MSc Program
Engineering Management

Starting up a semi-automated and modular mushroom production facility

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
Em.O.Univ.Prof. Dipl.-Ing. Dr.techn. Dr.h.c.mult. Kopacek Peter

Martin Gutmann, BSc

00430386

Vienna, 22.03.2023

Affidavit

I, **MARTIN GUTMANN, BSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "STARTING UP A SEMI-AUTOMATED AND MODULAR MUSHROOM PRODUCTION FACILITY", 74 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

Vienna, 22.03.2023

Signature

Starting up a semi-automated and modular mushroom production facility

Reactivating a small farm with compact indoor cultivation of high value mushrooms through standardisation, automation and IoT capabilities

Abstract

Agricultural innovation is the process whereby individuals or organisations bring new or existing products, processes, or ways of organisation into use for the first time in a specific context in order to increase effectiveness, competitiveness, resilience to shocks or environmental sustainability and thereby contribute to food security and nutrition, economic development or sustainable natural resource management. (FAO, 2019)

Over the last decades with the internet revolution and the constant development of tools (hardware and software) to make long distance communication faster and easier we were able to witness a slow increase in attractivity of the countryside2 for, especially but not exclusively, young digital natives and their families who can work from anywhere if there is an internet connection available. The climax so far and certainly a catalyst was/is the Covid pandemic where this option of living and working remotely became an interesting alternative for many people and companies who were forced to adapt to the situation and incorporate these „new" technologies, changing completely our relation to work and digital tools.

Agriculture is already undergoing huge technological transformations and new technologies are being used and implemented on all levels, from management tools to autonomous vehicles, to the use of drones and sensor technology, evermore connected by the lot. For beginners, initial investments in land and equipment can be a huge hurdle to get started, let alone the lack of knowledge. With the internet being a place where critical information can be exchanged on a massive scale, there is a chance to provide the knowledge and building plans for increased food security by offering an easy to set up, fully controlled and to some degree automated and highly productive cultivation system.

This thesis, with the above context, wants to explore the economic viability of a compact but largely automated and modular indoor farming system for high value crops, specifically gourmet mushrooms and/or microgreens and the potential market for a modular and digital farming system that can be monitored remotely. The modularity of this model should allow for scalability which will also be investigated.

The process will start with outlining the production process with all the relevant inputs and outputs to identify the needed hardware and software, machinery, conditions to grow a certain variety of mushrooms (there might be seasonal differences). For the scalability it is essential to identify modules which would automate certain steps in the process to be able to scale the production without increasing staff (i.e., mixing and bagging the substrate). Apart from the

material flow also the flow of data within the production process, from buying raw materials to accounting will be transparently displayed with the aim of identifying unnecessary interfaces for human interaction.

The research will cover appropriate literature and an extensive market analysis, there are already systems available on the market but rather at a large scale and mainly in an urban or industrial context. If possible, also visiting farms and interviewing farmers might be an interesting addition to this paper.

I have already tapped into mushroom cultivation, read a lot about it, successfully cultivated edible mushrooms indoors with different methods and want to refine the process by prototyping the system and compiling the necessary theoretical knowledge and data. Key for the prototyping will be the use of open-source tools such as Arduino and/or raspberry pi in vision of a possible replicability of this model.

The case study will be the farmlab.at, an existing farm in the southeast of Styria and a node in the global Fablab network which offers space and is already equipped with a lab infrastructure with tools such as 3D printing, CNC milling, laser cutting and electronics for prototyping. This function is rooted in the Fablab idea of open innovation and access to digital fabrication, in this case in a rural context. Starting from the given situation, a study of the local market, which is embedded in a strong culinary tradition, for mushrooms in B2B and B2C, necessary investments and turnover and a general investigation of the economic viability of such a business will be conducted.

Index

1. Introduction

Today we are facing a planet in crisis. On various fronts we must battle threats such as climate change, pollution, pandemics, increasing bilateral instability, deforestation, flooding, desertification, natural disasters, and plenty more. This thesis is not meant to deal with all the above issues but is singling out one topic which is of foremost importance and in close relation to all the crises mentioned above: agriculture and nutrition. The consumption of animal-based proteins (meat) is highly disputed, mainly because of its contribution to the emission of climate changing gases of around 80% of the total emissions produced by Agriculture in Europe (Peyraud, J., MacLeod, M., 2020).

Cultural definitions of "traditional food" but also, according to an OECD outlook for 2021 to 2030, a growing number of people worldwide who has left extreme poverty behind and is able to afford meat on a more regular basis is adding to the problem on a global scale (OECD, 2021). This can be one of many reasons for a growing number of people who decide to change their diet and become vegetarian or vegan – this means there is a growing demand of non-meat proteins in the market. Global players such as "Beyond Meat" are offering products like patties based on legume proteins already and are registered on the stock exchange market.

Nevertheless, whether this is a good or bad development is a moral discussion that must be addressed in a different context but plays a personal role in the choice of this topic.

Another factor within this topic is that over the last decades with the internet revolution and the constant development of tools, hardware, and software, to make long distance communication faster and easier, we were able to witness a slow increase in attractivity of the countryside for, especially but not exclusively, young digital natives and their families who can work from anywhere if there is a fast and stable internet connection available. The climax so far and certainly a catalyst was the Covid pandemic where the option of living and working remotely became an interesting alternative for people and companies, who were forced to adapt to the situation and incorporate these, "new" technologies, changing completely our relation to work and digital tools.

This move to the countryside leads also to new ventures in Agriculture. Agriculture is already undergoing huge technological transformations and recent technologies are being used and implemented on all levels, from management tools to autonomous vehicles, to the use of drones and sensor technology, evermore connected by the "Internet of Things" (Iot). For beginners, initial investments in land and equipment can be a huge hurdle though to get started, let alone the lack of knowledge in growing produce and managing the seasonal tasks which are inherent in the traditional form of agriculture. With the internet being a place where critical information can be exchanged on a massive scale, there is now a chance to supply the knowledge and building plans for increased food security by offering an easy to set up, fully controlled and to some degree automated and highly productive cultivation system. Especially indoor farming can be an interesting possibility for people who don't have access to land.

A more localized food production is essential for our common future, by building resilience, and the change in the behaviour of consumers towards a plant-based diet is a great business opportunity. We witnessed a global disruption in all supply chains because of covid and furthermore a disruption and price hike in the distribution of grain because of the Russian invasion of Ukraine. Many people around the globe became aware of the potential fragility of our food system. The effect was not so severe for rich countries such as Austria, nevertheless many countries have had severe impacts including looming starvation. With small farms, the food system can become more diverse and resilient on one hand but it also strategically important to support small initiatives to have a softer relationship with the environment.

Producing proteins in the form of mushrooms locally in an efficient and compact system has various advantage:

- local organic waste materials such as sawdust can be used,
- it can be done in a controlled environment,
- there is no need of long-distance transport, given that the local market is interested in the product,
- it can be done all year around,
- it can be easily started for the use in the family itself and
- it can be scaled up to become a business from a low-tech operation to full automation.

The market analysis will focus on Austria, for one because meat plays a distinguished role in the Austrian cuisine and the consumption has been growing steadily over the last decades. Also, Austria imports most mushrooms consumed from other countries, be it seasonal wild Chanterelles from Latvia or Serbia or Shiitake from Eastern European farms, based on observations of the labels of origin in supermarkets. The statistics is showing a much more interesting picture. In the period of 2019/2020 Austria exports all the local production of 2.300t while it imports almost nine times the amount for consumption (Statistik Austria, 2020).

Versorgungsbilanz für Gemüse 2019/20

Gemüseart	Erzeugung	Einfuhr	Ausfuhr	Inlands-verwen-dung [1])	Verluste	Nahrungs-verbrauch	Pro-Kopf in kg	SVG in %
	in Tonnen							
Champignons und Pilze	2.300	19.730	2.267	19.762	592	19.170	2,2	12
Erbsen	9.792	7.453	4.796	12.449	443	12.006	1,3	79
Gurken (Cornichons)	10.157	6.238	3.251	13.144	508	12.637	1,4	77
Gurken (Salat)	35.107	23.998	7.227	51.878	3.024	48.855	5,5	68
Karfiol	3.300	5.568	882	7.986	674	7.311	0,8	41
Karotten, Möhren	108.180	13.714	16.409	105.485	27.335	78.151	8,8	103
Kohl, Chinakohl u. ä.	23.733	16.119	1.953	37.899	5.813	32.086	3,6	63
Kraut weiß u. rot	36.275	15.836	3.484	48.626	5.145	43.482	4,9	75
Melonen	1.392	50.733	5.352	46.772	7.819	38.954	4,4	3
Paprika, Pfefferoni	14.981	40.618	7.655	47.944	4.811	43.133	4,8	31
Paradeiser	58.332	322.080	71.002	309.410	22.477	286.933	32,2	19
Rote Rüben	7.689	4.426	753	11.363	1.759	9.604	1,1	68
Salat (Häuptel-, Eissalat)	37.442	5.994	511	42.924	8.088	34.837	3,9	87
Salat (Sonstige)	9.319	31.507	3.819	37.007	4.549	32.458	3,6	25
Sellerie	11.825	3.154	236	14.743	3.051	11.692	1,3	80
Spargel	3.320	3.030	295	6.054	649	5.405	0,6	55
Spinat	14.505	4.471	4.805	14.171	725	13.446	1,5	102
Zwiebeln	141.645	38.148	59.358	120.435	39.226	81.209	9,1	118
Zucchini	7.139	15.615	1.348	21.406	2.775	18.631	2,1	33
Übrige Gemüsearten	84.325	196.874	76.801	204.398	30.069	174.328	19,6	41
Marktproduktion	620.758	825.306	272.206	1.173.858	169.531	1.004.327	112,9	53
Haus- und Kleingärten [2])	68.973	-	-	68.973	24.141	44.832	5,0	-
Gemüse gesamt	689.731	825.306	272.206	1.242.831	193.671	1.049.159	117,9	55

Q: STATISTIK AUSTRIA, Versorgungsbilanzen. - SVG = Selbstversorgungsgrad. - 1) Einschließlich Verarbeitungserzeugnisse aus Gemüse in Frischgewicht. - 2) Erzeugung geschätzt, da Anbauflächen nicht erhoben werden.

Figure 1: Import and export of mushrooms in Austria in 2020; Statistik Austria

The goal of this thesis is to develop a system that allows people to easily grow mushrooms on a scale and allows them to do a business with the cultivation and sale of mushrooms and mushroom products. The approach is twofold, on the one hand developing a schematic which makes the entire process easy to understand and replicate, even manually. The second approach is about finding possibilities where and how to automize the steps in the production line. One part which will be more theoretical, will be the mechanics (mixers, bag filler, tumbler, …). The other part will be the climate control based on Arduino and/or raspberry pi and necessary components such as light-, temperature-, CO_2- and other sensors. The data should be accessible online and the system should also be manageable remotely.

This innovative combination of open-source electronics and indoor farming of mushrooms, both topics are enjoying increasing popularity, is at the heart of this thesis and hopefully inspires people to make their own version of it, providing mushrooms for themselves and their community.

2. Background information

2.1. Mushrooms

Since Carl Linnaeus produced a structured approach to describe the biology that surrounds us, six so-called kingdoms were defined by researchers and scholars over the course of the following centuries, roughly because the number keeps changing depending on how life is classified. The six most used kingdoms for classifying life are: Animalia, Plantae, Eubacteria, Archaebacteria, Protista and Fungi. Fungi as a kingdom were defined after they had been firstly identified as plants and later as animals, never really fitting the definition hence their own category. Like animals the metabolism of fungi is not based on photosynthesis, but they are breathing in oxygen and emitting carbon dioxide. Also, like plants they are absorbing nutrients through a root system, called mycelium, but they are actively digesting matter of a wide range, producing and exuding enzymes to break up the structure of organic matter and making the nutrients available for ingestion. Often, depending on the variety of fungi, they even live in symbiosis with trees exchanging nutrients. Latest research showed that through the mycelium, trees can even support each other by sending nutrients and information about potential threats to other trees through an underground network of roots and mycelium called the mycorrhizal network or, in popular science the “wood wide web” (Porombka, 2014).

Mycelium is the actual organism, while the fungi that we search for in autumn or grow in farms are called fruiting bodies. These fruiting bodies are being produced as an extension of the mycelium for two main reasons:

1. When the mycelial network underground reaches its boundaries, which can be the mycelium of another genetically not identical fungi, a rock formation, or other limitations such as a grow bag or bucket, its only way of reproduction and change of location is through spores. The spores are being produced in the fruiting bodies and spread around the environment through wind, animals, insects, or other natural means.
2. Since mycelium itself thrives in a CO_2-rich environment with CO_2 being a by-product of its metabolism, fruiting bodies allow it to reach a layer in the atmosphere where the oxygen content is higher than the CO_2 content. This oxygen rich environment is needed for the sporulation.

This accounts only for some of the mushrooms we can find on this planet, there are thousands of varieties out there with a multitude of strategies to reproduce.

To frame this paper, the focus will be on saprotrophic varieties, mushrooms which are specialised in breaking down organic matter like straw or sawdust. These varieties are for example the strains of oyster mushrooms (*Pleurotus spp.*) or the Shiitake (*Lentinula spp.*). In contrast, Champignons (*Agaricus spp.*) are not interesting for this paper since they grow on already composted matter, such as manure, and are also grown on industrial scale all over the world.

What is important for this paper is the fact that the exchange of gases, the structure of the growing substrate and the control of the environment can be perfectly approached from an engineering perspective and reproduced in a controlled environment to mimic the natural conditions a certain variety of fungi would grow in, to produce fruiting bodies for culinary or medicinal uses.

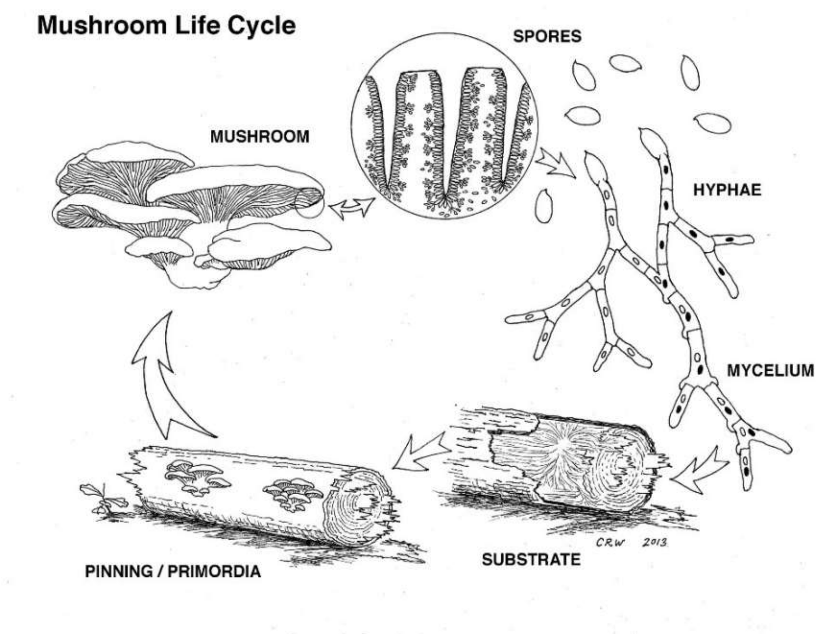

Figure 2: Life cycle of a saprotrophic mushroom; Cornell University; smallfarms.cornell.edu/

2.2. Growing saprotrophic mushrooms

As mentioned before, saprotrophic mushrooms are living off fresh organic matter. This can be leaves, sawdust, straw, grain husks and pretty much anything that is made of cellulose and lignin. It is important to mention that each strain of mushroom has its favoured food, when it comes to cultivation it is important to provide the right base for the mushroom s to grow on. Over the last millennia, humans all over the world developed different methods for cultivation. Eventually it is about creating a specific environment which allows a specific mushroom to thrive.

