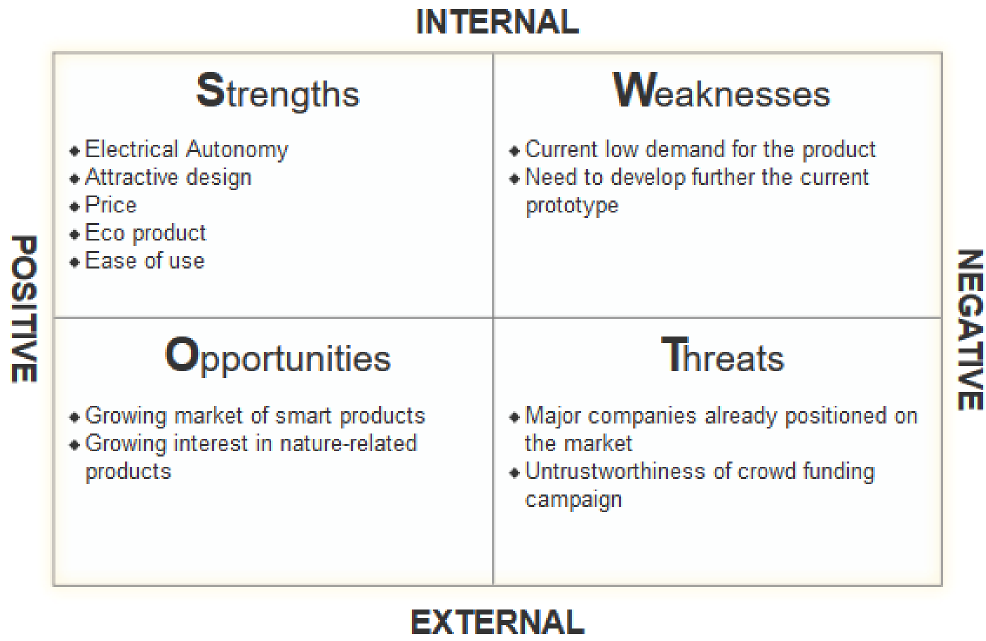


Figure 4.3: SWOT analysis

5 Project management

This section lists the different managerial tasks done during the span of the project. More specifically, we explained the choices made in term of timing and team organisation.

5.1 General strategy

The first stage of our project required extensive amounts of brainstorming, and to enable ideas to be as diverse as possible, the whole team worked together in order to reach our product concept.

After this initial stage, we decided to separate our team based on our own experiences and preferences. Indeed, while having the same study curriculum, our fields of expertise differ. We separated the team in three main groups: mechanics, electronics and management. Alexandre and Silvan made the mechanic department, Antoine and Arno were in charge of the electronics while Chloe and Victor worked in the management team, according to each group member strengths. This separation will also be justified later on in section 5.2.

While separate, coordinated weekly meetings with the whole group guaranteed that no misunderstanding appeared. These regular meetings were scheduled to check the progress of each other, and additional separate meetings between each subgroup enabled a constant progression throughout the semester.

In addition to this work separation, we decided to enable a flexible allocation for each of our members. Indeed, at some point in time, some tasks may have been more urgent than others, in these cases, some team members changed roles until the issue was resolved.
As an example, we ordered the first electronic parts on the 29th of October, but they were scheduled to arrive only ten days later, timespan during which the electronic subgroup was inactive, and could work on other tasks.

5.2 Work breakdown structure

Below in figure 5.1 you can find the Work Breakdown Structure (WBS) of the project. The first level shows the most general aspect of the project, the lower levels specify the more detailed aspect of the work packages. It is constructed by starting with the final product, represented as the top node, which is going to be subdivided into several work packages. It was done in the beginning of the product development to help with the repartition of the group members between the tasks at hand.

The goal of this procedure is to decompose the project into tasks that can be more easily managed and understood by each team members. The fundamental principle of the WBS is that it describes the entire workload of the project. This way, it completely describes the project itself. It is a fundamental step to be processed for every project since it helps dividing the tasks between the team members. Moreover, as most of the projects are multidisciplinary, evolving some electronics, mechanics, designs, management, etc. thus it usually requires engineers and other peers from different fields. A description of the project to be understood by everyone is necessary and the WBS is a perfect way to create such a description.

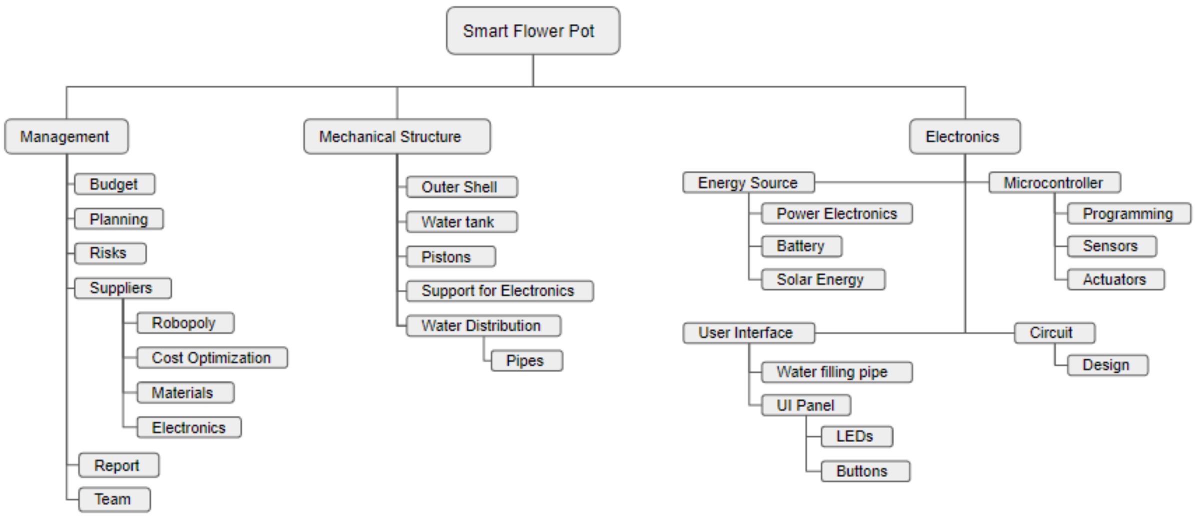


Figure 5.1: Our project WBS

The division of our team was made according to the three main branches shown.
This representation shows that the work is more or less balanced, but the complexity of the tasks in the *Mechanical structure* compensate for their low numbers.

5.3 Stakeholder analysis

The main stakeholders of our project are the project supervisors who defined the most important product requirements and provide funding for its development. Due to the time constraints, the suppliers were also an important stakeholder to consider, since delivery times or potential fabrication errors could have a considerable impact on the completion of our prototype. Furthermore, the final assembly of the individual components will be made between the Robopoly makerspace and the ENAC workshops, so they occupied a big part of our product development. The functionality of our design is aimed at optimizing its sales potential, innovativeness and convince the project supervisors. Thus, potential customers and our competitors (including other project teams) are also part of our stakeholders.

The stakeholders and their dependencies are shown in figure 5.2. The stakeholder analysis is a useful tool for us in defining our product requirements, as it defines clearly the different parties to please, as well as the interactions they develop.