This paper is not meant to cover the whole spectrum, here are some methods which seem to be widely used:

2.2.1. Growing on logs

Mushrooms usually get the chance to inoculate (populate) fresh wood if a tree falls to the ground and spores or mycelium get in contact with it. Especially traditional growers but also contemporary businesses are using this to grow mushrooms in a controlled way. Also here are various techniques, a very common one is:

- Trees are cut into pieces of a length which depends on how the following process is organised.
- With a drill, around ten-millimetre holes are drilled into the logs all around. The more holes there are and the closer together they are the faster the mycelium will colonize the log.
- Each hole is filled with mycelium. It can be growing on a substrate like grain and being injected with a pipette like tool, or for example on wooden dowels which can be hammered into the holes.
- The logs are covered to keep them moist. Small growers use plastic bags, commercial ones have greenhouses. Also keeping the logs stacked in the forest can be an option.
- After around one year (depending on the strain and amount of inoculation) the mycelium has taken over the log
- When the climatic conditions are right, mushrooms will form.
- These logs can be productive up to some years.

2.2.2. Growing in containers

A faster process is to fill the growing medium, which is correctly called substrate, into a container and inoculate the substrate. A wide range of containers can be used to doing this. It depends a bit on which kind of mushroom wants to be grown in what shape and the setup of the production line in general. Roughly containers can be categorized into reusable and single use. Important is that the containers allow the substrate and the mycelium to breath. The process is the same in its core:

- Mix the substrate, depending on the strain or to give the mushrooms extra energy to grow faster, the mix can be made from various materials. As mentioned above, most used substrates are based on sawdust or shredded straw.

- Fill the substrate into containers.
- Container and substrate need to be sanitized. Pasteurizing or sterilizing are very common methods, each with its advantages and disadvantages. For this the substrate and the container are being heated up to a certain temperature for a defined amount of time
- After the cool down, the containers are being inoculated with mycelium under very clean conditions to avoid contamination of the substrate.
- The containers are kept in a dark space for the so-called spawn run, the period where the mycelium is completely taking over the substrate.
- When the first mushrooms are forming, the primordia, or pinning, they need fresh air and light to grow properly.
- Through openings in the containers the mushrooms can grow out until they are being harvested

2.2.3. Cultivating mushroom gardens

Another method can be to have an outdoor area, mostly in a shaded area. Also here, several different techniques have been developed by humans throughout time. Be it for the cultivation of truffles, which are symbiotic mushrooms living together with the roots of certain trees, or saprotrophic mushrooms. For the latter, this can be one method:

- Inoculate logs like described in chapter 2.2.1.
- Dig a hole as deep as the diameter of the logs and make sure the soil can drain water.
- Put the logs into the hole and cover them with soaked wood chips, also between the logs.
- Cover everything with a thick layer of wet cardboard
- Cover with soil.

2.3. Market

Mushrooms and mushroom products were and are used in a vast amount and in various forms all over the planet and in every culture throughout history. Be it for food, as medicine or for ritualistic and recreational use. Yet, recently there has been quite an interesting development in terms of using mycelium as sustainable material for different industrial uses for example.

2.3.1. Gastronomy

The obvious market to go to with high quality mushrooms is gastronomy. Vegetarianism or veganism is getting increasingly popular in Austria, in 2017 around 5,7% of the population declared to be vegetarian, in 2021 the number increased to 11%, with participants stating "health reasons" for the change in their diet but also environmental protection (Statista, 2022). Mushrooms provide a high content of proteins and can therefore be a good alternative to meat. Meat on the other hand is coming under heavy criticism because of the disastrous impact on the environment on various levels. The water demand for a kg of beef is extraordinarily high, depending on the mode of meat production this can have significant impact on the local population. Soybeans are shipped from Latin- or South America to Europe to provide the livestock with proteins. Industrial scale meat production also increases the risk of epidemic spread of diseases for which the solution is to give the animals sometimes substantial amounts of antibiotics. In resume, for the conscious consumer the ethical and potential health implications are hard to accept.

Austria, which has the highest per capita consumption of meat in the European Union, is also going interesting ways when it comes to traditional food. Neuburger, a company from Upper Austria, is a producer of meat-based products such as "Leberkäse" and several types of sausages invested heavily into a new product line to serve the growing market of meat alternatives. The base for their products is mushrooms, rice, and eggs. In 2016 Neuburger invested five million Euros in a new mushroom production facility with the goal of a total investment of forty-two million Euros until 2026 (OÖN, 2016). In the meantime, the production is temporarily on hold due to the cluster of crises the world is facing. Neuburger, according to its own website, would not be able to provide the high-quality standards at the same price because of the steep rise in energy costs.

2.3.2. Supplements

HOST DEFENSE® Mushrooms™ — MUSHROOM BENEFITS AT A GLANCE	AGARIKON	CHAGA	CORDYCEPS	LION'S MANE	MAITAKE	REISHI	TURKEY TAIL
ANTIOXIDANT & DNA SUPPORT*		✓	✓	✓		✓	
BREATHING*		✓	✓			✓	
DIGESTION & MICROBIOME*		✓		✓		✓	✓
ENERGY & STAMINA*		✓	✓			✓	
GLYCEMIC BALANCE*		✓	✓	✓	✓	✓	
HEART SUPPORT*			✓			✓	
IMMUNE RESPONSE*	✓	✓	✓	✓	✓	✓	✓
LIVER & METABOLIC DETOX*		✓	✓			✓	✓
MEMORY, CLARITY & COGNITION*				✓		✓	
MOOD, STRESS & SLEEP SUPPORT*				✓		✓	
NERVE SUPPORT*			✓	✓		✓	
PERFORMANCE & ATHLETIC RECOVERY*		✓	✓			✓	

* THESE STATEMENTS HAVE NOT BEEN EVALUATED BY THE FOOD & DRUG ADMINISTRATION. THIS PRODUCT IS NOT INTENDED TO DIAGNOSE, TREAT, CURE OR PREVENT ANY DISEASE. 2CPROMO33 V4 • 8/22

Figure 3: Potential health benefits of different mushrooms; www.fungi.com; Paul Stamets

Mushrooms can also be interesting as food supplements. Distinct types have beneficial properties when it comes to the health of human beings (Stamets, 2000). Mostly sold as tinctures or powders, Reishi (*Ganoderma lucidum*), Lions Mane (*Hericium erinaceus)* or Chaga *(Inonotus obliquus)* are being used to enhance wellbeing or cognitive abilities. Research on these topics is ongoing and will not be covered here in this paper. What is of interest though is the process of powdering excess harvests of culinary mushrooms and selling them for use in winter for flavouring dishes.

2.3.3. Materials

Another potential application for mushrooms is slowly gaining traction in the construction industry, industrial design, fashion, and packaging industry. Researchers at the Fraunhofer IAP are looking deeply into the potential use of mycelium as a bio polymer for making a fungi-based leather which is durable and aesthetically close to its animal counterpart. Another field of study is the use of mycelium to create a composite for mouldable packaging materials (Fraunhofer, 2022). Multiple institutes, universities and private companies are developing systems, materials, and applications of mycelium composites to meet the demands of increasingly bio-conscious policy makers and consumers.

Figure 4: Acoustic panels made of mycelium, Mogu.bio

2.3.4. Medicine

Finally, also the potential future of psychedelic mushrooms in medical treatments is worth mentioning. Researchers in Switzerland and the USA have resumed to study the psychological and physiological effects on humans in treatments. This would be a very remote option for creating a niche market for mushroom based psychopharmaceutic drugs which would be probably covered by the pharmaceutical industry itself though.

Potential applications for fungi-based products are vast and it is an industry in its infancy. It is a good moment to tap into this future market now by learning the basics of mushroom cultivation and mycology.

2.4. Arduino

In recent years, the use of electronic tools has spread through society on a vast scale by becoming ever more accessible through the maker movement. The maker movement, people from all over the world who are interested in making their own devices, realising their own projects, or just simply experimenting with modern technologies instead of buying everything off the shelve, has grown rapidly. One invention that can be seen as a gamechanger when it comes to making electronics easily accessible is the Arduino platform. Developed by a group of people around Massimo Banzi, an Entrepreneur, Interaction Designer, Educator and Open-Source Hardware advocate from Italy, this system of programmable hardware brought input and output devices closer to the public because of the simple coding structure and well documented library of example codes on the one hand and its modularity on the other hand. Schematics and all relevant data are released under open-source terms, which means there are no secrets about how it is structured and encourages people to go even deeper into electronics. Since the first batch Arduino Uno has been made available on the global markets around the beginning of the 2000s, more than a hundred other products have been added to the environment, other boards, sensors, shields and recently also a “Pro” version which is more oriented to industrial use. Through the “dashboard,” devices can be controlled remotely, and data can be checked on the go.

2.5. Summary

Mushrooms are complex organisms and occur in various strains with a multitude of potential use cases everywhere in nature. They are highly specialised species which grow in every climate zone and nearly every ecosystem. Different strains are also specialised in thriving on different kinds of nutrition, the most common cultivated mushroom for example, the Champignon, needs pre-digested substrate such as manure or compost whereas saprotrophic strains grow only on fresh biomass like sawdust or agricultural by products like grain husks.

All mushrooms have in common that the actual organism is a network called mycelium which exudes enzymes to break up organic matter and digest it to gain nutrients. The mushrooms we see on the surface and collect are the fruiting bodies which have the main function of producing spores for being able to inoculate other food sources. The mycelium and the fruiting bodies need a completely different mix of gasses to be able to grow properly.

Over the last millennia different human cultures have developed various ways for cultivating mushrooms, be it indoors or outdoors, with the goal of getting controlled access to the multitude of properties and applications of either the mycelium or the fruiting bodies. These applications can be nutrition, which is the most common. Also, for medical reasons mushrooms play a great role for humanity, thinking for example of penicillin. Another application for fruiting bodies is the supposed beneficial properties for the enhancement of human performance, by strengthening cognitive capabilities for example. Last in this list but not least is the use as material for design objects and construction. Research, for example at the Fraunhofer Institute, is aiming to make a kind of leather out of mushrooms. Also, businesses are forming, one example being the company Mogu.bio from Italy which makes acoustic panels out of substrate and mycelium.

The growing conditions for mushrooms can be recreated using classical engineering. The combination with digital platforms and microcontrollers such as Arduino or RaspberryPi, this option is becoming accessible also for non-professionals. Such a system, developed in an open-source way, would give access to mushroom cultivation to a larger group of people who don't need to be specialists, potentially contributing to a diversification and increased resilience of the food production system in general.

3. Methodology

I have already gained some hands-on experience with mushroom cultivation of edible mushrooms indoors and outdoors with different methods and want to refine the process by prototyping a system and compiling the necessary theoretical knowledge and data. Key for the prototyping will be the use of open-source tools such as Arduino and/or raspberry pi in vision of a replicability of this model. This is rooted in the experience I gained in prototyping while attending the Fab Academy program back in 2015 in Barcelona.

The process will start with outlining the production process with all the relevant inputs and outputs to name the needed hardware and software, machinery, conditions to grow a certain variety of mushrooms (there might be seasonal differences). For the scalability it is essential to find modules which would automate certain steps in the process to be able to scale the production without increasing staff (i.e., mixing and bagging the substrate). Apart from the material flow, also the flow of data within the production process, from buying raw materials to accounting will be transparently displayed with the aim of showing unnecessary interfaces for human interaction.

The prototyping, which is important for testing assumptions, and also the boundary condition for the business case will be done at the farmlab.at, a small farm in the southeast of Styria and a node in the global Fablab network which offers space and is already equipped with a lab infrastructure with tools such as 3D printing, CNC milling, laser cutting and electronics for prototyping. This function is rooted in the Fablab idea of open innovation and access to digital fabrication, in this case in a rural context. Starting from the given situation, a study of the local market, which is embedded in a strong culinary tradition, for mushrooms in B2B and B2C, necessary investments and turnover and a general investigation of the economic viability of such a business will be conducted.

3.1. Literature research

An outstanding source for information on cultivating mushrooms is Paul Stamets, a researcher from the United States who dedicated his life to not only research but also outreach, to make his knowledge available in an easy-to-understand manner for everyone who is interested in mushroom cultivation. Another resource in terms of literature on mushrooms is Tradd Cotter with his book on farming mushrooms where he is also describing in detail his experiments and fieldwork about using mushrooms for the remediation of contaminated soil. Merlin Sheldrake as a biologist who wrote his Ph.D. about fungal networks has written an outstanding book about fungi and is a great source of inspiration and understanding the vastness of the mycological world.

For the electronics and prototyping part, I compiled a comprehensive list of books which are listed in the bibliography at the end of this paper.

3.2. Open source and open innovation

"The open ethos isn't limited to software. A number of related movements have sprung up in the past few decades, each dedicated to sharing, transparency, and collaboration" (Brasseur 2018; 4)

For this paper most of the theoretical work will be prototyped for testing, the goal is to build upon this theory and create a functional prototype at the farmlab.at. The electronics around Arduino, code libraries and documentation of the hardware, are all offered online. Even though the code for this project will be specifically written for it, the open-source libraries allow for a faster development of a prototype.

Being part of the Fablab network, an international community of makers from all possible kinds of backgrounds, working loosely together and sharing immense amounts of knowledge, will help with the prototyping. Eventually one production unit will be set up with all the technology installed to allow for remote monitoring and controlling the growing conditions of mushrooms. The growing being only a part of the process calls also for open innovation in other aspects of the overall process. This can be logistics, material handling or any other aspect within the cultivation sequence. The results will be made available to make a discussion and collective improvements possible.

3.3. Case studies and visits

The internet is offering a huge amount of content related to mushroom farming, especially on YouTube (list of relevant channels in appendix B) countless growers are sharing their approach to cultivating fungi, giving insight to their experience and knowledge openly. For getting a better understanding, visiting a running farm is essential. At various occasions I had the chance to visit professional farms. One, "Bolets ben fet" in the north of Barcelona, Spain, offered to give a tour through all the process and after the visit a presentation of the company history. This farm has been running successfully for the last twenty years. Also in Barcelona, I was invited to visit the studio/laboratory of the “BioBabes Collective” who is researching various applications of micro-organisms in design and industry, among it using mycelium for creating design objects like surfboards. Also, the “Pilzhof Gross” which is a start-up in the vicinity of the farmlab.at, was welcoming and showed the operations and especially the conversion of the different spaces.

3.4. Business simulation

The business part aims at calculating the potential capacity for a full-scale cultivation of gourmet mushrooms, the needed investment, ROI and all relevant KPI’s as well as the potential yield of such an operation. To give it a frame, real conditions in terms of space will be used, therefor plans and a scenario of material flow from raw materials to finished product to waste will be incorporated into this work.

3.5. Prototyping

Prototyping is essential for testing the theory. Another way would be simulation but, in this context, there should be a real product at the end – edible mushrooms. Being involved in the maker movement allows for tapping into a great pool of information on how to use certain machines or workflows to get from a theory or an idea to a working prototype and eventually have a sound base to keep developing until an idea becomes a viable marketable product.

At the farmlab.at a series of digital and classical machines are available to rapidly prototype, be it with 3D printing, CNC milling or laser cutting, the realisation of an idea is at the fingertips.

3.6. Summary

Combining the cultivation of living organisms with engineering is probably as old as agriculture itself. For this specific case, it is important to get a deep understanding for the way mushrooms function, how they grow and which boundary conditions the need to produce a high-quality product in adequate quantities. This knowledge can be best gained by studying the theory on one hand through reading, but even more important is to see how other people are approaching the same topic. For this reason, visits to commercial growers of gourmet mushrooms and to designers working with mycelium as a potential future material for constructing objects have been essential to understand the workflow and see the scale of such an operation. Furthermore, prototyping the ideas proposed in this thesis plays a vital role, first of all because there is the opportunity in terms of space at the farmlab.at, and because there is a prototyping infrastructure in place which allows to rapidly turn ideas into objects for testing. Another aspect is that there is already some of the machinery and devices at the farmlab.at in place to be used for growing mushrooms.

4. The cultivation of mushrooms

For the cultivation of gourmet mushrooms various requirements need to be met, which will influence the workflow and efficiency of the cultivation. The workflow however is depending heavily on the method of cultivation chosen for production, and so does the necessary investment in machines and consequently the business model. The main dimensions of such an undertaking are as follows:

- **Logistics** – what needs to be where, when, and how. This is important for the raw materials as much as it is for the substrate and eventually the harvested mushrooms. Not to forget, also the used substrate needs to b handled and disposed of or used for making other products which can be a contribution to the overall business.
- **Space** – various separate rooms with different conditions are essential for a professional growing business. In every stage of the process, different requirements need to be met to guarantee a high-quality production by limiting the dangers which could lead to a failure of the crop.
- **Raw materials** – a mix of different ingredients which makes the substrate where the mushrooms can thrive on. Every mushroom strain has different requirements when it comes to the composition of what it grows on. Some are very specific and therefor harder to cultivate, for example Maitake (*Grifola frondosa*), whereas others like the Oyster mushroom (*Pleurotaceae*) are much less picky when it comes to the substrate.
- **Energy** – climate conditions should be controlled even though there are mushrooms for various climate zones. By stabilizing the climate, future harvest become more predictable, and a high quality of the produce can be achieved when the right conditions for the specific mushrooms can be provided.
- **Time** – even with automation, a mushroom farm needs constant attention to check the progress of growth and being able to decide for the right moment for harvesting. Growing spaces need to be prepared or cleaned out, harvest needs to be packed and shipped or transported to the clients etc. Where possible, tasks can be automated but not every step has the potential.

- **Market** – marketing, prizing, delivery, need to be analysed and an according strategy must be put into place

4.1. The chosen method of cultivation

After having experimented with the different methods illustrated in chapter 2.2. in the past on the farmlab.at, the most controllable way of growing mushrooms is to use containers. Specially to start the operation, using standard growing bags, which can be purchased in bulk from various providers, has many advantages:

- **Standardization** – with predefined containers, the whole system can be set up to perfectly integrate operations and modules. This makes running the farm much leaner and eliminates random events as much as possible. Buying and selling becomes a standard operation as well, which makes the business more predictable
- **Modularity** – the setup for cultivation can be tuned to perfectly fit with the size of the bags and vice versa, the bag can be chosen according to the dimensions of the growing setup. This allows for increased efficiency throughout the operation.
- **Measurability** – by standardizing the size of the container, there is a predictable outcome after a predictable amount of time. Nineteen litres of inoculated substrate will produce an average of four kilograms of mushrooms weekly (Cotter, 2014). By keeping records and analysing the data the actual ratio can be calculated and adapted in the overall accounting of the business.
- **Contamination** – the substrate is protected from contaminants while in the bags. Given that there is no contamination getting into the bag between sterilizing and inoculating the substrate, the mycelium has no competition in colonizing the substrate. This allows for a very rapid takeover and therefore production of fruiting bodies.

The downside of using these single use bags is of the environmental aspect. Further on in the business, a change to reusable containers is certainly a good option to become more environmentally conscious in the production. For cleaning and reusing the containers, time or investment in machinery needs to factored in. These costs must be analysed and dealt with when the business is running.

There are several reasons for choosing this more industrial approach over the more natural. There are various advantages but downsides of growing on logs or in mushroom beds as substrate outside are too dominating:

- **Unpredictability** – it is not easy to predict the amount of produce coming out of an inoculated log or bed. Depending on the thickness, age and general condition of the substrate, mycelium will take different amounts of time to colonize it.
- **Contamination** – being exposed to the ground and outside air, contaminants such as spores of other mushrooms or bacteria can compete with the inoculated substrate. Therefor the number of mushrooms harvested will vary. Experiments with inoculated logs inside were not successful. Even with ventilation and moisturizing the logs were not growing healthy mushrooms.
- **Climate** – also the climatic conditions cannot be controlled. They have immense influence over the performance of the mycelium. Especially the moment of fruiting body production could be missed and therefor the production lost.

4.2. Which mushrooms to cultivate?

It is hard to say how many species of mushroom are possible to cultivate and are edible. There are some factors to consider though when it comes to choose the mushrooms for a business. There are the most common gourmet mushrooms, the case studies revealed that commercial growers tend to choose what is already grown somewhere else. This might come from the fact that certain strains can be ordered online and come with defined grow parameters. A choice must also be influenced by the eventual product which will be sold. In chapter 2.3. we have seen that mushrooms have different properties and applications. Depending on what is the market to get into a mushroom must be chosen. To limit the extend of this paper and the experimentation, we suppose to grow edible gourmet mushrooms for the local gastronomy or medicinal mushrooms which will be turned into powder or tincture.

The most inspiring and motivating results come from easy to grow mushrooms. As mentioned above, experiments have been done already, with different techniques but also different types of mushrooms, most of them successful. In the following table, the mushrooms chosen for this paper are listed with growing parameters based on the description in *Organic Mushroom Farming and Mycoremediation* (Cotter, 2014):

Table 1: Mushroom strains, and growth parameters

Common Name	Latin Name	Temp. range	Substrate	Inoculation to fruiting indoors	Comment
Enoki	*Flammulina velutipes*	7-13°C	hardwood sawdust	3-4 weeks	coldshock for fruiting
Maitake	*Grifola frondosa*	16-21°C	hardwood sawdust	4-8 weeks	
Lion's Mane	*Hericium spp.*	13-18°C	hardwood sawdust	3-4 weeks	strain must match wood type
Shiitake	*Lentinula edodes*	2-21°C	hardwood sawdust	7-10 weeks	different strains for different climates
Oysters	*Pleurotus spp.*	depends on sub species	agricultural by products, hardwood sawdust	3-5 weeks	very easy to grow

For the research described in this paper, the genus Pleurotus is the most convenient type, since initially the focus is set on setting up the process. Later, experimenting with different strains will be implemented to offer a greater variety of mushrooms to the customers.

4.3. Important aspects to consider before cultivation

4.3.1. Risks and hazards for people and business

Two main topics are important if mushrooms are to be grown successfully and safely. No harm or damage should be inflicted on the grower and the farm and no contamination of the substrate should jeopardize the forecast quantity and quality of the product.

4.3.1.1. Contamination

At different stages in the cultivation process there are different levels of contamination risk to the production. Contaminated substrate can lead to the loss of a whole batch or even the whole production in the worst-case scenario. To reduce this kind of risk, general cleanliness of the facilities is a top priority. Floors and surfaces must be kept free of any dirt or rests of substrate and mycelium. In defined areas, such as the lab, the growing chambers and the inoculation room, special protocols apply when it comes to disinfecting surfaces and making sure the air itself is filtered to prevent other organism like bacteria or other types of fungus to populate the substrate. Especially between sanitizing the substrate and sealing the bags after inoculation the risk is very high. Another problem in this context can be the presence of rodents. One way of dealing with this can be a series of traps set up to catch the rodents, at the “Bolet ben fet” farm cats are a very effective way of keeping the rodents away.

4.3.1.2. Health risks

Also, for the growers and workers special precautions need to be taken. The aim of producing fruiting bodies is to send spores out to colonize a different area. If there is a room full of mushrooms sporulating, the air will be heavily loaded with spores. To prevent this dust to enter the lungs and cause health issues, wearing a mask, especially in the fruiting areas, is mandatory.

For disinfecting surfaces and hands, alcohol can be used. On one hand there is a risk of damages to the skin, on the other hand there is a fire hazard, special precautions need to be taken to avoid any danger resulting from that. Instead of using an open flame for sterilizing tools an electric sterilizer should be used and extinguishers must be placed in the respective areas.

Various rooms are needed to run a mushroom farm commercially. These rooms need to be separate to minimize the danger of contamination of the substrate, tools and eventually mushrooms. All these rooms should be finished in a way that allows for easy cleaning and/or disinfection. Also, the sequence is of immense importance because the flow of material and people need to be organized in a way to minimize contamination.

4.3.2. Logistics

Logistics is an overarching topic just like safety. To store and move material and products around the space is defining the efficiency of every business. As seen above, when it comes to growing mushrooms, there is an additional risk of contamination. This can not only be reduced by cleanliness but also by keeping certain movements of material as short as possible to reduce the time of exposure to potential contaminants. Not only contamination but also wasted time and energy must be limited to have a successful operation without burning people and material.

4.4. Raw materials

The literature and the internet show that there is a plenitude of ways to cultivate mushrooms, though there are key ingredients for every operation of this sort. To begin with, saprotrophic fungi grow on fresh organic matter such as straw, other agricultural side products and/or sawdust, the latter coming mostly from hardwood trees such as oak, chestnut, beech, or alder. This base for growth, mixed with further ingredients to adjust the pH is called the substrate. Water content and the pH of the substrate determine whether the growth of the mycelium can be at peak performance or not and hence the yield of fruiting bodies for sales on the market. Regular measurements especially in the beginning are key to get a valuable experience and speed up the process of substrate preparation.

The other ingredients which will supply additional energy for the growth can also be wheat, soy, or rice husks and are an annual by-product of the harvest of staple crops. Depending on the machine used for the harvest, either they drop directly to the ground to be left to decompose or are removed later in a separate process. If they are stored in a dry environment, it is possible to have enough for a whole growing season. One aspect that needs further investigation is the practicability of separating them and bagging them in a reasonable way without interfering too much with the harvesting which is always the most stressful time of the year for farmers. Time is extremely valuable since harsh weather could jeopardize the entire work of the year – if it rains farmers might have to wait several days to weeks until restart the harvesting again or even lose the crop to rotting.

Water is key to growing good produce. There is clean drinking water from a shared well with the neighbouring farm on the premises.

4.5. The process of cultivation

Growing mushrooms in bags is about defining and following a certain line of actions to produce good quality mushrooms. This protocol contains the following main steps and parameters.

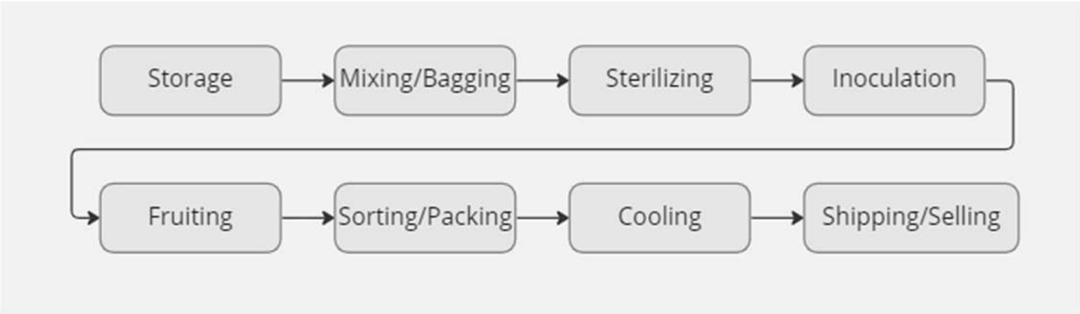

Figure 5: Processes from beginning to grow to selling; Gutmann

4.5.1. Storing materials

The storage facilities need to be dry and spacious for the raw materials. Enough space and an even floor to move big bags and other types of containers around is making the operations efficient. Heavy load shelves would allow for the storage of big bags vertically. This would allow for the purchase of husks in the harvesting season and having enough of them in the storage for a year. Changes to the recipe of the substrate can be avoided through this practice since the additional ingredients do not vary.

The following materials are stored in this facility:

- Sawdust in big bags or pallet mounted boxes
- Husks in big bags or pallet mounted boxes
- Lime in bags or buckets
- Grow bags

Another room which can be important for starting up a mushroom farm is a dedicated laboratory. Here, cultures of varied species or varieties of mushrooms can be isolated, cultivated and expanded into spawn, which can later be used to inoculate the substrate. Usually, petri dishes are filled with a nutritional media based on Agar-Agar are inoculated either with a piece of fresh mushroom (cloning) or spores extracted from sporulating mushrooms. For that a clean and easy to sterilize surface is important as well as contaminant free air. Best choice would be a stainless-steel workbench as they are used in professional kitchens. Furthermore, for storing the cultures and diverse kinds of mycelium, the laboratory needs to be equipped with a fridge. In a range between 3-7°C, mycelium of species from temperate climate zones can be stored for several months (Cotter, 2014) in a dormant state. For providing perfect conditions to grow samples on petri dishes, a small incubator is needed.

The laboratory is especially interesting if a grower wants to be independently growing varieties of mushrooms which are found in the local forests or simply wants to have a certain "library" of strains with known characteristics to be able to react to changing conditions. There are growers in the area around the farmlab.at who are getting the prepared bags delivered and focus solely on the fruiting and sales.

4.5.2. Mixing and bagging

For the mixing of the substrate according to the recipe a scale is essential. Once there is a working recipe established it must be repeated precisely. The weighed ingredients will then go into a mixer, this can be a large container with the mixing itself done by hand or a compulsory mixer as it is used commonly in construction. After analysing what established mushroom farmers use, a trough mixer is the best choice. Ideally it has an exit nozzle which allows for the filling of the growbags directly from the mixer, eliminating the need to use a shovel for getting the substrate from the mixer into the bags – even with the help of a funnel this is a meticulous task putting significant strain especially on the back of the worker. In combination with a rotary feeder, a constant quantity of substrate in the bags can be achieved. This would increase the accuracy and predictability of the growth in a later stage. For a convenient and ergonomic way of working, a workbench will also contribute positively to the flow of tasks performed. A pallet truck will allow to move big bags and pallets around. The pH of the substrate is also important as well as the water content. Where the pH depends on the chosen strain, the water content should be at the limit to leaving a puddle at the base of the bags. To get the water content right, a recipe must be established, and a series of tests done to find the right amount of water that needs to be added to the substrate. By taking out samples of the mixed substrate and weighing it, the water content can be determined following the protocol established after the test series.

4.5.3. Pasteurizing or sterilizing

For the substrate to be as clean as possible and to remove potentially competing or even deadly lifeforms such as other strains of fungi or bacteria it is essential to sanitize the substrate. There are two major ways of doing this, one being at low temperature, around 80°C with zero pressure over around eight hours or with an autoclave at approximately 121°C and a pressure of 1bar for around two hours. After that, the bags should also cool down inside the steaming device.

For making an autoclave there is professional knowledge and equipment needed. For safety reasons an autoclave must be certified to guarantee a safe operation since steam under pressure can be extremely dangerous. An autoclave is a fixed installation in a dedicated place, and it usually can't be moved around.

In contrast, making a pasteurizer, since there is no steam under pressure the safety risks are low, is possible to achieve with rather easily available materials and tools. One way of doing it is to insulate a steel barrel and connect it to a steam generator. This is a rather flexible and low-cost option. It also allows for having various barrels which would allow a serial production of sanitized bags. There is a higher risk for some contaminants left in the substrate, which is not the case if an autoclave is used.

4.5.4. Inoculation

Here is one of the most critical operations happening throughout the whole production chain. Inoculation means that the freshly sterilized substrate in the bags is mixed with the mycelium which has been growing on a grain substrate, the spawn. It is critical because the sterilized bags need to be opened and therefor are in danger to be contaminated with unwanted biology such as fungi or bacteria. A sterile workbench is the go-to option for the growers I have seen.

The sterile workbench consists of a table with an easy to clean and disinfect surface such as stainless steel or laminated fibre boards. From a design point of view ideally there are no corners where dirt could accumulate, and no materials like raw wood are used for the construction which could be inhabiting fungi or bacteria.

Another critical point is also the air quality in the space. Airborne contaminants are a huge risk for rendering a whole batch of the production useless if bacteria get into the substrate. A satisfactory solution could be the use of HEPA filters in combination with a laminar flow hood. If this setup is switched on early enough to have the entire volume of air in the space being filtered, the inoculation process should be close to risk free, given that the inoculation is being done correctly. The laminar flow hood, being positioned behind the workbench, also makes sure that there is a constant flow of filtered air blowing over the work area in a horizontal way. Therefore, no contaminants coming from the worker's clothing or breathing can enter the critical zone. It is critical to open the bags only inside this airflow and keep them in the flow until the inoculation is done and the bags have been sealed. This might be easier to achieve if there are two filters side by side. The sealing can be done through welding the plastic with a special sealer. The sealer is a clamping device with a hot wire, melting the plastic and welding the opening shut. There are also clips for sealing available on the market, but it seems to be rather impractical and slow.