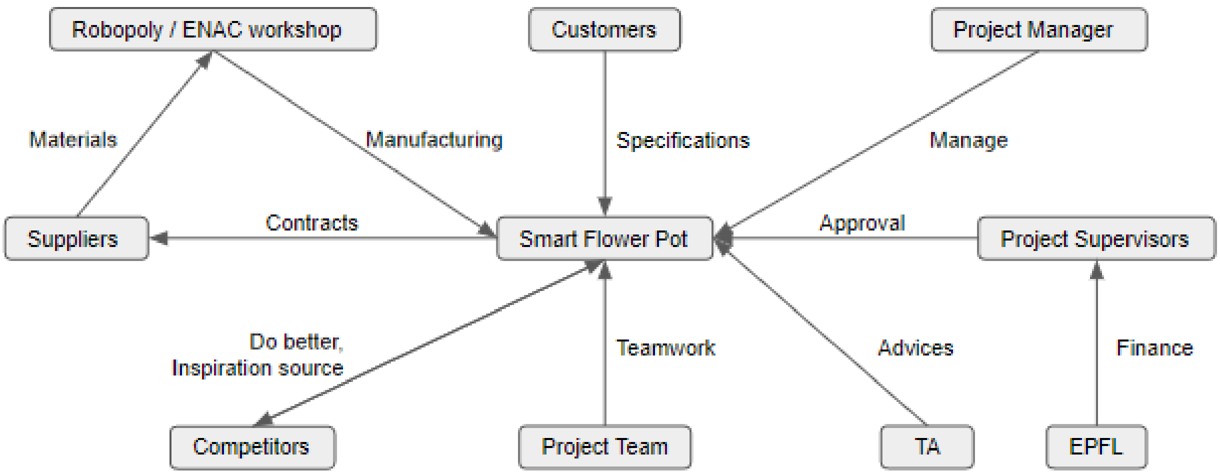


Figure 5.2: Stakeholder analysis

5.4 Project budgeting

The following table in figures 5.3 and 5.4 presents our expenses compared to expected costs. In total, we spent 250CHF on components and 60CHF on delivery costs. The total amounts are comparable to what we had planned, we can still notice some components being far cheaper that expected (such as the valve in figure 5.4) or way more expensive, such as the o-rings and shipping costs seen in figure 5.3.

Better planning would have allowed us to save money on components we bought but didn't use, for example the LCD that we rejected after having ordered it due to its relatively high consumption. Had we had more time, we could have selected a nicer type of wood and built a custom PCB. These would have costed more but they would have made the prototype better.

The final production costs have been listed in section 2.4.3 and would be way lower than the prototype costs by amounting to around 45CHF per unit.

Mechanical parts				
Name	**Elements**	**Proto costs CHF**	**Est. costs CHF**	**Shipping CHF**
Outer pot	Wood	25	50	Obi
Water Tank	PVC tube	*23*	10	Shop
	Piston Plexi	*33*	45	Ateliers archi
	Shaft	0		10
Inner pot	Standard clay pot	*3*	5	Obi
Tubes	Aquarium tubes	*4*	5	Obi
Spring	Ressorts du Léman	0	15	Sponsored
O-rings	Internal O-ring x11	7.02	2	with big O-ring
	External O-ring 190mm x2	23.69	15	33.84
	Total	118.71	147	43.84
	Total Prototype	162.55		

Figure 5.3: Budget for the mechanical components

Electronics				
Name	Elements	Proto costs CHF	Est. costs CHF	Shipping CHF
PCB	Arduino Uno	22.74	24	6.88
	Shield battery and solar	16.91	28	with battery
Solenoid valve		2.48	12	2.68
LED		0.5	1	Robopoly
LCD display		12.71		with battery
Potentiometre		0.93	1	with battery
Breadboard		5.25	5	with battery
Buzzer		1.63		with battery
Sensors	Soil Moisture	11.08	7	with Arduino
	Magnetic prox sensor	4.55	4	with Arduino
Booster	12V	4.9	5	with Arduino
USB cord		2.92		with Arduino
JST cord		1.17		with Arduino
Battery		26.71	20	6.88
Solar Cells	x3	12.25	20	with battery
Small electronics	resistors, connectors, etc	2.4	5	with battery
	Total	129.13	127	16.44
	Total Prototype	145.57		

Figure 5.4: Budget for the electrical components

5.5 Gantt chart

5.5.1 Initial plan

The first Gantt chart we constructed was voluntary highly optimistic. We did this to force ourselves to work as much as possible in the beginning as to not be overwhelmed in the end of the product development.

Using our WBS graph, we separated the work from the three main parts (Management, Mechanical, Electrical) into three groups of two people, as described in the previous sections. Each group were able to work on their specific section of the project but also to help other groups during meetings and other group discussions.

In addition to this Gantt chart, we kept a journal for each of our group meetings throughout the semester. This file is linked in section F.

5.5.2 Deviations

The main deviations from our original Gantt chart were from a time point of view, as we organised well our work repartition between members. As a result, the Gantt chart changed a lot on the span of the development. As an example, the engineering and design of the piston mechanism was originally thought to happen in week 7. However, uncertainties on the different elements of the electronic section -such as where should the moisture sensor should be placed- lead to delays. Some parts took more time than expected, since we voluntarily compacted the work in short amount of time, but overall the process flow of the project was good.

We haven't had the need to reallocate team members in different work groups, which proves our team organisation to be efficient from the beginning. The mechanical section revealed to be more demanding than we expected in the beginning. For this reason, some team members from the electrical and management teams spend some time helping the mechanical team.

Below, the final Gantt Chart for the project. Only the weeks starting from week 7 are displayed since the previous steps of the project are straightforward.

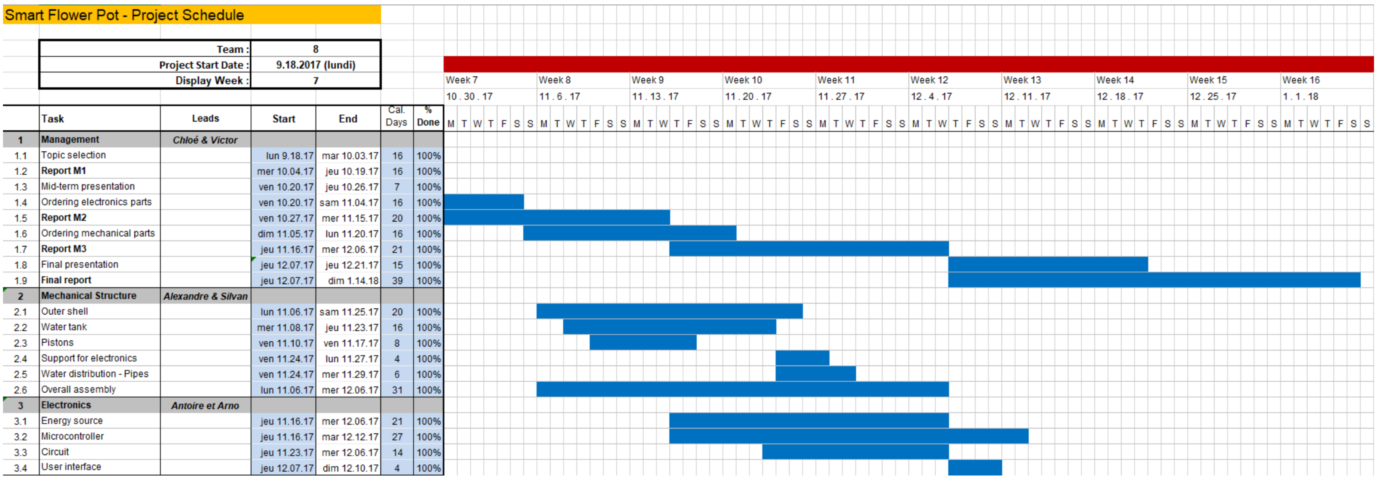


Figure 5.5: Final Gantt chart

5.5.3 Reflections

The final decision regarding the tank filling system took a long time to finally be decided which caused us some minor delays in the realization of the prototype. Its realization does not appear in the Gantt chart but was globally realized at the same time as the report M3.

One problem that could have happened was the ordering and delivery of the valve. Since it is a very important part of our system, we should have order it sooner to avoid any risk of problem with its operation in case it arrives late, which happened. Fortunately, the latter worked well after some adaptations of the electrical system were made.
A better implementation in the Gantt chart would have been to take the delivery lead times into better consideration for each product we selected. In this case, the main problem was that we spend too much time deciding on which valve to choose, and that when the choice was done, all the website where it was available offered only long deliveries.

A similar issue arose for the HDPE tubing. Even though buying it in a 3m long format could have been a solution from the start, finding a place that was at the same time willing to cut it for us proved to be a bigger challenge than expected, and resulted in long delays in the prototype fabrication.

5.6 Work repartition

Arno:
I participated in the brainstorming and design process that took place at the beginning of the project. Later on, I was responsible to find some components for the creation of the prototype. My implication in the project was more in the creation of the prototype even I helped for the multiple presentation and reports.

Alexandre:
During this project, I was able to participate in the creation of the mechanical plans and 3D modelling of the product (Solidworks model). I also took care of the general organization of the planning and was able to participate, in part, in the construction of the prototype. I was also able to give feedback throughout the project to our assistant to summarize some of the thoughts on the project and get feedbacks.

Antoine:
I had several main responsibilities throughout the realization of the project such as designing the electronic circuit from scratch, managing the power electronics and implement it on the Arduino board through the code illustrated on Annex E. I was also part of the building team. Even if

I mainly implemented the electronic circuit in the prototype, I also helped by machining some parts and brainstormed to solve the unexpected problems. Finally I also helped in the writing of the milestones and solved the exercise 2 of the Manufacturing Systems Modelling mini-project.

Chloe: At the beginning of the project, I was an active contributor to ideation and design during the brainstorming sessions and mechanical design definition. Later on, I did most of the components research to find which components and suppliers would be the best for our prototype, as well as a lot of market research. Finally, I helped with the construction of the prototype for the final presentation.

Silvan:
I was responsible for the mechanical aspect of our product. This includes the design and dimensioning of the cylinder, piston, seals, spring mechanism and the pedal used for refilling. Furthermore, I was involved in the choice and acquisition of the materials for these components. During the last weeks, I dedicated a large part of my time to the assembly of the prototype.

Victor:
My main implication in the project was inside of the management branch. In the beginning of the project, I worked on planning and budgeting while helping with the concept development, focused on the IP search in the middle of the semester, and helped with the prototype fabrication in the final weeks. In addition to that, I contributed to the writing of the reports.

6 Conclusion

During the realisation of this project we encountered all the different events and surprises of building a new product. The main problems arose during the manufacturing of the prototype. Of course our work as engineers is to overcome them, or even better to predict and avoid them.

Looking back at our journey, there are some things we could have done better such as ordering the main parts sooner. As the workload has been separated in a dependant network, if the critical path gets delayed, all the other nodes get stuck by this central delay. This is not optimal at all and can be easily avoided.
Moreover, there was some small designing mistakes that have been realised only during the assembly of the prototype, which is of course too late. Such errors could have been avoided by simply double checking the drawing views.

However, we were able to overcome all of these problems by brainstorming inside the group and finding ingenious solutions. Everything has been done in a good group atmosphere which allowed us to come to the final presentation with a working principle and prototype.
In conclusion, this project was a first step for us to build a general understanding of the different steps from thinking about a new product to build the prototype. For any engineer, this is a fundamental skill to possess and even more for an engineer in our field i.e Microengineering as we are trained in multiple fields and ought to have insight in every aspect of a product. Such a knowledge is crucial for a "to-become" Project Manager.

7 Acknowledgements

We would like to thanks some of the people we had the chance to collaborate with during the span of the project.

- Mr. Stéphane Vittet of *Ressorts du Léman* for generously providing for free the spring needed for our project.
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- Robopoly, for opening their doors to provide us with a makerspace.
- The ENAC workshop, for providing the PMMA sheets and letting us use the workshop machines.
- Bernoulli, for his equations.

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A Initial project idea - G. Baldessarelli

During Giada Baldessarelli's lecture, we were given the task of brainstorming on a topic idea. After 4 rounds of individual brainstorming, we joined our ideas to try to find common topics that interested our whole team and could be feasible as a project.

Individual Ideation:
During the first round, each of us came up with many topic ideas, such as a hand-held fan, RC fish, loudspeakers, phone charger, computer mouse, alarm clock, toaster, mini biogaz refiners, GPS tracker, etc.
During second round, we were challenged to come up with ideas that could work with technologies from 100 years ago. We struggled to find ideas that wouldn't rely on electronics and on technologies we're used to having. Ideas included a kettle, radio, bicycle, camera, air and water filters, etc.
Third round was about coming up with ideas that could have social impact. Some ideas generated before could also fit in this category. We came up with an emergency radio with GPS, water tester and purifier, solar-powered devices, cooking devices, mosquito killers, drones and more.
During last round, we had to find ideas of things that could cost less that 7CHF. We though of a multifunction pen, water bottle, smart mug, battery...

Clustering:
While presenting our individual ideas to the team, we started off by selecting our "best" ideas, or those that might fit as a topic for the project. We wrote down a list of these ideas and talked about our common ideas, then filtered them by feasibility and interest as a topic.
Then, we clustered our remaining ideas into categories of similar technologies (GPS, fan, speakers and more) and selected about 10 ideas. These were analysed by 5 criteria: innovative, actionable, specific, price and social impact.

Idea Selection:
From these ideas, we picked out a few that we judged best for our project, and for each we wrote down: why it is a good idea, market and social impact, microengineering content, complexity, innovation potential and implementation challenges.
These ideas were:

- a smart alarm clock, large market, innovative components can be integrated easily
- an UV detector for detecting risks of sunburn for people with sensitive skin or to optimise solar panels placement
- a loudspeaker has a growing market, has both electronic and mechanical aspects, and innovation is possible via gadget functionalities
- a portable fan can be very profitable in hot countries, it is easy to create, but lacks an innovation prospective

At the end of this stage, it appeared that the UV detector was the best idea. Indeed, a similar product didn't exist yet on the market, but we estimated that a relatively high population that could be interested. In addition to that, its innovation potential and microengineering content were also high, ideal for a class project. The energy side of the device, when used as a solar panel placement tool, also gave it a social impact.

Presentation:
Our task for the first deadline was to present the chosen idea in the form of a PowerPoint document. We tried to create a document that would show our product effectively without needing to present it ourselves. We solved this task by using eye-catching slides and easy to remember points. These slides can be found in annexed file *group8-initial-presentation.pdf*.