The following step is about shaking the bags to have the mycelium mixed properly with the substrate. This can be done by hand but can be quite laborious depending on the size of the batch. As seen on *Bolets ben fet* farm in the north of Barcelona, Spain, a tumbler tube going through the wall of the inoculation room could be immensely helpful. It is a rotating tube, about twice the size of an inoculated bag, with around two degrees of inclination. Inside the tube there are strips of rounded off wood screwed to the sides. By placing the sealed bags into the rotating tube, they gently tumble out into the following room where they are placed on shelves.

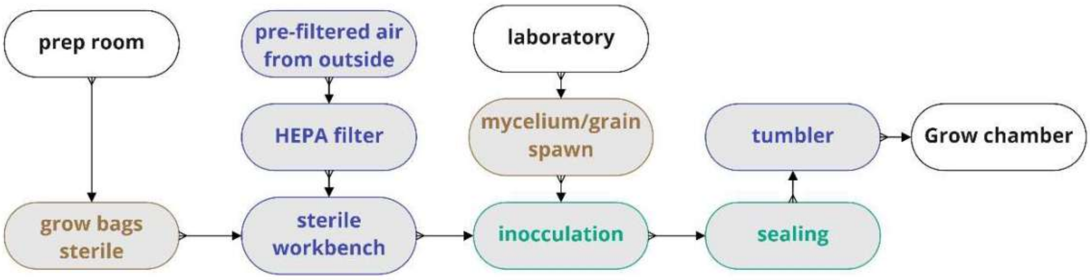

Figure 6: Flowchart inoculation room (brown: material, green: labour, blue: infrastructure); Gutmann

4.5.5. Spawn run

For the spawn run, which is the term used for the time the mycelium is taking over and completely colonizing the substrate, the bags should be placed in a dark room. All the above-mentioned species have similar requirements when it comes to growing conditions. Even if the ideal temperature range for the growth is different, they need a high CO_2 content and darkness for the spawn run. This will mimic the conditions in the forest floor or a piece of wood laying on the forest floor with CO_2 being a heavy gas an accumulating in the ground. There is only rare air exchange needed since the mycelium needs a CO_2 rich environment. Indoors, these conditions must be provided to simulate the conditions in the forest floor, where it is dark, and the mycelium is constantly exhaling CO_2. To make sure the mycelium is not exposed to light later in the process as well, some growers use black bags, with regular transparent bags to be able to check for contaminations in the substrate. Properly sterilized substrate has no competing organisms in it which means the mycelium can focus all the energy on taking over its new habitat. The spawn run can vary heavily depending on the strain of mushrooms. Oyster mushrooms are amazingly fast and aggressive in colonizing, others, such as Shiitake and Maitake, take much longer.

4.5.6. Fruiting

Broken up pieces of mycelium grow until they reach a boundary condition, in this case the plastic bag, or another piece of mycelium of the same DNA, which makes it fuse back together. As soon as the limits of growth have been reached, the mycelium switches into a kind of survival mode. This would be the fruiting phase; it starts with the so-called pinning where tiny clusters of mycelia will form. Here the black bags and the transparent control bags come into play again. When there are visible clusters of pins visible, the grower cuts opening into the side of the bags. These clusters grow and turn into the fruiting bodies or mushrooms, trying to grow towards the O_2 rich environment, therefor in the fruiting phase the conditions need to change in the environment. For good growth three conditions need to be created: the content of CO_2 must drop dramatically to prevent the fruiting bodies from growing in an elongated fashion, the mushrooms need a light source to develop colours and the space needs a high humidity to prevent the fruiting bodies from drying out and becoming wrinkly. A disadvantage of using only transparent bags can be, that there are fruiting bodies growing under the plastic and not only at the holes

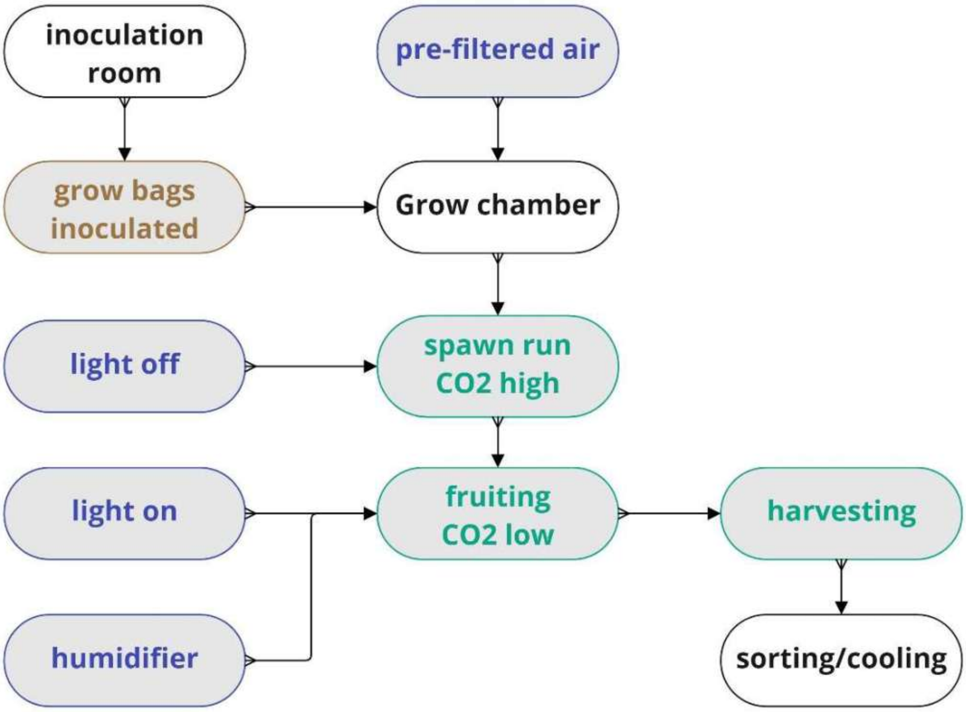

Figure 7: Flowchart growing chamber (brown: material, green: labour, blue: infrastructure); Gutmann

where they are supposed to grow out of the bag. If possible, the spawn run, and the fruiting happen in the same room to not have to move the bags around too much.

4.6. Energy

Energy plays a vital role in indoor farming in general. Best results are achieved if an organism can be provided with stable conditions adjusted to the requirements in time. These requirements can change over the life cycle of an organism. It might need different climate conditions or nutrients throughout the year. Fungi from temperate climates for example can be triggered to go into fruiting by exposing them to cold temperature, cooling the substrate core down to below 15-18°C (Stamets, 2000). There are two main options when it comes to mushrooms. Either the room is actively conditioned, for example with an HVAC device, or the mushrooms are chosen to fit the seasonal changes in temperature. The latter is the approach we want to try at the farmlab.at to minimize the energy consumption. The best option would be a hybrid approach with seasonal mushrooms and the HVAC being installed as a backup to buffer unexpected changes.

4.7. Summary

There are many ways of cultivating mushrooms. Which method to choose depends mainly on

- what is the aim to produce and sell at the end of the process
- which kind of growing conditions are there
- which level of experience does the grower have
- what kind of raw material is available
- which market opportunities are there
- at which scale should the operation be

Different methods have been tried out at the farmlab.at in the recent years, some more and some less successful. In principle, mushrooms can be grown indoors or outdoors, both ways have advantages and disadvantages, mainly depending on whether the intended use is for domestic use or sales to the market. There are growers, the case study has shown, who grow commercially outdoors on inoculated logs. One exemplary benefit I the extremely low need in energy and the fact that logs produce mushrooms for some years. Also, the trash produced by this method is negligible. Indoor growing in containers has the benefit to allow for controlled conditions when it comes to the climate and hygiene as well as potential issues with animals, like slugs, eating the produce. Another benefit is that the production is predictable and there are manageable threats by pests like mice.

Each method has distinct steps that need to be followed. At the beginning is the raw material, each variety of mushroom has its preferred so-called substrate which it can thrive on. This could be logs as described above, it can be sawdust mixed with supplements like agricultural by products or any other kind of organic matter. For good results, the substrate must meet certain criteria among which the pH and the water content are the most critical.

After preparing the substrate, it needs to be sanitized. For outdoor methods, growers might submerge the logs in water for an extended amount of time. Indoors, heat treatment is the most common method. A low budget but less aggressive method is pasteurization with steam. The containers filled with substrate are being put into a container and, at atmospheric pressure, steamed for some hours. A more thorough but also more investment intense way of sanitizing is to autoclave the substrate. Under pressure and at 121°C the contaminants are being killed, to make sure there is no competition for the mycelium in the substrate left.

The following step is the inoculation. Here, pieces of mycelium growing on grain, called spawn, are mixed into the sanitized substrate. Therefore, the bags need to be opened and there is a risk of contamination. To reduce this risk, this step happens in a clean room. Hygiene is the most important issue here. This goes for the worksurfaces as well as for the air, which must be filtered, and all the tools used. Also, the right protocols need to be followed when handling the bags and materials. If growing on logs, holes are being drilled in close vicinity and the spawn, either in form of inoculated dowels or loose spawn, is injected into these holes. After injecting, the holes must be sealed to avoid contaminants to enter.

Next is the spawn run, the period where the mycelium is completely taking over the substrate. Depending on the chosen variety and the method this can take around three weeks to up to one year. Logs can take a long time because of the density of the material whereas sterile substrate for the absence of competition in combination with oyster mushrooms is extremely quickly. In this phase, naturally the mycelium is living in a CO_2 rich and dark environment. Indoors this means a dark chamber with little gas exchange.

When the mycelium reaches boundary conditions, the end of a log or the plastic barrier of a bag, it wants to change location and find a new habitat. Therefore, so called fruiting bodies are produced. These fruiting bodies have the purpose of producing and spreading spores to inoculate substrate somewhere else. This is the time indoor growers growing in bags or containers must change the gas composition of the atmosphere. More ventilation and cutting holes into the bags provides the oxygen the fruiting bodies need. Also light becomes important for the proper development of the mushrooms. The third important factor in this phase is humidity. To protect mushrooms from drying out, the air needs to be humidified. For outdoors, this is seasonally provided by fog or rain.

Eventually, the fruiting bodies can be harvested and prepared for sales. Depending on the clients wishes, the mushrooms need to be sorted and packed before going into the cold storage waiting for shipping or pickup. Excess produce can also be dried and milled into powder and sold as flavouring.

5. Semi-automated mushroom farm at the farmlab.at

5.1. Spaces

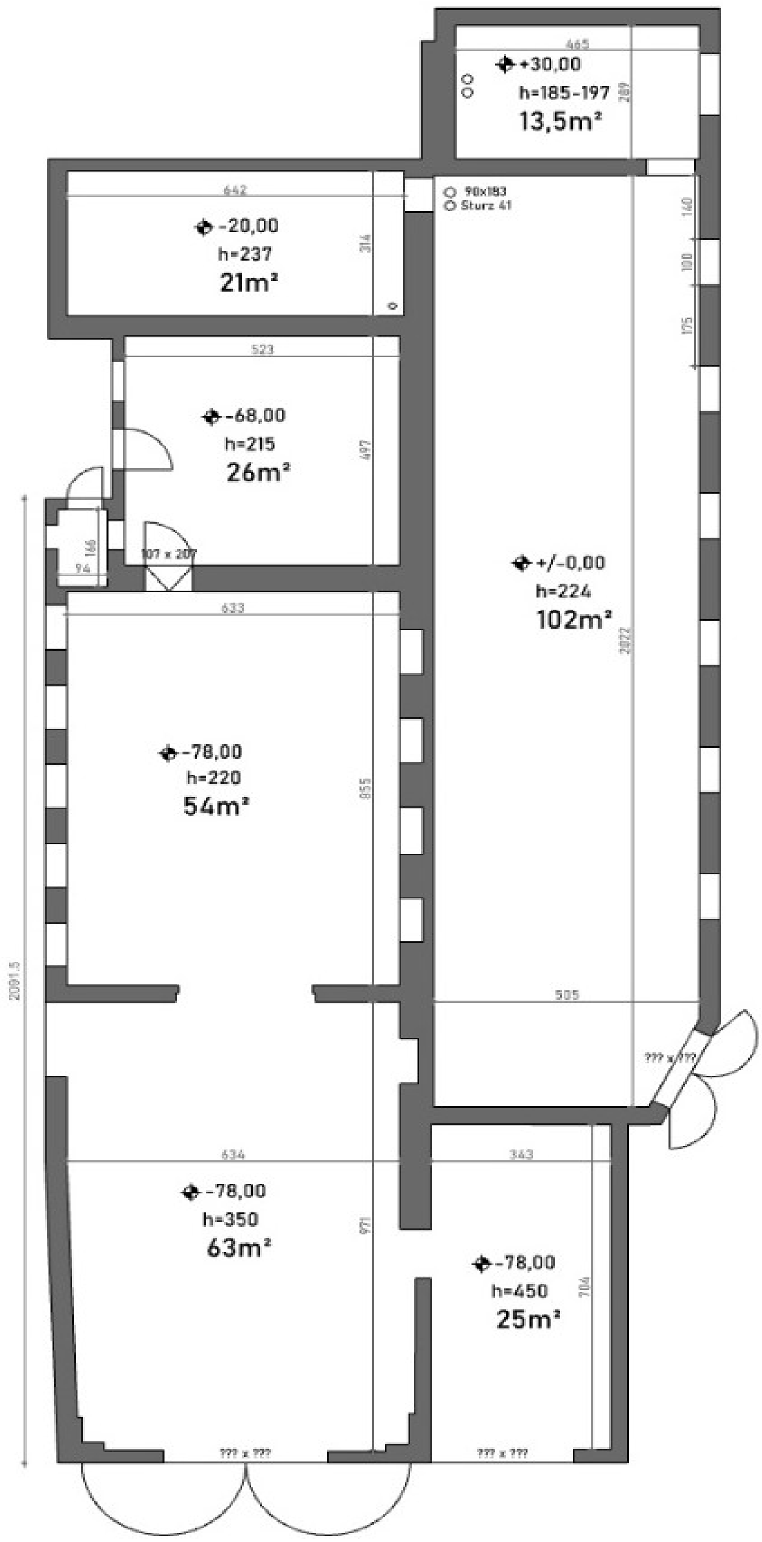

Figure 8: Status quo of the usable surface in the barn; Gutmann

The barn on the farmlab.at had been used for raising livestock up until the mid-1990s. Having been abandoned with all the necessary constructions like boxes, gutters, and fences in place and unused, the family decided to remove these installations and put a smooth concrete floor in place to make the rooms more accessible and usable as a storage facility. The construction works happened around 2005. During the process, infrastructure such as electricity and water outlets were left in place or even modernized to address the security aspects and make them compatible with state-of-the-art connectors. The electrical installations are surface mounted which keeps a certain flexibility to react to changing uses. For the mushroom production it means, the infrastructure can be adapted easily.

Being built into the side of a hill there are various levels with a maximum difference in height of around eighty centimetres. For the ease of use, some openings will have to be made and ramps will connect the different levels to keep operations as smooth as possible when transporting material around. To start the business, some spaces will be shared. Here it is beneficial to have isolated grow chambers which will keep contaminants away from the mushrooms.

For the start-up phase, some functions will be grouped and happening in one room to make prototyping easier. In the following chapters I will describe the scenario of an optimal use of the spaces in terms of safety and productivity.