B Dimensioning

B.1 Mechanical

Water tank:
To have an efficient and autonomous flower-pot while making the refills user-friendly, we calculated the needs of the average plant that would fit in our flower pot. We finally decided on a 1.5L

water tank so that the user can simply refill the tank from a standard water bottle. A water tank with this capacity easily fulfils the minimum requirements that we defined in the beginning of the project.

$$\begin{aligned}\Delta z_{piston} &= \frac{V_{tank}}{A_{piston}} \\ &= 5.33cm\end{aligned}$$

Water pressure:
The pressure in the water tank is created by the weight of the plant and the force of the compressed spring. A part of the load is carried by the friction force between the seals and the piston.

$$P_{water} = \frac{m_{plant} \cdot g + F_{spring} - F_{friction}}{A_{piston}}$$

The height of the water column above the position of the piston is directly proportional to the water pressure.

$$\begin{aligned}P_{water} &= g\rho_{water}z_{water} \\ z_{water} &= \frac{m_{plant}g + F_{spring} - F_{friction}}{A_{piston}g\rho_{water}}\end{aligned}$$

The spring is initially when the tank is empty already pre-compressed to assure sufficient pressure at all times and not only when it is under maximum compression. The spring we chose has a spring constant of $1250\frac{N}{m}$ and is pre-compressed by $\Delta z_0 = 4cm$. The maximum deformation of the spring is $\Delta z_0 + \Delta z_{piston} = 9.33cm$ which lies in the admissible range for the chosen spring. Finding contact pressure and area of the O-rings on the PVC would require FEM simulations. The friction force was therefore estimated to be about 30N. We assumed a compression of 4% of the O-rings since PTFE is much more rigid than for example nitrile rubber with a contact surface of 0.5mm times the circumference. The results are summarized in the table below. We assumed that the mass of the piston and the filled plant pot is 5kg.

Tank	z_{water}	$m_{equivalent}$
Full	49mm	16.8 kg
Empty	25mm	10.1kg

Table 1: Summary of mechanical calculations

Lever:
The force that the user needs to apply to lift up the piston when the tank needs to be refilled is determined by the ratio of the lever length and the perpendicular distance from the axis to the pivot on the piston guide rod.

$$m_{user} = \frac{d_{\perp}}{l_{lever}} m_{equivalent}[kg] \quad (1)$$

We aim to get a reduction of at least 0.5 but ideally as low as the mechanical design and aesthetics allow. It has to be noted that the Solidworks schematics presented in this report have not yet been optimized in this regard.

Piston guiding:
The piston needs to slide even when the load is not applied in the centre. The conditions for sliding can be found by considering both sets of O-rings separately. Considering that the guide rod does not guide the piston head, the torque induced by the friction force f_1 has to be smaller or equal to the torque induced by the normal force R_1. If the torque from the friction force is too high the piston will further tilt and block completely.

$$\begin{aligned}f_1 d_{piston} &< R_1 b_1 \\ \mu R_1 d_{piston} &< R_1 b_1 \\ \mu &< \frac{b_1}{d_{piston}}\end{aligned}$$

The maximum friciton coefficient μ that would be slightly higher in reality since the guiding rod opposes the tilting of the piston head. The eccentric load causes the friction force in the piston bearer to increase. The sliding condition for the two O-rings in the piston bearer is

$$F > f_2 = \mu R_2$$
$$F\frac{d_{piston} + d_{rod}}{2} = b_2 R_2$$
$$F > \mu F\frac{d_{piston} + d_{rod}}{2b_2}$$
$$\mu < \frac{2b_2}{d_{piston} + d_{rod}}$$

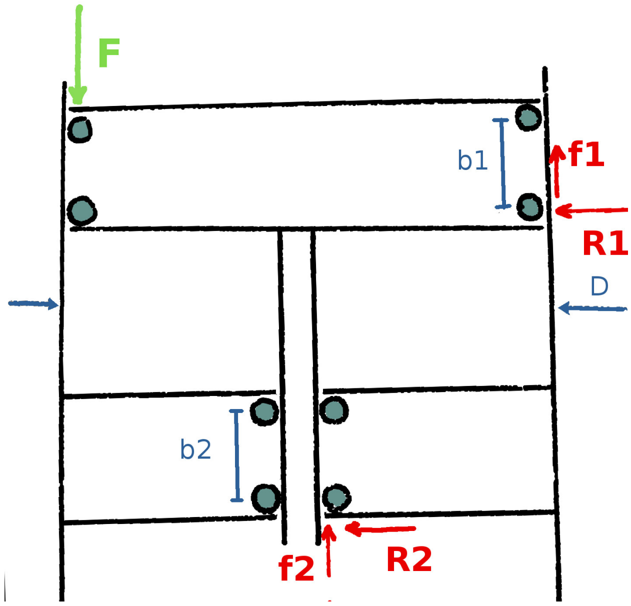

Figure B.1: Simplified schematic of reaction forces on the piston when a eccentric load is applied

With $d_{piston} = 190mm$, the maximum friction coefficient admissible is $\frac{10}{190} = 0.0526$. PTFE has a friction coefficient of $\mu_{PTFE} = 0.05$, so the piston does not require any additional guiding structures to slide.

B.2 Electronic

B.2.1 Battery pack:

We chose the battery pack in accordance to the current draw from the different elements of our circuit. We first estimated the global draw with the values given below.

- the Arduino Uno has a quite high consumption for a micro-controller, with a current draw of 25mA when in use
- the solenoid valve we chose has a listed current draw of 100mA when in use, and 0mA when not used due to the valve functioning principle. We estimated a percentage of open of 5‰, amounting to around 7 minutes every day. This gives us an average draw of 0.5mA
- the LEDs used as user interface for battery and water level have a current draw of 20mA. We considered that the LEDs will be lighted only 20% of the time as they indicate low levels of water and battery
- the soil humidity sensor data-sheet lists the current draw at 5mA maximum
- the magnetic proximity sensor used is a Reed switch, which doesn't draw power directly, but we considered a 5mA draw for its interface

Globally, the calculated current draw of our electronic circuit is 52.5mA. We wanted an autonomy around three days without using the solar panels, in order to be able to hold enough energy for two days without any sun exposition. A simple calculation gives us a needed battery capacity of 3800mAh.

The battery we decided to use has a capacity of 5200mAh, which gives us 4.1 days of battery. It is a Li-Ion battery, which offer a good weight over capacity ratio and a good recharge longevity.

B.2.2 Electronic Circuit

Knowing the properties of the Arduino board and the different electronic sensors/actuators we purchased, a specific circuit had to be designed to overcome some problems. The qualitative circuit can be observed on Figure D.1.
First, a resistor had to be connected in serie to the LEDs to avoid a too high current draw. A standard resistor of 220Ω has been used for this purpose.
To manage the connection between the solar panels and the battery, the "Solar Charger Shield v2.2" product has been used. This way, we did not have to design anything to manage this problem. However, this shield did not have a specific pin to measure the voltage of the battery. As knowing the level of the battery to detect when this latter one is low is a crucial element of such a product, we designed a tension divider bridge to measure the voltage of the battery. One problem of such a circuit is that it continuously consumes power. To limitate this current consumption, big resistors has been taken. Two resistors of 27 kΩ in serie has been mounted resulting in a $0.093mA$ constant current draw. This measure has been verified with a multimeter.
The problems began bigger with the Valve. We purchased a valve requiring a voltage of 12V and a current of at least 100mA to work. Knowing that the output voltage of the Arduino board is 5V and the maximum output current of the digital pins is 40mA, we had to design a circuit to increase the voltage and current to make it work. To accomplish such a challenge, we used a Step-Up component to increase the voltage from 5 to 12V and a transistor to increase the current. We designed the transistor circuit from scratch but the Step-Up was bought already built.
First, one has to know that the Vcc pin of the arduino can furnish up to 200mA and the transistor we used had a gain β of 155. Considering this, the following development has been made to create a working circuit :

$$\begin{aligned} I_c &= 100mA \; and \; \beta = 155 \\ V_{be} &= U_j = 0.6V \\ I_b &= \frac{I_c}{\beta} \Rightarrow I_b = 0.64mA \\ V_b &= V_{cc} - V_{be} = 4.4V \\ R_b &= \frac{V_b}{I_b} = 6875\Omega \end{aligned} \tag{2}$$

Thus, putting a 6875 Ω resistor should theoretically give a 100mA current through the Valve whenever the 4th arduino pin is "High". As we did not consider the inner resistance of the cables and the imperfect characteristics of the different components, a resistor of 5000Ω has been used. It resulted in a current draw of 120mA through the valve. Using this circuit and the Step-Up component, we managed to make the valve work.
For the Soil Moisture sensor, the Magnetic sensor and the Potentiometer, no specific electronic circuits were necessary.

C Technical drawings

The only technical drawing that we included is the piston. Indeed, the different wood parts and the main DN200 tubing were machined differently on the Solidworks and for the prototype. Moreover, their design will most certainly change until final production. Apart from these, our project didn't call for any other parts to do

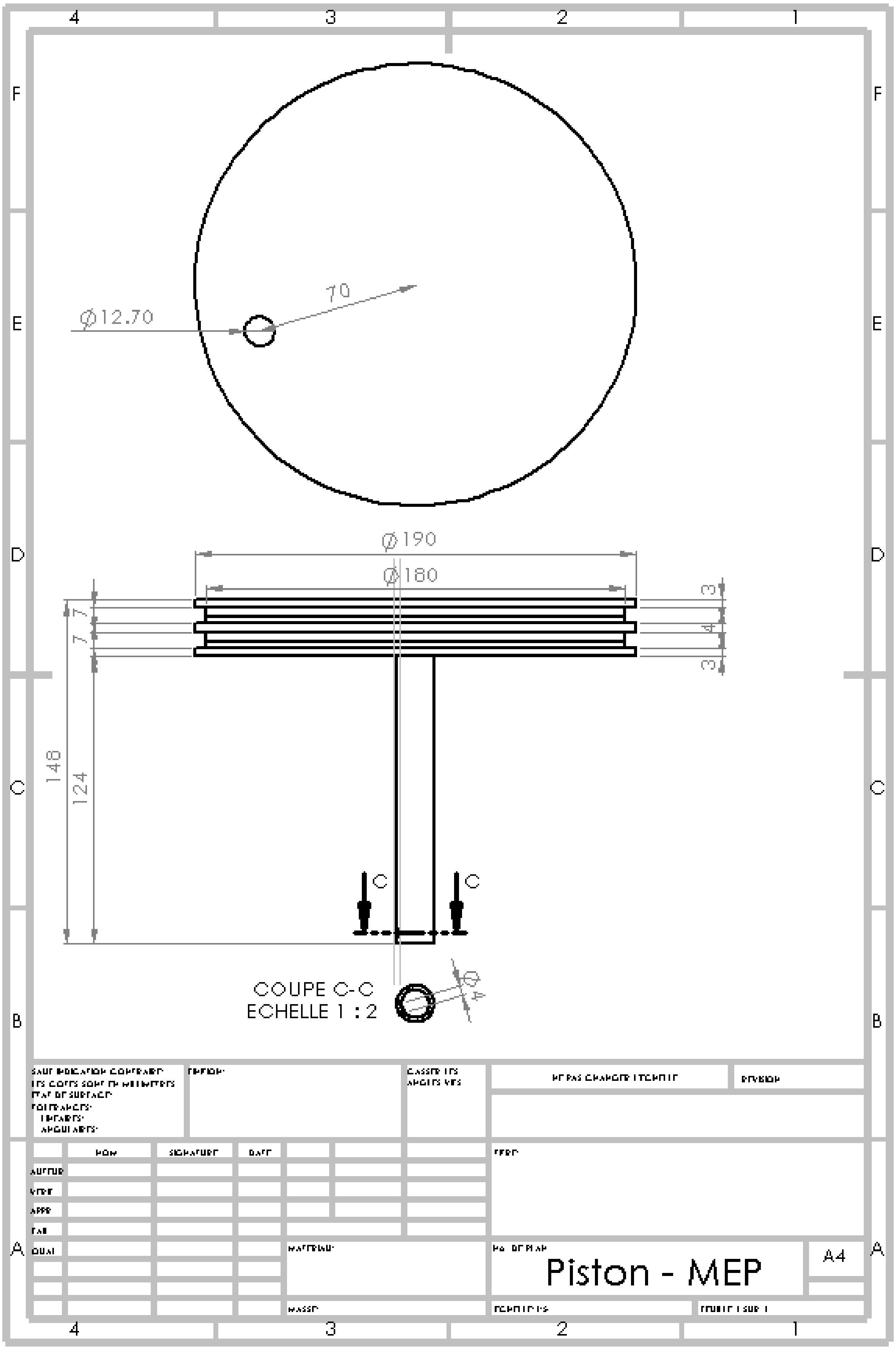

Figure C.1: Sizing and global view of the piston

D Circuit diagram

Below in figure D.1 you can find our simplified circuit. Please note that as the battery is managed through an Arduino shield, we couldn't draw it correctly in our figure. It is displayed with a small asterisk.