5.1.1. Storage, mixing and bagging of the substrate

In this space, pallets with big bags for the different ingredients of the substrate will be used. Since this work is using the farmlab.at as a case study the first step is to identify the availability of such material in the area. There is a sawmill in the vicinity which is specialised in sawing hardwood lumber only. The distance is approximately 15km or 20min driving which is a reasonable distance. As convenient alternative also wooden pellets, as they are used for biomass heating systems, could be used as a substrate although the prizes for wood pellets have been skyrocketing in the last heating season.

Since the big bags are made of woven fabric, some ventilation will limit the growth of mould on the sawdust especially. Sawdust is not totally dry because the logs are cut while the wood is still fresh. Big bags are also the most convenient way to move materials around with a pallet truck after unloading from a trailer. To expand the storage capacity, a heavy load shelf will be installed to make the most of the vertical space. An electric forklift will help to manage the movements of material.

Clean water is available on the premises through a shared well with the neighbours, who also used to raise livestock in the past. The assumption is that quantity must be enough for a mushroom operation since in the past both farms were raising livestock from this shared well which is much more intense in terms of water consumption.

Several 380V electricity outlets are already in place and will provide everything needed for preparing the substrate and running the mixer. Even though not being ideal because of its volume, for starters a standard freefall concrete mixer will be used for the mixing of the substrate. They are relatively cheap and can be sold after the start phase of the project is over and a scale up is done. From the mixer, the substrate will be moved into a trough. For now, a small shovel will be used to move the substrate into special grow bags. The bags are available online and come already equipped with a filter tissue which allows the mycelium to breath while keeping contaminants out. With the shovel it is relatively precise to have even amounts of substrate in each bag.

Later in the project a change towards a trough mixer with a bigger volume making it possible to mix the exact amount of substrate needed to produce one batch will increase the productivity. There are models available with a nozzle which could be used for filling the bags. Combined with a rotary valve also the amount of substrate would be automatically the same in every bag. Additionally, a funnel will help with the filling to avoid the loss of too much material.

Until this point in the process, the environment is still not necessarily sterile, as the following step is the steaming. The filled bags are being folded closed and stacked into an insulated metal barrel which is moved to the steaming space.

5.1.2. Steaming

An autoclave is a big investment and dangerous to build unless the technical knowledge and the appropriate tools and skills are available. To stick with the open-source and “do it yourself” approach, the steaming barrels for simple pasteurization will be the choice. The insulated steel barrels, connected to a steaming device powered by an electric heating coil, allow also for a flexible and mobile production of sanitized substrate. The steam generator can also be self-built although there is always a risk when working with steam. The blueprints *of Oak and Spore Mushrooms* (link in Appendix B) from New Zealand are available in their online store. When installing this kind of device, it is very important to make sure the steam can exit the barrel safely and without obstructions. If pressure would build up inside the barrel, a dangerous situation might be created, leading to injuries or damage! In terms of space, it is important to recognize that both methods produce a high degree of humidity. Doing the pasteurizing in the inoculation room would be counterproductive because it would saturate it with steam which is not ideal for a clean room. Neither is steam wanted in the storage which must be dry. Therefore, the ideal place would be a well-ventilated area which can also be kept clean in an uncomplicated way.

Many growers have an outdoor space, covered by a roof, to avoid damage to their buildings through condensation. Although, the longer the way from the pasteurizer to the inoculation room the higher the risk of contamination. Ideally the inoculation room is close or even adjacent to the pasteurizing room. After cooling down, either the bags are removed from the pasteurizing container and brought to the following room or, even better, the whole pasteurizer is moved. This would reduce a contamination risk dramatically and it would be easy to disinfect the surface of the container before entering the inoculation room through wiping or spraying it with isopropyl alcohol.

The situation in the farmlab.at provides an alternative option to the outdoor steaming in the small room between the storage and bagging room and the inoculation room. By constructing a simple ramp of around 10% inclination it will be easy to move steaming barrels between he rooms with the pallet truck. There are already two openings in the ceiling which can be connected to a duct and a ventilator, and a window which can be used to allow fresh air from outside to ventilate the space sufficiently. Being a distribution room, it can’t be used for anything else within the logic of operation. Its vicinity to the inoculation room makes it ideal in terms of logistics but it is also a great plus, saving time and energy as well as reducing the risk of contamination. The barrels can cool down in the steaming room and, still closed, moved into the inoculation room where they will be opened in front of the laminar flow hood inside a filtered air stream.

To begin mushroom production the time of eight hours is also acceptable, and should the operation generate enough income and the production maximum is reached at some point, this would be an already identified bottleneck to eliminate and speed up operations by reducing bag production time from eight to two hours. At that moment it will be necessary to calculate whether it is viable to invest in an autoclave or just increase the number of barrels and steam generators.

5.1.3. Laboratory

The laboratory is important for growers who are cultivating their own spawn or collect wild mushroom species and experiment with different strains.

5.1.4. Inoculation

This is the most demanding of all the spaces in terms of hygiene. Here is the greatest risk of contamination of the substrate bags because they must be taken out of the pasteurized barrels coming from the steaming room. The surfaces in this room must be easily cleaned and maintained. Ideally the inoculation room is completely empty and doesn't provide any habitat for contaminating organisms. Recently a concrete floor has been put in place including underfloor heating options. Being such a crucial room to the operation and success of the business, most of the investment will be allocated here to reach the required quality.

The floor will be sealed with a two-component epoxy resin and sand, which is very durable, easy to clean and sanitize but also provides the necessary working safety through the anti-slip properties of the added sand since there might be water on the ground after taking out pasteurized bags from the barrels. The walls and ceiling will be painted with lime wash, which has disinfecting properties and, applied regularly like once a year, sanitizes the surface. In a later stage, tiles could be glued to the wall to make cleaning easier, but this has no priority at the present state. Also, an existing duct in the ceiling can be used to extract air. A second duct must be opened to allow fresh air to enter the space. A filter will be crucial to avoid contaminants to enter the room. Ideally the air coming in would already be filtered through a HEPA filter. These filters are quite expensive though and delicate. Depending on the quality, a HEPA filter can filter out most of the particles in the air. To avoid a constant change of the HEPA filter, a filter box to pre clean the air is advisable. Ideally the box has filters of different roughness behind each other. Some schematics show also an additional electrostatic air cleaner (Stamets, 2000).

For the inoculation room a H14 filter will be sufficient. To make sure the air is clean enough when the inoculation will begin, the filter system will be switched on thirty minutes before the inoculation starts. During this cleansing period, the duct for exterior air will be closed to recycle only the air already in the room making sure it is free of any contaminants. Since also the mycelium has self-defence capabilities, going for the H14 should be enough, even if there is a bacterium entering the substrate bags, the mycelium would be capable of destroying it.

BS EN 1822-1 2019			ISO 29463-1 2017		
Filter class and group	Overall value		Filter class and group	Overall value	
	Efficiency (%)	Penetration (%)		Efficiency (%)	Penetration (%)
E10	≥ 85	≤ 15			
E11	≥ 95	≤ 5	ISO 15E	≥ 95	≤ 5
			ISO 20E	≥ 99	≤ 1
E12	≥ 99.5	≤ 0.5	ISO 25E	≥ 99.5	≤ 0.5
			ISO 30E	≥ 99.9	≤ 0.1
H13	≥ 99.95	≤ 0.05	ISO 35H	≥ 99.95	≤ 0.05
			ISO 40H	≥ 99.99	≤ 0.01
H14	≥ 99.995	≤ 0.005	ISO 45H	≥ 99.995	≤ 0.005
			ISO 50U	≥ 99.999	≤ 0.001
U15	≥ 99.9995	≤ 0.0005	ISO 55U	≥ 99.9995	≤ 0.0005
			ISO 60U	≥ 99.9999	≤ 0.0001
U16	≥ 99.99995	≤ 0.00005	ISO 65U	≥ 99.99995	≤ 0.00005
			ISO 70U	≥ 99.99999	≤ 0.00001
U17	≥ 99.999995	≤ 0.000005	ISO 75U	≥ 99.999995	≤ 0.000005
Filter efficiency is for most penetrating particle size (MPPS)					

Figure 9: Classifications of HEPA filters

5.1.5. Spawn run and fruiting

For the final stages of the production, separate chambers will be used. By controlling the environment inside the chambers, both, the spawn run, and the fruiting can happen in the same space. For convenience and modularity, the choice is to get indoor cultivation tents. These tents are usually used to grow plants indoors but according to a case study, provide all requirements needed to grow mushrooms. Here are the aspects which are in favour for this method:

- Easy and fast to set up
- Relatively cheap in comparison to a fixed structure made of solid walls.

- Easy to clean and sanitize on the inside
- Light tight, no light comes out and no light gets in which might trigger a premature fruiting
- Modular and scalable

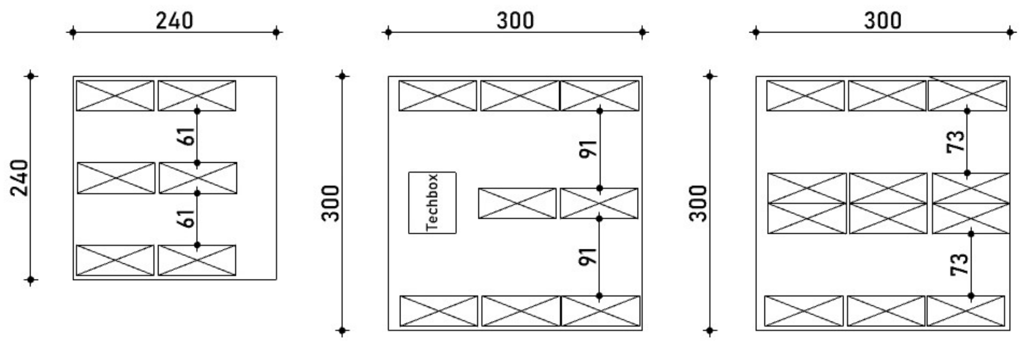

Figure 10: Comparison of different grow chamber setups; Gutmann

The ideal size for the growing chambers resulted to be three by three metres. Optionally chambers of 2,4m x 2,4m were interesting because they seemed to be cheaper. The comparison below and the diagram showing the actual distribution of shelves inside the chamber. It is very clear that the three-by-three metre chambers are the better choice and take the most advantage of the available space in terms of floor covered on one hand and providing sufficient space for the shelves which will hold the bags. Each shelf will hold around twenty bags with substrate and each growing chamber up to seven shelves. Theoretically there would be enough space for up to twelve shelves but space for harvesting, infrastructure and cleaning would be limited. In the table further down, capacities are being compared, the convenience setup being easier to maintain and the most density of shelves to illustrate the potential production. Each shelve has a dimension of 91 x 36 x 183cm and five levels. Every level can hold up to 160kg, which is more than enough since each bag weighs around 5kg there is a maximum of four bags in each level.

Table 2: Comparison different sized chambers and shelving; Gutmann

		max convenience	max shelves
per chamber	**2,4 x 2,4 m**	**3,0 x 3,0 m**	**3,0 x 3,0 m**
cost chamber	340,00 €	500,00 €	500,00 €
m^2	5,76	9	9
€/m^2	59,03 €	55,56 €	55,56 €
shelves/chamber	6	9	12
bags/shelve	20	20	20
bags/chamber	120	180	240
Invest/bag	2,83 €	2,78 €	2,08 €

full scale 102m²	**2,4 x 2,4 m**	**3,0 x 3,0 m**	**3,0 x 3,0 m**
investment chambers	2.380,00 €	3.000,00 €	3.000,00 €
% floor covered	41,1	55,1	55,1
chambers max.	7	6	6
bags max.	840	1080	1440
Invest/bag	2,83 €	2,78 €	2,08 €

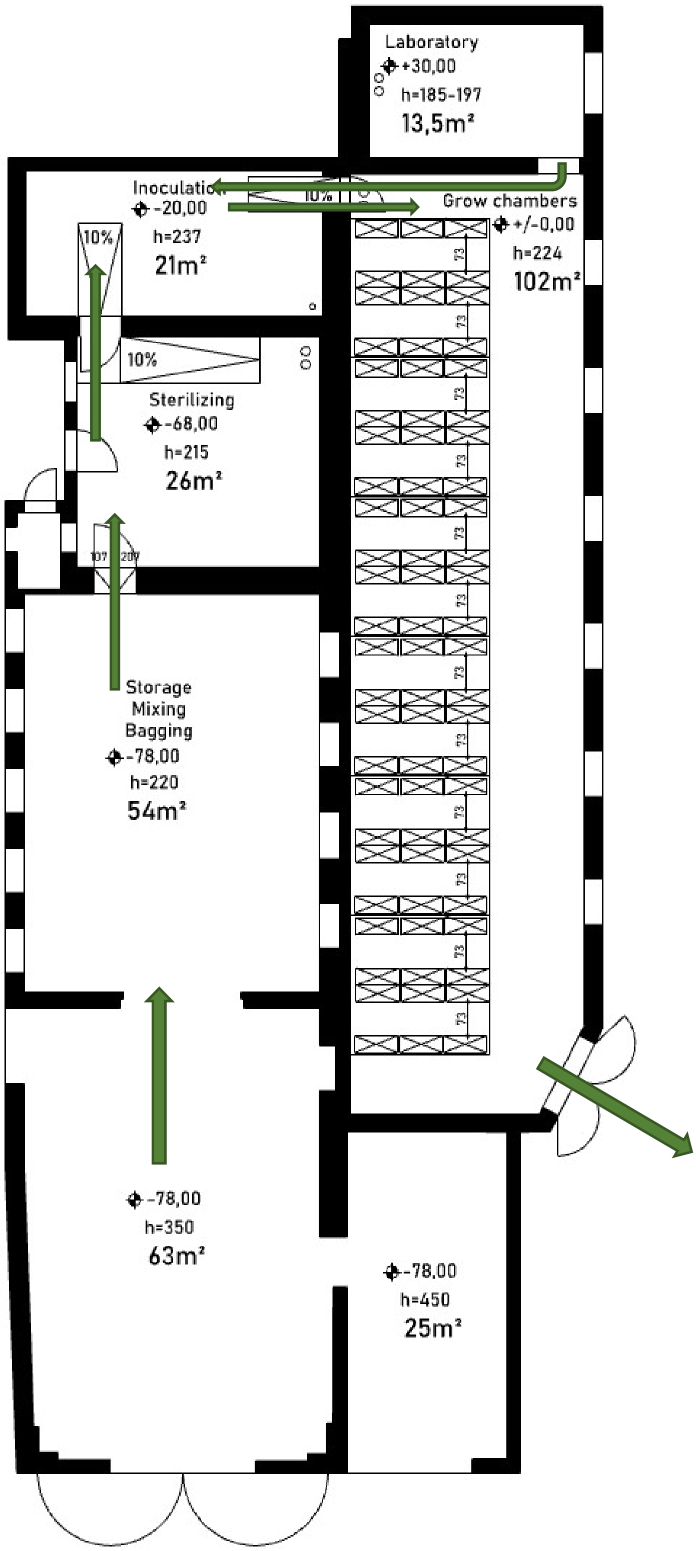

Figure 11: Layout and flow of materials in a full-scale production at farmlab.at; Gutmann

5.2. Automated climate control

Arduino has wide range of great products for makers and educators. All easy to use and well documented. With the Arduino Pro series not being on the market for a long time the list of documentation and realised projects is not as long but the products promise to be more durable, for example adapted to the use outside over an extended time.

5.2.1. Arduino Edge Control

For this project, the decision fell on the Arduino Edge Control, a board specifically designed for smart agricultural use and automation of cultivation. It comes with predefined capabilities such as connectors for water mark sensors, solid state relays, latching devices for controlling motorized valves, digital and analogue Inputs, and outputs to be able to power it with a battery and/or a photovoltaic panel. Furthermore, there is an onboard SD card slot for storing data and two slots where MKR shields can be plugged in directly, which can further enhance the capabilities of the AEC.

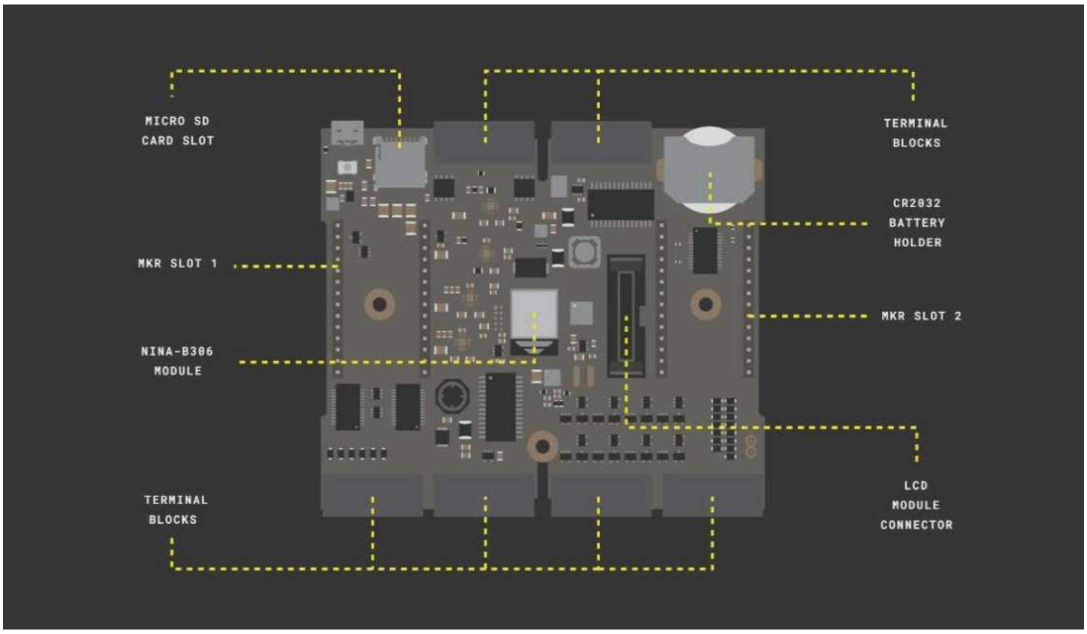

Figure 12: Arduino Edge Control Topology; docs.arduino.cc

The terminal blocks allow for the connection of the following external devices:

- 8 x 5V analogue sensors
- 4 x 4-20mA sensors
- 16 x watermark sensors

- 16 x Latching Devices (e.g., Motorized Valves)
- 4 x configurable solid-state Relays.
- LCD screen

Table 3: Specifications for the Arduino® Edge Control (docs.arduino.cc)

Board	**Name**	Arduino® Edge Control
	SKU	AKX00034
Microcontroller	nRF52840 (64 MHz Arm® Cortex-M4F)	
Digital Input	**Edge sensitive wake up pins**	6
Digital Output	**Latching relay command outputs with drivers**	8
	Latching relay command outputs without drivers	8
Relays	**60V/2.5A galvanically isolated solid state relays**	4
Analog Input	**4-20mA inputs**	4
	0-5V analog inputs	8
	Hydrostatic watermark sensor input	16
Terminal Block Connectors	**18 pin plug in terminal block connectors**	6
Power	**Power Supply**	12 V Acid/lead SLA Battery Supply

		(Recharged via solar panels)
	Power Consumption	Low power (up to 34 months on a 12V/5Ah battery) 200uA Sleep current
Connectivity (* Requires Arduino MKR board)	Bluetooth® Wifi* 3G*NB-IoT* LoRaWAN®*	
Peripherals	Full-speed 12 Mbps USB Arm CryptoCell CC310 security subsystem QSPI/SPI/TWI/I²S/PDM/QDEC High speed 32 MHz SPI Quad SPI interface 32 MHz 12-bit 200 ksps ADC 128-bit AES/ECB/CCM/AAR co-processor	
Memory	**Onboard Flash memory**	1 MB
	Onboard QSPI Flash memory	2 MB
	SD-Card	Interface for SD Card connector (through expansion port only)
Operational Temperature	-40° C to +85° C (-40° F to 185°F)	
Dimensions	**Width**	86 mm
	Length	104 mm

5.2.2. MKR WIFI 1010 module

The AEC will be configured to be able to remotely control the settings and check the status of the input- and output-devices. There are a couple of shields available to connect the AEC to the internet, for example LoRa or 3G/4G boards just to name two. To unlock the IoT capabilities, one of the MKR slots is equipped an Arduino MKR WIFI 1010 module. This has been identified to be the best way given the fact that the space is partially underground, which might interfere with a 4G based solution and there is already an internet connection available in the room from an earlier project which can be reused.

Table 4: Specifications for the Arduino MKR WiFi 1010

Board	**Name**	Arduino® MKR WiFi 1010
	SKU	ABX00023
	Compatibility	MKR
Microcontroller	SAMD21 Cortex®-M0+ 32bit low power ARM MCU	
USB connector	Micro USB (USB-B)	
Pins	**Built-in LED-Pin**	6
	Digital I/O Pins	8
	Analog Input Pins	7 (ADC 8/10/12 bit)
	Analog Output Pins	1 (DAC 10 bit)
	PMW Pins	13 (0 - 8, 10, 12, A3, A4)
	External interrupts	10 (0, 1, 4, 5, 6, 7, 8 ,9, A1, A2)
Connectivity	**Bluetooth®**	Nina W102 uBlox module
	Wi-Fi	Nina W102 uBlox module
	Secure element	ATECC508A

Communication	**UART**	Yes
	I2C	Yes
	SPI	Yes
Power	**I/O Voltage**	3.3V
	Input Voltage (nominal)	5-7V
	DC Current per I/O pin	7 mA
	Supported battery	Li-Po Single Cell, 3.7V, 1024mAh Minimum
	Battery connector	JST PH
Clock speed	**Processor**	48 MHz
	RTC	32.768 kHz
Memory	**SAMD21G18A**	256KB Flash, 32KB SRAM
	Nina W102 uBlox module	448 KB ROM, 520KB SRAM, 2MB Flash
Dimensions	**Weight**	32 g
	Width	25 mm
	Length	61.5 mm

5.2.3. MKR ENV shield

Within the MKR family there is a shield available for measuring basic environmental data. I find this useful mainly to see the conditions the board is working in and whether these conditions are not harmful to the electronics, especially humidity. All electronics are installed outside the grow chamber and only the most relevant sensors will be located inside.

Table 5: Specifications for the Arduino® MKR ENV Shield

Shield	**Name**	MKR ENV Shield	
	SKU	ASX00011	
	Compatibility	MKR	
Communication	I2C and analog		
Storage	Micro SD card slot		
Sensors	**Temperature (HTS221)**	**Range**	15-40 (celsius)
	Humidity (HTS221)	**Range**	20-80% rH (relative humidity)
	Barometric pressure (LPS22HB)	**Range**	260-1260 hPa (hectopascal)
	Ambient light (TEMT6000)	**Range**	Max 650 LUX.
Dimensions	**Weight**	32 g	
	Width	27 mm	
	Length	68.6 mm	

5.2.4. Gravity Analogue CO2 Sensor V2.0

The spawn run, the occupation of the substrate by the mycelium, and the fruiting are happening in the same chamber to avoid unnecessary movements and handling of the growing blocks. For one, every time a block is being moved around there is a loss of time and energy, and the risk of contamination or damage is rising. This means there are two climate scenarios happening in the same space. To be able to control and monitor the status in the chamber remotely a CO_2 sensor is used for getting the necessary data. The sensor itself is an MG-811 developed by dfRobot and is based on a chemical reaction depending on the CO_2 concentration in the air.

Table 6: Specifications of analog CO2 sensor

Operating Voltage	5V
Interface	Gravity Analog
Surface	Immersion gold surface
Connector	High quality
Output	One digital output
Onboard	Heating circuit
Size	32x42mm (1.26x1.65")

5.2.5. Grove Digital Light Sensor V1.1

For fruiting bodies, it is essential to have a light source in the growing chamber. This will help with a healthy and aesthetically pleasing appearance of the mushrooms going into sales. If mushrooms grow in an environment lacking light, they tend to be pale and have an elongated shape. For controlling the situation in the growing chamber, a digital light sensor is in place to detect potential errors in the lighting system or simply human mistakes like accidentally turning the light off after checking the status of the mushrooms.

The chosen sensor from Grove can be used to detect three different spectra of light, the reading can be controlled by the Arduino code:

- Human visible
- Infrared
- Full spectrum

For this application the human visible spectrum will be used. This is to avoid potential erroneous readings coming from a different light source. The human visible range of wavelengths should be narrow enough to limit errors. Alternatively, the upper and lower threshold can be defined individually.

Table 7: Specifications of digital light sensor

Items	Min	Typical	Max	Unit
Supply voltage, VDD	3.3	5	5.1	V
Operating temperature	-30	\	70	℃
SCL, SDA input low voltage	-0.5	\	0.8	V
SCL, SDA input high voltage	2.3	\	5.1	V

5.2.6. Grove Relay V1.2

Based on the readings of the different sensors, actuators are being turned on or off depending on phase the growing blocks are in at the time. Since the Arduino boards are running on a maximum of 12V, relays allow to connect and control machinery running on 240V. For the ease of use and low prize, Grove relays are the go-to solution for this aspect. The following three functions will be controlled by relays:

- Ventilation
  - Directly controlled by the CO_2 sensor, ventilation will make sure that the atmosphere inside the grow chamber will always be adjusted to the stage in growth of the mushrooms. Since mushrooms have a metabolism similar to animals, absorbing oxygen and releasing CO_2, fresh and clean air needs to be provided for a good development of the produce. To safe energy and limit the risk of contaminants entering the grow chamber, the ventilation should not have to run continuously but rather only when needed. Therefor the measured CO_2 will start the motor through the relay when a certain threshold has been reached. The actual ppm-threshold needs to be tested once the prototype has been built, to see which level of CO_2 can be tolerated in the grow chamber without compromising the growth performance.
- Humidifier
  - During the fruiting, mushrooms need high levels of humidity of above 80% to avoid wrinkling or drying out. The humidity levels received from the MKR ENV Shield will switch on the vaporizer when the level drops below this threshold. As soon

as a value of 95% is reached the humidifier can be switched off again to avoid an excess of moisture.

- Light
    - The third relay is used to be able to turn on or off the lights remotely through the Arduino IoT cloud.

Table 8: Specifications of Grove relay

Parameter	V1.2
Operating Voltage	3.3V~5V
Operating Current	100mA
Relay Life	100,000 Cycle
Max Switching Voltage	250VAC/30VDC
Max Switching Current	5A

5.2.7. Arduino Code

There are two ways of programming an Arduino device. The Arduino IDE (Integrated Development Environment) with the latest version being 2.0.3. The IDE is free to use and allows for managing the different boards as well as the necessary libraries and so called "sketches", as Arduino calls the programs which can be run on the boards. Also available and convenient for people who want to use the Arduino Cloud is the web editor. It's mandatory to register online for accessing the web editor and it keeps everything nicely organized on one platform. This platform also offers the setting up of IoT devices in a very graphical and easy to understand way. Data can be recorded, visualized in real time and devices can be remotely controlled through for example a smart phone.

If working with the Arduino IDE installed on the computer locally, it is important to install the necessary libraries for the boards and shields used for the project. The following libraries are to be installed:

- WiFiNINA – for connecting the MKR WiFi 1010 to a Wifi network
- ArduinoBLE – it allows to connect to the MKR WiFi 1010 via Bluetooth
- Mbed Core – essential to run the Arduino Edge control

The practical benefit of using the web editor is that all the sketches are stored on the cloud for one and secondly, no libraries need to be installed since by choosing the board, the libraries are automatically included into the code. For this reason, the web editor was chosen to start with programming the Arduino MKR WiFi 1010 board.

5.2.8. Flowchart

Before starting to write the code for controlling the different input and output devices, a flowchart is essential to keeping an overview and the basic logic present whenever needed. The following flowchart describes the connections and functions of the different devices and illustrates the flow of data:

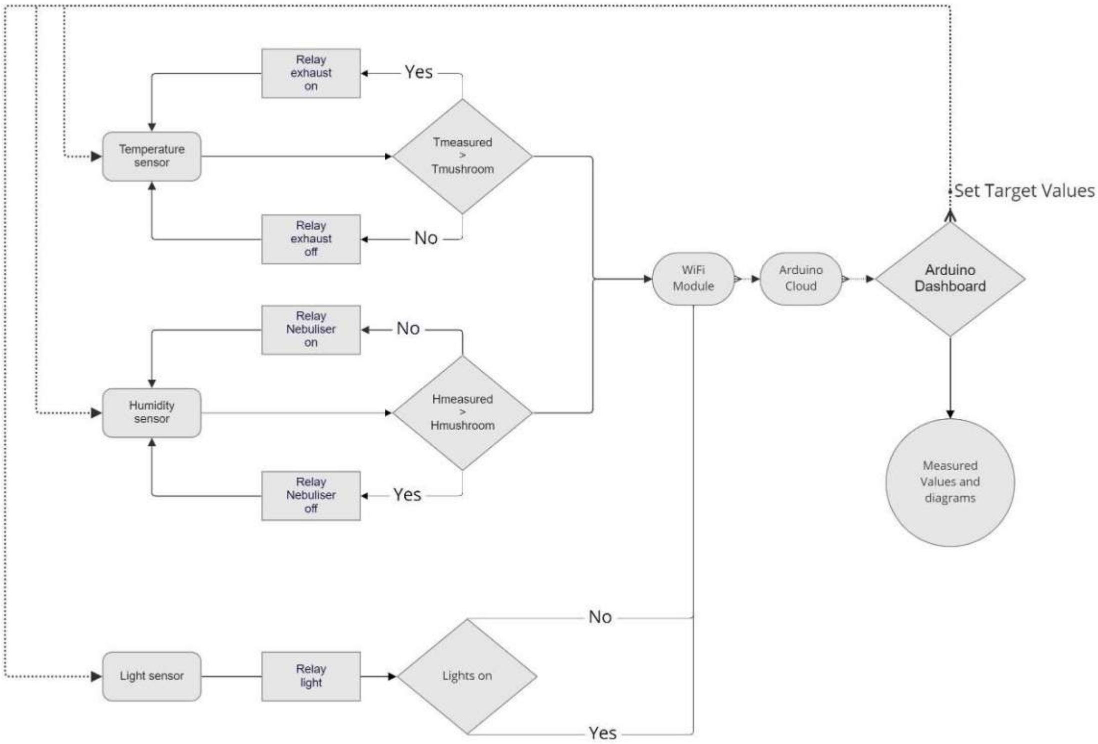

Figure 13: Flowchart of functions; Gutmann

5.2.9. Arduino Cloud/Web editor/ IoT dashboard

The most convenient way to work with Arduino is the web editor to get started with the programming of the board. The biggest benefit is the ease of use and the overview of all the activities. Every project can be stored on the cloud which is also the platform managing the data streams from the sensors, over the boards to any remote device. Whether it is home automation or monitoring of a mushroom production facility all the way to integrating voice command through Alexa or Google can be realized with Arduino products and the cloud. For beginners the pricing is very convenient, two projects, or “things” as Arduino calls it, are for free which allows for prototyping and getting familiar with the environment. Anytime it is possible to upgrade the account to be able to have more projects running in parallel. For the case of the farmlab.at mushroom farm at full capacity these services would amount to roughly two euros per month which is negligible in the overall project finances. This plan called “Entry” allows for ten things running in parallel. Furthermore, it has the benefit of additional functions such as API’s and fifteen days of data retention.