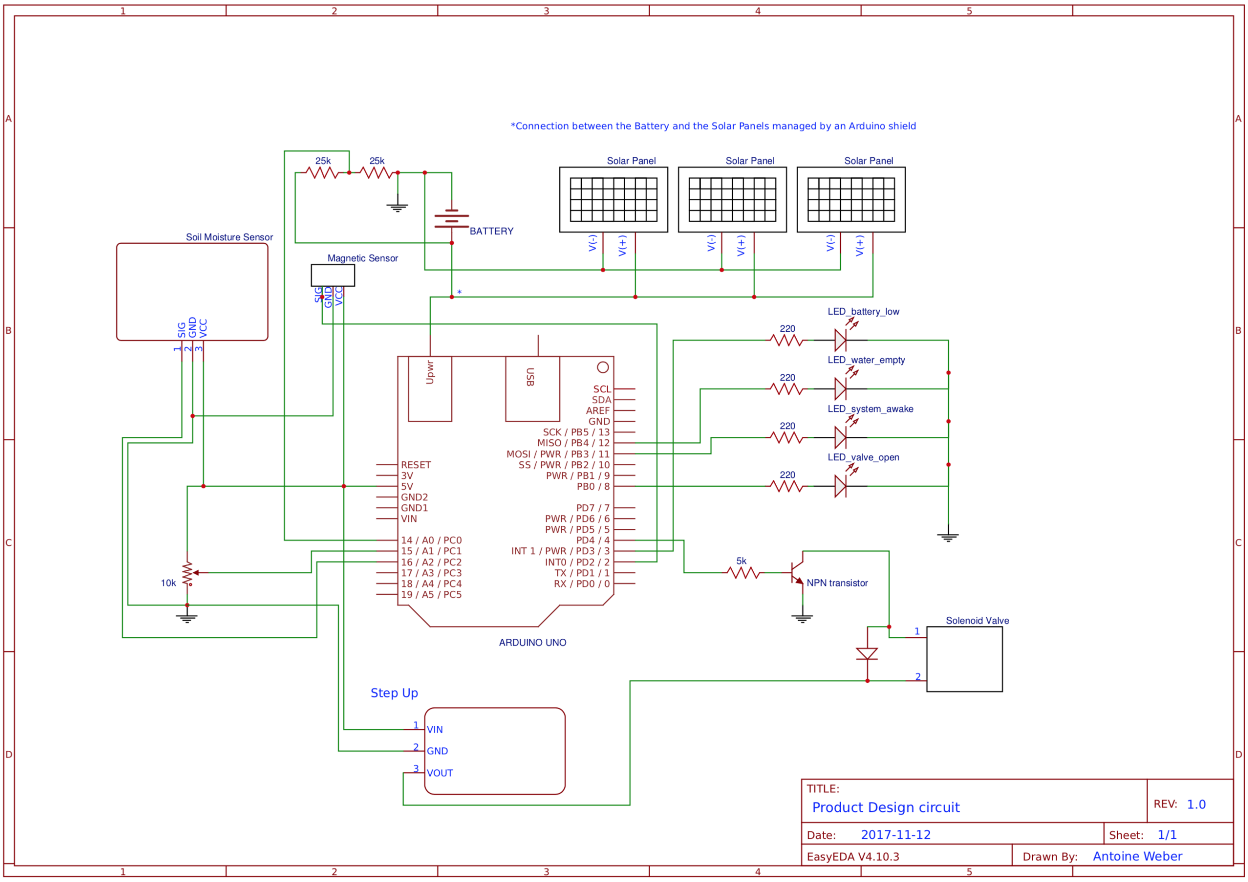

Figure D.1: Electronic circuit

E Arduino code

In listing below you can find the code uploaded on our Arduino. The final production code will should very similar, apart from small calibration modifications.

```
// libraries for hibernating
#include <avr/sleep.h>
#include <avr/wdt.h>
#include <avr/power.h>
#include <avr/interrupt.h>

// constant definition
const int pin_led_awake = 11;
const int pin_led_water_empty = 12;
const int pin_led_valve_open = 8;
const int pin_led_batterylow = 3;
const int pin_sensor_water_level = 2;
const int pin_valve = 4;
const int pin_input_humidity = A2;
const int pin_input_tuning = A1;
const int pin_measure_voltage = A0;

float pente = (260-520)/(100-84); //regression slope
float h = 260 - pente*100;
```

```

int numb_loop_sleep = 2; //will sleep for 8x sec. Here x is set as 2 (16s, for presentation)
int water_level;
float humidity;
float tuning;
float sensor_value_humidity;
float wanted_humidity;
float battery_value;
float tension;
float vcc_true;

float threshold = 3.5;  // battery threshold


// function checking the actual voltage of the battery
void check_tension()
{
    battery_value = analogRead(pin_measure_voltage);
    vcc_true = read_true_vcc();
    tension = (battery_value*vcc_true/1024)*2;

    if (tension < threshold){
      digitalWrite(pin_led_batterylow,HIGH);
    }
    else {
      digitalWrite(pin_led_batterylow,LOW);
    }
}

// function testing if the plant need to be watered
void check_humidity()
{
  sensor_value_humidity = analogRead(pin_input_humidity);
  tuning = analogRead(pin_input_tuning);
  wanted_humidity = map(tuning, 0, 1023, 70, 100);
  humidity = (sensor_value_humidity - h)/pente;

  if (humidity < wanted_humidity){
    digitalWrite(pin_valve, HIGH);
    digitalWrite(pin_led_valve_open, HIGH);
    delay(15000);
    digitalWrite(pin_valve, LOW);
    digitalWrite(pin_led_valve_open, LOW);
  }
}

// function checking the water level
void check_water_level()
{
  water_level = digitalRead(pin_sensor_water_level);
  if (water_level == LOW){
    digitalWrite(pin_led_water_empty, LOW);
  }
  else {
    digitalWrite(pin_led_water_empty, HIGH);
  }
}

// watchdog interrupt
ISR(WDT_vect)
{
    wdt_disable();  // disable watchdog
    check_tension();
}
```

```

void myWatchdogEnable(const byte interval)
{
  MCUSR = 0;
  WDTCSR |= 0b00011000;
  WDTCSR =  0b01000000 | interval;

  wdt_reset();
  set_sleep_mode (SLEEP_MODE_PWR_DOWN);
  sleep_mode();  // sleeping enabled from here. Waits for the interrupts
}

//CODE TAKEN FROM SCOTT ON THE "https://provideyourown.com" WEBSITE
//function checking the real voltage applied on the pins of the Arduino
long read_true_vcc() {
  #if defined(__AVR_ATmega32U4__) || defined(__AVR_ATmega1280__) || defined(__AVR_ATmega2560__)
    ADMUX = _BV(REFS0) | _BV(MUX4) | _BV(MUX3) | _BV(MUX2) | _BV(MUX1);
  #elif defined (__AVR_ATtiny24__) || defined(__AVR_ATtiny44__) || defined(__AVR_ATtiny84__)
    ADMUX = _BV(MUX5) | _BV(MUX0);
  #elif defined (__AVR_ATtiny25__) || defined(__AVR_ATtiny45__) || defined(__AVR_ATtiny85__)
    ADMUX = _BV(MUX3) | _BV(MUX2);
  #else
    ADMUX = _BV(REFS0) | _BV(MUX3) | _BV(MUX2) | _BV(MUX1);
  #endif

  delay(2);
  ADCSRA |= _BV(ADSC);
  while (bit_is_set(ADCSRA,ADSC));

  uint8_t low  = ADCL;
  uint8_t high = ADCH;

  long result = (high<<8) | low;

  result = 1125300L / result;
  result = result/1000;
  return result;
}

// interruption routine
void InterruptRoutine()
{
  check_water_level();
}

void setup() {
  pinMode(pin_led_awake, OUTPUT);
  pinMode(pin_led_water_empty, OUTPUT);
  pinMode(pin_led_valve_open, OUTPUT);
  pinMode(pin_valve, OUTPUT);
  pinMode(pin_led_batterylow,OUTPUT);

  pinMode(pin_measure_voltage,INPUT);
  pinMode(pin_sensor_water_level, INPUT);
  pinMode(pin_input_humidity, INPUT);
  pinMode(pin_input_tuning, INPUT);

  attachInterrupt(digitalPinToInterrupt(pin_sensor_water_level), InterruptRoutine, CHANGE);
}

void loop() {
```

```
  digitalWrite(pin_led_awake, HIGH);
  check_humidity();
  digitalWrite(pin_led_awake,LOW);
  int i;
  for (i=0; i<numb_loop_sleep;i++)
  {
    myWatchdogEnable (0b100001);  // 8 seconds
  }
}
```

Listing 1: Arduino code

F Journal

Throughout the semester, we kept a journal for each of our group meetings. Each entry corresponding to one whole group meeting, as we didn't include the small sub-group meetings. The journal can be found in joined file *group8-schedule.pdf*.

Please note that at the end of the semester, the electrical system was done, there was no more management tasks that required immediate attention so we all focused on the mechanical prototype fabrication. For this reason, and as we decided that all entries wouldn't be very useful later on, we didn't keep track of the day-to-day progress made from the 8th December.

G Manufacturing Systems Modelling exercises - O. Gallay & R. Filliger

Below you can find the exercises made in application of the lectures *Manufacturing Systems Modelling*, presented by guest lecturers Olivier Gallay and Roger Filliger.

G.1 Workflow 1

For the general production dipole consisting of two machines M_1 and M_2 with a buffer B in between the two machines, the stationary mean production rate $\langle U \rangle$ is

$$\langle U_{dipole}(h) \rangle = \frac{U}{1 + I_{dipole}(h)} \tag{3}$$

where h is the size of buffer B and U the production rate of both M_1 and M_2. In the particular case that we are considering, the machines have identical flow characteristics ($r_1 = r_2 = r, p_1 = p_2 = p$, $U_1 = U_2 = U$). Hence, $I_1 = I_2 = I$. The indisposability of the dipole can be expressed as

$$I_{dipole}(h) = I(1 + \frac{1}{1 + \frac{1}{2}F(h)(1+I)}) \tag{4}$$

$$F(h) = \frac{rh}{U} \tag{5}$$

For a dipole where $I_1 \neq I_2$, the indisposability is given by

$$I_{dipole}(h) = I_1(\frac{(\frac{\alpha}{\beta})^2 e^{\Gamma h} - 1}{\frac{\alpha}{\beta} e^{\Gamma h} - 1} \qquad I_2 = \frac{\alpha}{\beta} I_1 \qquad \Gamma = \frac{\alpha - \beta}{U}(\frac{r_1}{1+\alpha} + \frac{p_1}{1+\beta}) \tag{6}$$

These equations can now be used to aggregate the machines and buffers and calculate the overall production rate in both production lines.

Production line a):

Starting with the first two upstream machines M_1 and M_2, Equation 4 is used since the indisposability of both machines is equal. Without a buffer, this results in

$$I_{12} = 2I \tag{7}$$

$$I_{12} = \alpha_{12} I \tag{8}$$

Equation 6 can be used to aggregate the effective machine M_{12} with indisposability I_{12} and M_3 with the buffer B_{23}.

$$\Gamma = \frac{1}{U}(\frac{r}{1+\alpha_{12}} + \frac{p}{1+\beta}) \tag{9}$$

$$= \frac{1}{U}(\frac{r}{3} + \frac{p}{2}) \tag{10}$$

$$I_{123}(h) = I(\frac{\alpha_{12}^2 e^{\Gamma \cdot 3h} - 1}{\alpha_{12} e^{\Gamma \cdot 3h} - 1}) \tag{11}$$

The effective machine M_123 and M_4 constitute a dipole without any buffer space in between ($h = 0$). Equation 6 can be used again with $I_{123} = \alpha_{123} I$ and $\beta = 1$.

$$\Gamma = \frac{1}{U}(\frac{r}{1+\alpha_{123}} + \frac{p}{2}) \tag{12}$$

$$I_{1234} = I(\frac{\alpha_{123}^2 e^{\Gamma \cdot 0} - 1}{\alpha_{123} e^{\Gamma \cdot 0} - 1}) \tag{13}$$

Production line b):
Similar to a), the machines and buffers can subsequently be aggregated using Equations 4 and 6. Starting also upstream, the first dipole consists of the identical machines M_1,M_2 and B_{12}. Since their indisposabilities are equal, Equation 4 is used again.

$$I_{12} = I(1 + \frac{1}{1 + \frac{1}{2}F(h)(1+I)}) \tag{14}$$

$$= I(1 + \frac{1}{1 + \frac{rh(1+I)}{2U}}) \tag{15}$$

$$I_{12} = \alpha_{12} I \tag{16}$$

The two remaining aggregation steps are done by applying the same formula and reasoning as shown in Equation 11.

$$I_{123}(h) = I(\frac{\alpha_{12}^2 e^{\Gamma_{12} \cdot h} - 1}{\alpha_{12} e^{\Gamma \cdot h} - 1}) \tag{17}$$

$$I_{1234}(h) = I(\frac{\alpha_{123}^2 e^{\Gamma_{123} \cdot h} - 1}{\alpha_{123} e^{\Gamma \cdot h} - 1}) \tag{18}$$

$$\tag{19}$$

The overall mean production rate for both production lines is thus

$$\langle U_{1234}(h) \rangle = \frac{U}{1 + I_{1234}(h)} \tag{20}$$

where I_{1234} is the overall indisposability of the respective production line.

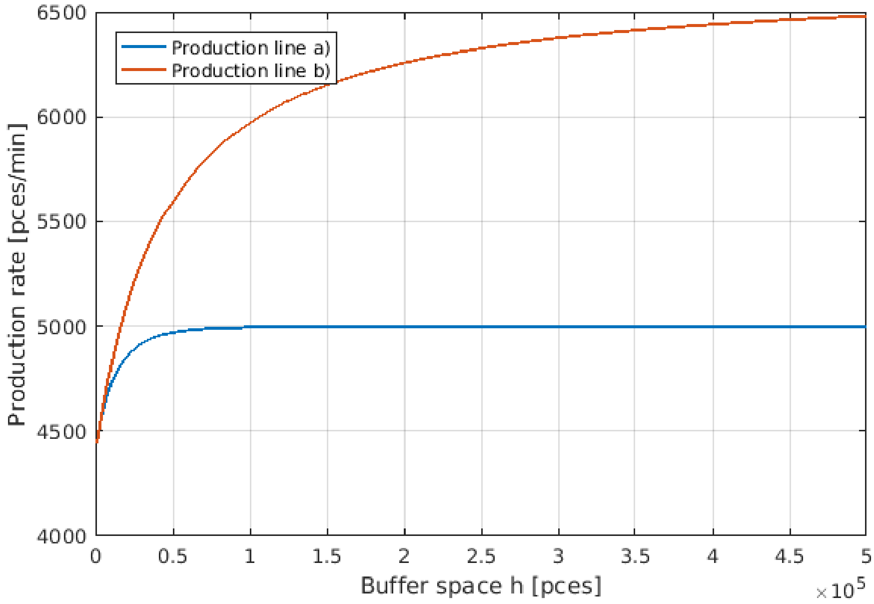

Figure G.1: Production rate for production lines a) and b) as a function of h

Conclusion: From Figure G.1 it can be deduced that by distributing the total available buffer space evenly between the machines, the mean production rate of the whole production line approaches the production rate of a single machine. Concentrating all the available buffer space in one place limits the production rate because the variability in productivity of some of the machines is not buffered.

G.2 Workflow 2

For this exercise, it is complicated to find an analytical solution to the problem. Hence, AnyLogic has been used to simulate the different throughput of the system considering different buffer sizes. Knowing that the total buffer space was 10, the goal was to perform an optimal distribution of the buffer space between the 3 available buffers.
The system is illustrated in Figure G.2.