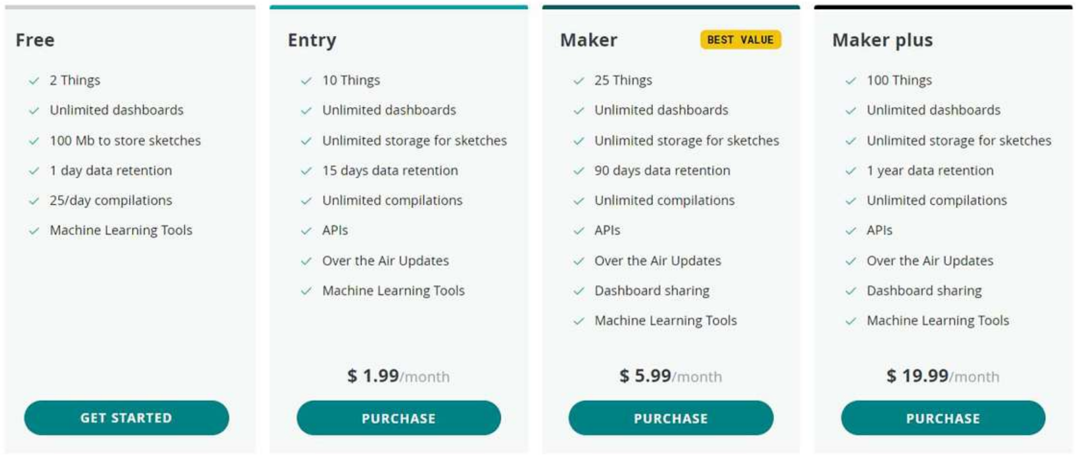

Figure 14: Arduino IoT cloud services compared; https://cloud.arduino.cc/plans/

It is a very flexible platform to create IoT projects. To begin with, the user should create a “thing”, which is the name of the project. According to the flowchart in the previous chapter, variables should be defined. These variables will be used later in the project and should represent the functions in the flowchart. To take an example, to be able to control the light in the chambers, a variable representing the value of the light sensor has to be defined. This variable will be used in the code where a threshold can be defined. Is the value below the threshold, the light is considered to be off, is it above the threshold it can be defined as on. Therefore, a simple Boolean widget showing the status based on the measurement of the sensor can show the status. A second variable which will control a relay will give the opportunity to manually turn the light on or off.

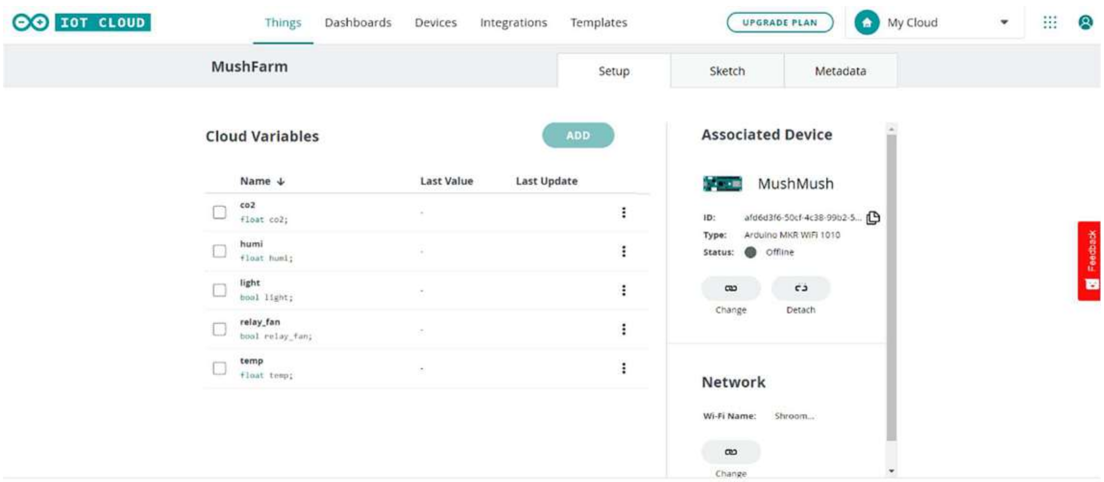

Figure 15: Interface for defining the variables representing sensor data and functions; https://create.arduino.cc/iot/things

The web editor is versatile because it is not necessary to install the libraries which are needed to program and run different boards. Automatically all the necessary libraries are being called once the right board is connected and chosen. Another benefit is, especially when using the MKR WiFi 1010 or any other board that can be connected to the internet, is, that the web editor offers different tabs for different data. The secret tab is used to store the network name and the password which is being called by the actual code. When sharing code, the sensitive data doesn't have to be manually removed and therefor can't be accidentally shared with others.

There is also a read me tab which allows the maker to describe the project, define the license under which the project is shared and can be used by others and a very detailed parts list or any other relevant information. Especially for open-source projects this is a very useful function since all the relevant information is stored in one place and is available to other makers when needed.

All the codes for the different projects are stored on the side of the interface. This keeps the desktop tidy and all projects neatly organized. This way the operation of a farm, which might have its separate account can be structured in a very lean way, allowing for quick trouble shooting and modification. For every software project the documentation is key to allow others to take over control and understand the logic of the setup for example.

At the bottom of the interface there is a monitor, providing feedback about the general state of the program, such as the size and how much of the available space on the board the program occupies, but also potential errors if something is missing or the programme itself has an error.

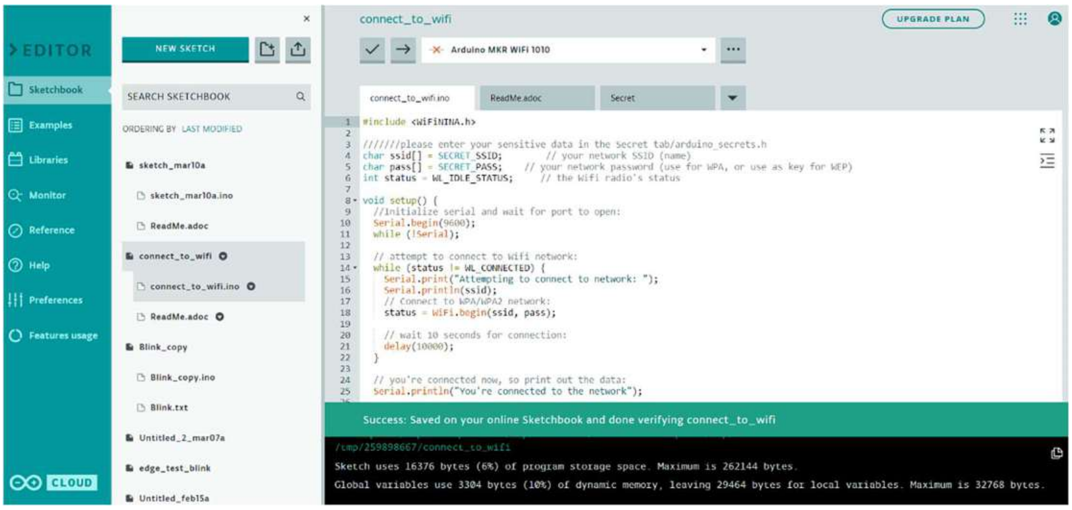

Figure 16: Interface of the Arduino web editor; https://create.arduino.cc/editor

Eventually the dashboard can be set up. It can give an overview of the status of several sensors, be it simple values or more graphical gauges showing the extreme values is a matter of taste. Important is that these values, given a stable internet connection, can be monitored in almost real time. With the Entry level plan one request per second can be realised and shown on the dashboard. For monitoring the conditions in the lab this is sufficient. Furthermore, switches can also be installed which allows for manual control over the different devices. If a person left the lights on in a spawn run phase after checking for pinning, remotely the light can be turned off. This is not a trivia function since early lighting can lead to premature pinning in the substrate which can lead to a reduced harvest. The dashboard can be designed freely by changing the size and position of each widget. Two versions can be defined, one for the big screen and one for a mobile device.

Once the layout is defined, each widget can be linked to a variable being represented in the code. The Entry level plan allows for ten variables and therefor ten widgets representing measured values or functions. Automatically these variables

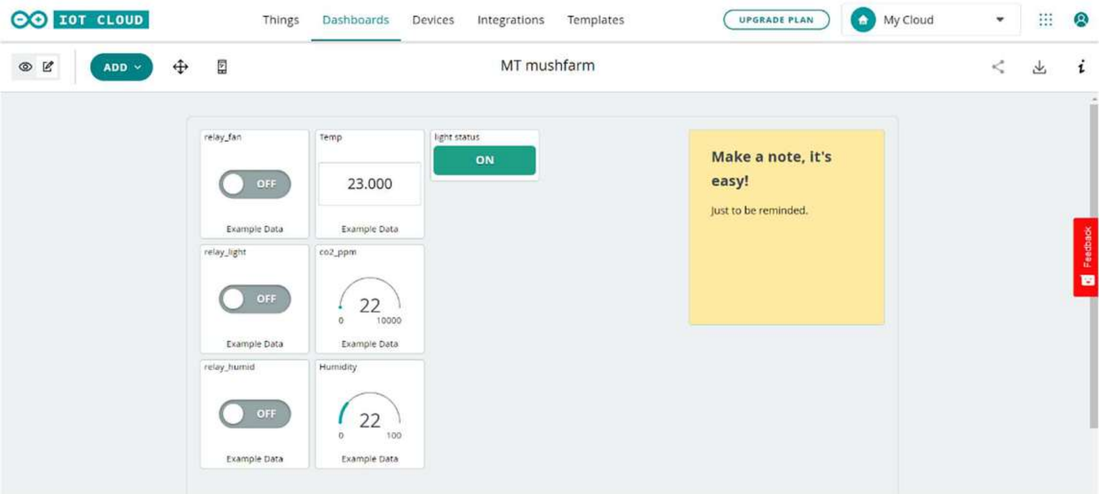

Figure 17: Arduino IoT Dashboard; https://create.arduino.cc/iot/dashboards

Eventually, to be able to cover an operation illustrated above, with six chambers running at full production capacity, each chamber will be its own thing in the cloud. Therefore, the Entry plan will not be sufficient anymore because it does not offer the number of variables needed. Here it is the Maker plan that offers enough capacity for six dollars per month – still a rather cheap cost for the potential it offers. It includes twenty-five things and data storage for ninety days.

5.3. Business

To be able to estimate if a mushroom start-up makes also economic sense, this chapter will deal with the numbers behind such an operation. To better understand the dynamics, I want to show the costs and revenues of a single chamber and extrapolate the costs and revenues for a potential full-scale operation within the boundary conditions of the farm. The boundary conditions which are the most difficult to change are the available spaces. The availability of electricity and water could potentially be increased with relatively little effort and investment. Building another barn would be a significantly higher expense.

Machines and devices as well as consumables like the growing bags and raw materials need to be considered for calculating the business. An inventory with actual prices will give an overview of the costs to get started and builds a base for the calculation of the ROI, with the market research providing the current sales prizes of gourmet mushrooms. Eventually a view on marketing will close this chapter.

5.3.1. Inventory

In Austria, farmers are under a special tax scheme. They pay a flat tax based on the fictional productivity of the farm based on what kind of land it consists of, in return the whole accounting is simplified and does not require any detailed figures to be delivered to the tax office. Another simplification is that the VAT cannot be deduced and therefore investments are also done with VAT included hence also the prices shown in the inventory are all with VAT included.

For better readability the inventory is split into general inventory, inventory per automated fruiting chamber and inventory for one production cycle with the chamber fully loaded with bags and twelve shelves.

5.3.1.1. General inventory

The general inventory is shared for the whole operation and includes all the machinery and stationary devices such as workbenches, the mixer etc. It should be a one-time investment and last for years. It is also independent of how many growing chambers there are, with the only limitation being the maximum amount of substrate in sanitized bags can be produced per day. If there is a bottleneck at some point, the choice of machinery needs to be reconsidered. This kind of inventory is variable in its impact on the overall business since the more output the business has, meaning the more chambers are active and produce is sold, the more the investment is spread over the whole operation and decreases per unit sold.

Table 9: General inventory for a mushroom farm

Device	amount	€/piece	total expense
palett truck	1	1.000 €	1.000 €
big bag	6	50 €	300 €
steel barrel 213l	3	90 €	270 €
concrete mixer 180l	1	470 €	470 €
bag sealer	1	90 €	90 €
stainless steel table 200x60	2	240 €	480 €
fan-filter unit H14, 116cm	1	1.160 €	1.160 €
ductwork 100mm	50	9 €	450 €
steam generator	1	1.800 €	1800 €
			6.020 €

5.3.1.2. Inventory per fruiting chamber

The Inventory per growing chamber is different in its nature. It has a fixed cost once the system is tuned to perfection and can be replicated, in theory, endlessly. The investment is linear, and so is the ROI per chamber.

Table 10: Inventory for one fruiting chamber

Device	amount	€/piece	total expense
grow tent 300x300	1	500 €	500 €
shelves	12	80 €	960 €
blower 350m^3/h	1	70 €	70 €
Arduino edge control	1	220 €	220 €
CO2 sensor	1	57 €	57 €
Arduino MKR WiFi 1010	1	34 €	34 €
Grove relay	3	3 €	9 €
Arduino MKR ENV shield	1	36 €	36 €
Light sensor	1	6 €	6 €
Humidifier	1	200 €	200 €
			2.092 €

5.3.1.3. Inventory per grow cycle

A recurring inventory and therefor cost is the material needed for setting up one grow cycle. It simply consists of bags, substrate, and spawn (which for this example will be bought from a provider) as well as the energy costs for running the cycle. In this context, the time for the spawn run is crucial. The electricity needed can at this stage only be estimated but certainly plays a role given the cycle time of several weeks. The situation at the farmlab.at is favourable since there is an array of in total 8kWp photovoltaic panels on the roof of the barn.

Table 11: Inventory to start one grow cycle

Device	amount	€/piece	total expense
grow bag	240	0,5 €	120,0 €
spawn	12	10,0 €	120,0 €
substrate	1200	0,2 €	240,0 €
			480,0 €

5.3.2. Investment

The most basic setup for starting a mushroom farm (not to confuse with home growing for domestic use only) consists of a series of machines and infrastructure as we have seen above. These Investments have been done at the farm in the last years, meaning some of the machinery and equipment is already present.

Nevertheless, to be able to produce efficiently and with high quality, some changes in the distribution of spaces will be needed. Especially putting in some flooring and probably later on if the business is gaining traction, some of the rooms could be insulated to safe expenses for energy and/or be less dependent on seasonal temperatures. This would allow to produce the most valuable mushrooms all year around.

5.3.3. Market research

Different ways of selling the produce have certain advantages and disadvantages.

The supposedly easiest way is to sell the entire production to a supermarket chain. This would require a high volume and tight delivery times. After investigating the retail prices at Spar and Billa supermarkets in Vienna, organic oyster mushrooms cost around 20€ per kilogram. Given hat the supermarket also has a margin on the produce as well as the producer, the only way of making a substantial profit is through high volumes. This might be not a valid option for small producers or start-ups though.

The second case study was at the Pilzhof Gross in Kapfenstein. Apart from delivering gourmet mushrooms to local shops and restaurants, they sell straight to the customers in their little shop alongside other products. One kilogram of Oyster mushrooms sells for 16€. For the calculations of the farmlab.at, 15€ will be a good base for a conservative estimate.

5.3.4. Personnel

At full scale, this is for sure not a one-man-show anymore. Traditionally, running a small farm is a family business where everyone is helping together to get the produce from the raw materials to the market. At the farmlab.at this would be no option now; therefor external help would be needed to cover all the tasks. Since the work is not necessarily in need for high skills but rather experience, the model of Bolet ben fet Farm could be interesting. There, the company is offering jobs for handicapped workers or long term unemployed, giving them a chance to also take over responsibilities for harvesting or inoculation for example. Even though the work can be very repetitive, it is also rewarding to see something grow so fast. Workers should be motivated to do this job in general, particularly because the scope of the operation should allow for full transparency for the customers. This makes the working conditions and the social mission a part of the project.

5.3.5. Marketing

To be able to sell the mushrooms, marketing will be essential. Different actions and media will be needed to make potential customers aware of the possibilities to buy excellent mushrooms.