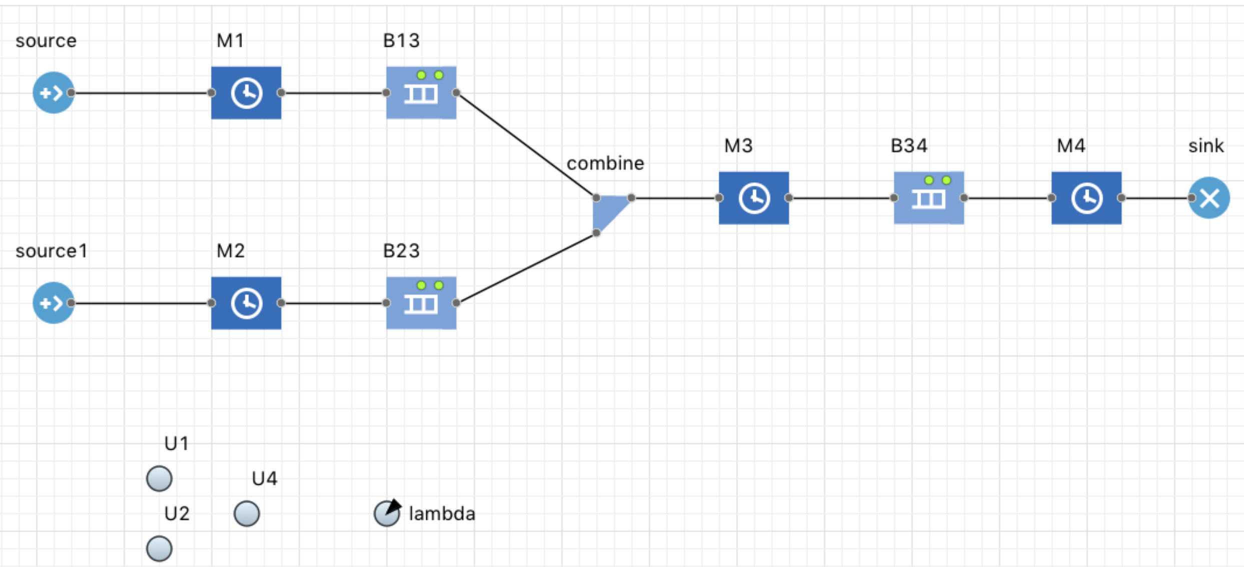

Figure G.2: Assembling System

As said in the specifications, the 4 different machines followed different laws for their pro-

cessing time. The first and the third followed an exponential law of parameter $\frac{1}{4}$ which gave $U1 = U3 = exponential(0.25)$. The second machine followed a binary law between 2 and 10 with probabilities 0.75 and 0.25 respectively. To implement this, a Bernoulli law has been used the following way : $U2 = 2 + 8Bernoulli(0.25)$. Finally the fourth machine followed a simple uniform law, implemented by $U4 = uniform(3, 5)$.
The next step was to perform the simulation. Figure G.3 illustrates the results as an histogram. If one tries to sum all the different tries, the result won't be the total number of different possibilities. Indeed, we rejected from the beginning some repartitions which didn't make any sense to avoid performing useless computation. For example, as the third machine is dependant on both machine 1 and 2, assigning a buffer space of 0 for machine 1 for example, and 8 for machine 2 is intuitively not optimal. Thus such cases have not been tested.
Moreover, all the possibilities containing a buffer space of 0 could not be tested on the AnyLogic software, hence such repartitions have not been tested. However, a buffer space of 0 is equivalent to no buffer at all which would join the cases we judged as useless seeing the assembly outline.

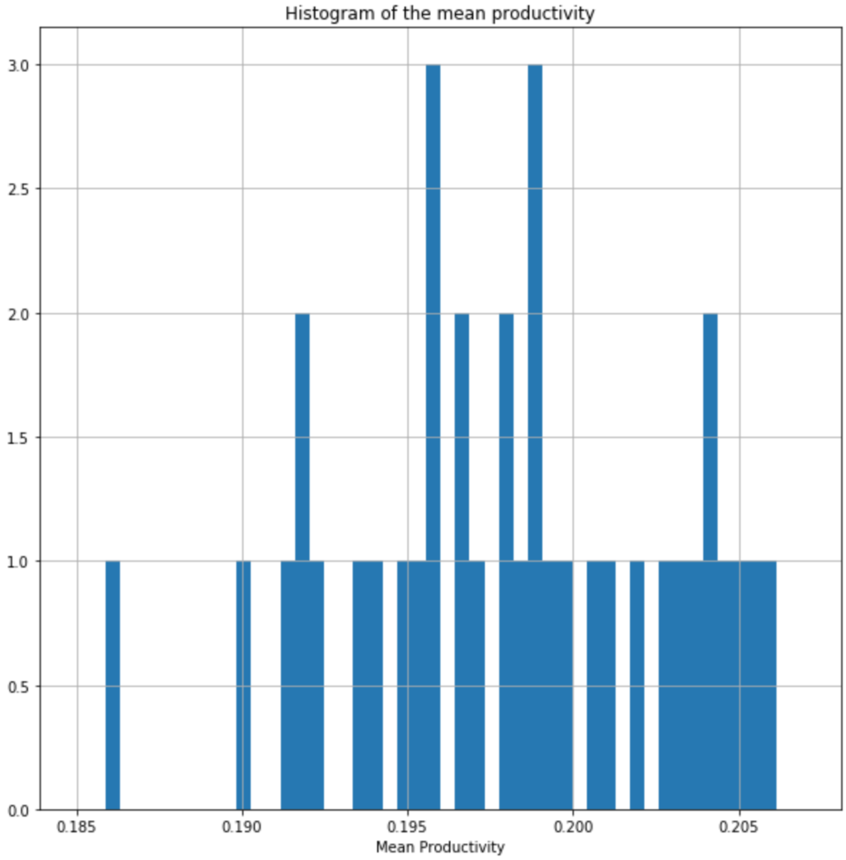

Figure G.3: Results Obtained

The maximum throughput has been observed for the following distribution :

- B13 = 4, B23 = 3, B34 = 3
- Throughput = 0.206 product per time unit.

However, we observed that the repartition $\{B13 = 4, B23 = 4, B34 = 2\}$ was close to this latter one. To assess if there really is a difference between these two repartitions, we performed a bilateral T-Test with a 0 difference hypothesis. If the resulting t-score is greater than the t-critical-score, we can reject our hypothesis and conclude that the repartition $\{B13 = 4, B23 = 3, B34 = 3\}$ is better. If the t-score is smaller than the t-critical-score, the hypothesis is not rejected which means that there is no significant difference between the two samples. The result is illustrated on Figure G.4.

t-Test: Two-Sample Assuming Unequal Variances

	Variable 1	Variable 2
Mean	0.206	0.204853
Variance	1.76E-05	1.75E-05
Observations	15	15
Hypothesized Mean Difference	0	
df	28	
t Stat	0.74881	
P(T<=t) one-tail	0.230108	
t Critical one-tail	1.701131	
P(T<=t) two-tail	0.460217	
t Critical two-tail	2.048407	

Figure G.4: Results of the Student's t-test

The resulting t-score ("t Stat") is inferior to the t-critical-score ("t Critical two-tail") using the 95% quantile, which means that we cannot reject the 0 Mean difference hypothesis. This means that there is no significant difference between the two samples. Hence we can ensure that the two different repartitions gave roughly the same results.
The two variances of both repartitions are also illustrated on Figure G.4.

To conclude: For such a system, the optimal repartition of the buffer space to achieve the highest throughput, considering a total buffer space of 10 units, is either $\{B13 = 4, B23 = 3, B34 = 3\}$ or $\{B13 = 4, B23 = 4, B34 = 2\}$ achieving a throughput of approximately 0.205 product per time unit.

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