- **Word of mouth** – this is the most basic form of marketing and very effective. Starting with family and friends, giving them samples to try and tips on how to prepare the fresh produce is step one. Another key information is how to store mushrooms properly. People need to feel comfortable to spend more than they are used t when buying classic Champignons.
- **Website** – the above-mentioned information, alongside standard information such as address, contact details and a map, will be provided on a website. Customers need to be able to read up on the recipes but also it is easy to share with friends.

- **Social media** – for providing transparency and show customers how their mushrooms are being grown, pictures and social media content is essential to invite them to participate in the process, from mixing the substrate to selling the mushrooms.
- **Logo** – every business needs a logo. The farmlab.at has a logo already which can be adapted and speak for the mushroom part of the overall project.

5.3.6. ROI

Based on the inventory in chapter 5.3.1, the total investment for one growing chamber is around €8.600. To be on the safe side, adding 15% for unexpected changes or price increases, makes an investment of roughly €10.000 for getting the general equipment, one fully equipped grow chamber and the material for starting one grow cycle at maximum capacity.

The ratio of substrate to mushroom harvest is around 5:1, five litres of substrate produce on kilogram of mushrooms (Cotter, 2018, 106). Based on the market prices from the previous chapter, the ratio of substrate to mushroom and the inventory figures, the investment is covered by already three full grow cycles. This is a conservative calculation, considering that one bag of substrate can fruit up to three times, which shows that there is a good business opportunity.

Table 12: Calculation of return on investment

General inventory	6.020 €
Inventory per fruiting chamber	2.092 €
Material per grow cycle	480 €
safety expenses 15%	1.289 €

Initial setup costs	**9.881 €**

240 bags of 5 l substrate	1200 l
1 kg of mushrooms per 5 l	240 kg
15€ per kg of Oyster mushroom	**3.600 €**

ROI	**3 cycles**

5.4. Summary

Growing mushrooms can be quite straight forward and easy to start. Basic principles of hygiene need to be taken seriously but it is possible to get started in the kitchen and/or bathroom of a flat in the centre of a metropolis. This would be the sufficient scale for providing enough mushrooms for a small family, grown on food waste such as coffee grinds to give an example. Mushroom farming can be a quite complex business though when it is scaled up.

When it is scaled up and thought to be a rewarding business the requirements become stricter, not only in materials handling and hygiene but also in terms of space and investment in infrastructure and machinery needed. Space is a key factor when it comes to commercial growing of gourmet mushrooms for two main reasons. For one, enough volume must be produced of course to have enough turnover for making a living. Secondly, the different spaces, used in the correct sequence, prohibit unwanted organisms such as bacteria or other fungal species and moulds from contaminating the substrate. Contaminated substrate is not only a loss in materials but also in time and therefore cost. In extreme cases, when production and demand are equal, customer's needs cannot be satisfied, and the resulting lack of reliability might lead to the loss of clients and bring the business into troubled waters.

The different spaces need to be connected and each of them must meet certain requirements when it comes to climatic parameters, size for hosting equipment, free space for workers to move around fluidly to not waste time and resources and of course in terms of hygiene. At the beginning of the process, hygiene is not a big issue. Raw materials coming from a sawmill, or a farm will be hosting already myriads of unwanted organisms of all different kinds and biological kingdoms. Nevertheless, the right storage conditions must be respected and provided. Further on in the process the hygiene aspect is becoming more and more important, with the laboratory and inoculation room being the most critical. Here the mycelium will be mixed in with sterilized substrate and any contamination could be a threat to the business as mentioned above. The space itself as well as strict protocols can reduce the risk of contamination significantly.

In the final stage of the growing process, in the grow chambers, hygiene is very important of course but here the bags or buckets with the inoculated substrate are sealed and have a fabric for gas exchange. This fabric is fine enough to keep contaminants out of the container. The crucial and most critical aspect here is to provide the right conditions at the right moment to make the development of the mycelium as fast as possible. When it is time for opening the bags for the fruiting stage, the climatic conditions and the composition of the atmosphere must dramatically change. These conditions are different for each variety of mushrooms and ideally each chamber is technically equipped for providing these changes in a controlled manner. With easy to program microcontroller boards such as Arduino, in combination with sensors and ventilation this kind of control could be reached. For monitoring the conditions remotely, Arduino provides cloud services. This service can be used to collect the data, illustrate it, and store it for later use and comparison. Furthermore, the IoT platform allows the user to remotely control all the connected devices. This kind of control can increase efficiency and security o the operation, with the right illustrations on the dashboard, the current state of the different growing chambers can be monitored, and human error can be limited. Eventually the produce h to be handled, sorting, packaging, and cooling are important steps before the mushrooms can go on sale.

The business is the critical part. As in every venture an investment must be made to set it up. Depending on the dimensions of the operation several calculations must be made to check whether the business can be profitable before going out to investors or taking out a loan for purchasing the necessary equipment.

In this scenario, necessary equipment has been listed with approximate prizes based on online shops. With this base of information, the general investment in machines, the investment for each growing chamber and the investment for starting a growing cycle have been separately calculated. Together with the market research, where producers have been mapped and retail prices checked to compare the investment with the sales of production. This allows to see on which scale the return on investment can be reached and when. With the capacity of each chamber being able to produce around 240kg per grow cycle, an investment of about 10.000€ and a sales price of 15€ it would take around three cycles to reach the ROI. Including marketing and expenses such as transport, 4 cycles are more realistic.

6. Conclusion

Farming mushrooms in general is a very interesting activity which can, on a small scale, produce a fresh, healthy, and environmentally sound source for protein which is not involving the intense raising of livestock under questionable conditions. On top of that, it can be educative, learning how to handle a laboratory and work under clean conditions with fascinating biology. More and more people are tapping into the growing of mushrooms and are happily sharing their results in social media for others to learn. This abundance of resources can be very tempting for adventurous minds and generate satisfaction and delicious produce very quickly. If done right, within a few weeks one can prepare a delicious meal. The availability of specific information online is a vast resource and online-traders are offering everything needed to start growing.

When it comes to growing mushrooms on a big scale for commercial reasons everything needs to be scaled up but already on a relatively small scale it can become very productive and generate an income. The boundary conditions at the farmlab.at would theoretically allow for an intense setup, generating sufficient income for a family to live comfortably. Theoretically, for two main reasons. For one the competition has a head start already, meaning experience in growing and handling but also in terms of marketing and growing a sound customer base in the pandemic years. In the recent years a couple of growers appeared on the map in the area. The second main reason is that big companies see a potential in growing gourmet mushrooms on a big scale to be able to deliver to big supermarket chains for a reasonable prize. If the choice for the customer was to buy the cheap industrial champignons or to buy extraordinary mushrooms from the small grower in the region there was a good opportunity for farmers to tap into a great income stream with relatively little effort.

Mushrooms can be produced in many ways. From outdoor cultivation in beds to inoculating logs of hardwood trees to growing in sealed containers like plastic bags or bottles and buckets. If there is sufficient space available, production can be moved into special tent like structures indoors which can provide sufficient levels of hygiene for commercial production. Hygiene is the key factor for an efficient production without the loss of material, time, and money due to contamination in the substrate. For limiting this danger, for indoor cultivation the use of bags or bottles is the safest way to approach a mushroom business. Before getting to this point though, the right substrate for the chosen mushroom species must be prepared and filled into containers. These containers, provided by specialised traders, can be sanitized either in a steaming process at low temperatures (around 80°C) or at high temperatures (121°C) in an autoclave under pressure (above one bar). This is the critical phase, a separate room equipped with a HEPA filter laminar flow unit on a sterile workbench provides the right conditions for inoculating the containers without contamination.

When it comes to automation, Arduino offers an opportunity to work with a big community which is very helpful for saving in investment. On top on saving money, the generated knowledge about the technology allows an individual or a start up to keep control over the implemented technology. This has the potential to limit further recurring costs for service technicians once a problem appears, because errors can be fixed alone. The learning curve can be steep but for a person with some technical skills and some time there is no problem to realize even complex systems. These systems can start simply but being open for customization, can grow in complexity and functionality over time and according to the needs of the mushroom farmer. The community not only offers help but also shares projects with step-by-step explanations which can be easily replicated and implemented. The open-source availability allows the user also to get deeper into the technology and the basic functions which allows for the total customization according to the needs of the project. This high degree of autonomy is not only economically interesting for a small business but in a bigger picture can contribute to a higher resilience of the food production system overall. At a certain point, here undefined since it would wonder too far off the purpose of this theses and depends very much on the resources and technical skill of the business constellation, outsourcing he maintenance and configuration of the control system does make probably sense. Unless this open approach to control hardware and software could justify the hiring of a skilled person to focus just on that. With the Arduino IoT cloud platform, remote access to and control over the devices is a great asset too. Not only can troubleshooting be done remotely but also data can be received in almost real time depending on the prizing chosen. For growing mushrooms real time data is probably not even necessary, what is more important is the number of variables a project can cover (as in the above example three relays, humidity, CO_2 and light sensor status and values) and how many projects can be run in parallel.

Automation in this context for this kind of project cannot stop at the climate control level in the fruiting chambers. Also, on the hardware side there is a huge potential to at least semi-automate certain steps in the process. One could be a filling device for the bags, a version of a rotary valve for example could be constructed in a relatively simple way. This would speed up the filling and reduce strain on the worker. Furthermore, it could increase the precision of the amount of substrate filled into the bags, streamlining the process.

To further increase efficiency, the spatial distribution of tasks and functions plays a big role to have a lean process from sourcing and storing materials, to bagging, steaming, and handling to harvesting, sorting, and storing. Each of these steps can be made more efficient with low tech open-source hardware. Also, a venture into machine learning combined with computer vision based on Arduino Pro modules like the Nicla Vision board could be a method to speed up the sorting process for example. A camera above the sorting table can recognise the mushrooms spread out and the table and, on a screen, they could be marked according to size. The machine learning part would make the whole process more accurate over time again saving time and increasing productivity. This is just to illustrate the vast range of possibilities Arduino could offer for an open-source farming model. The ease of use of digital tools, and microcontrollers based on open-source hardware is ever increasing. Arduino especially has been growing immensely over the last years and they are offering increasingly versatile tools for automation. The release of the Pro boards is another leap, getting more specific in the use cases and harnessing the latest technological developments such as AI and computer vision to bring them closer to the citizen rather than being a black box only highly specialized and equipped personnel can handle. This development allows for grassroots ventures into the combination of our daily lives with technological enhancements and is not only geared towards industry 4.0 but rather the citizen 4.0.

Economically, this kind of venture makes sense. Even though the hype around mushrooms has already attracted several people to venture into this direction, the potential of mycelium in a broader sense, not only for food, is holding immense potential. Gourmet mushrooms are just the most obvious market but there are people and initiatives as well as high level research institutions such as the Fraunhofer institute and various Universities who are researching the use of mushroom mycelium as a future material for construction or industrial design. Also, the medical potentials still need to be researched thoroughly, be it for treating mental health issues or other serious conditions. Not to forget, there is a market for supplements, powders or tinctures made of medicinal mushrooms, which seems to be gaining traction.

For making a case the calculations in this paper show the huge potential of mushroom production in economic terms even with the most straight forward approach of classic food production. Using the production of edible mushrooms to finance further research of other applications could be the most interesting way to break out of a battle with emerging big producers. It seems to be early enough to get into the market although it is more difficult than pre-covid. In any case, at the farmlab.at the space is available which would be the biggest investment. This makes the other investment into equipment relatively small in comparison therefor the risk is extremely limited. The ROI could be theoretically reached after selling the production of roughly four fully equipped grow chambers. In order to not have to focus on the full stack from sourcing to production to sales and marketing, a collaboration with other growers might be an option, joining forces in a cooperative way. In the long run, mycelium as a material seems to be niche enough to make it interesting for being an early adopter while having the economic base covered.

In chapter 5.3., it is clearly demonstrated, that comparing different modules for production and then choosing to invest a bit more is a crucial step in general and pays off later. Maximizing the use of the most expensive asset, space, is an important step for maximizing profits. The tents are also allowing for a scaling up of the production according to the needs rather than building fixed chambers. This system keeps a certain flexibility built into the process.

For the mushroom project at the farmlab.at, prototyping and experimenting will continue.

7. Bibliography

7.1. Agriculture

Hartman, Ben; *The Lean Farm – How to minimize waste, increase efficiency, and maximize value and profits with less work;* Chelsea Green Publishing 2018

European Commission, Directorate-General for Agriculture and Rural Development, Peyraud, J., MacLeod, M., *Future of EU livestock: How to contribute to a sustainable agricultural sector ?* : final report, Publications Office, 2020, https://data.europa.eu/doi/10.2762/3440

OECD

https://www.oecd-ilibrary.org/sites/19428846-en/index.html?itemId=/content/publication/19428846-en (17. 12. 2021)

Statistik Austria, Hg., Eva Krall, *Statistik der Landwirtschaft 2020,* Verlag Österreich GmbH, 2020

Statista.de, https://de.statista.com/statistik/daten/studie/503929/umfrage/umfrage-zu-essgewohnheiten-in-oesterreich/

FAO https://www.fao.org/science-technology-and-innovation/innovation/en

7.2. Mushrooms

Stamets, Paul, *Growing gourmet and medicinal mushrooms*, Ten Speed Press; 3rd edition (25 Oct. 2000)

Cotter, Tradd, *Organic Mushroom Farming and Mycoremediation: Simple to Advanced and Experimental Techniques for Indoor and Outdoor Cultivation*, Chelsea Green Publishing (9 May 2015)

Goldscheider, Stefanie; *Speisepilze selbst anbauen – für drinnen und draußen;* blv Buchverlag 2018

Sheldrake, Merlin, *Entangled life, How fungi make our worlds, change our minds and shape our future*. Random House 2021

Fraunhofer Institute, https://www.iap.fraunhofer.de/de/Projekte/Biomaterialen-aus-Pilzmyzel.html

7.3. News

Porombka, Stephan, *Wood Wide Web*, NZZ 2014

OÖ-Nachrichten; https://www.nachrichten.at/wirtschaft/Neuburger-Rieseninvestition-abseits-vom-Leberkaese;art15,2432081

7.4. Programming/Arduino/IoT

Natheem, Arsath, *Handbook of Arduino: 100+ Arduino Projects learn by doing practical guides for beginners and inventors*. Independently published (5 Nov. 2021)

Thorpe, Nathan, *Arduino: Advanced Methods and Strategies of Using Arduino*, independently published (13 Feb. 2020)

Kofler, Michael; Kühnast, Charly; Scherbeck, Christoph; *Raspberry Pi: Das umfassende Handbuch. Über 1.000 Seiten in Farbe. Mit Einstieg in Linux, Python und Elektrotechnik*. Aktuell zum Raspberry Pi 4, Rheinwerk Computing; 7th edition (30 Jun. 2021)

Kühnel, Klaus; *Arduino: Das umfassende Handbuch*; Rheinwerk Computing; 1st Edition (28 Sept. 2020)

Singh, Rajesh; *Iot-based Projects: Realisation with Raspberry Pi, NodeMCU and Arduino*; BPB Publications (13 Feb. 2020)

Brasseur, VM (Vicky); *Forge your future with Open Source*; The Pragmatic Programmers 2018

Arduino Website; https://docs.arduino.cc/

7.5. Prototyping

Pearce, Joshua M., Open-Source Lab: How to Build Your Own Hardware and Reduce Research Costs, Elsevier; New edition (17 Dec. 2013)

List of abbreviations

- AEC Arduino Edge Control
- EU European Union
- GHG Greenhouse Gas
- IoT Internet of Things
- ROI Return on investment

List of figures/charts/diagrams

Appendix

GroCycle – Low tech mushroom farming

https://www.youtube.com/channel/UC-jOgJRKA9vHnSVR8Oe_wbA

Southwest Mushrooms

https://www.youtube.com/c/SouthwestMushrooms

The Humble Fungus

https://www.youtube.com/c/TheHumbleFungus

Oak and Spore Mushroom Farm

https://www.youtube.com/c/OakandSporeMushroomFarm

Blueprints of steam generator:

https://www.oakandspore.co.nz/collections/all-products/products/steam-generator-blueprint