FACULTY OF AGRICULTURAL AND ENVIRONMENTAL SCIENCES
DEPARTMENT OF BIORESOURCES ENGINEERING
BREE 495 - ENGINEERING DESIGN III

Controlling Development Conditions for Vertical Mushroom Cultivation Using Automated Growth Chamber

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1. INTRODUCTION

As the global population continues to rise, the demand for food is ever-increasing. By 2050, the world population is projected to reach approximately 9.7 billion. (Benke & Tomkins, 2017) Additionally, the population is accumulating more wealth, resulting in the tendency to eat more. It has been estimated that more food will need to be produced in the next 35 years than all the food that has ever been produced in human history (*The Challenge,* n.d.). As a result, pressure on agricultural production to generate larger yields will continue to increase to properly respond to global demand (Beacham et al., 2019). The limiting factor to this expansion is that the agricultural sector is facing many challenges. Amongst various other factors, land degradation, climate change, and water usage are highly prominent issues. As populations continue to exploit land with conventional agriculture, the reality of these challenges is becoming evermore pertinent.

In order to overcome the aforementioned challenges and provide sustainable food production, humans must find efficient, new ways to reinvent these techniques. Controlled environment agriculture (CEA) is a concept that has been gaining more interest that could help tackle the current and future challenges associated with conventional agriculture. CEA's are systems in which crops are grown with specific aspects of their environment controlled in order to reduce pests, increase efficiency, sustainability, yield, and cost savings (Autogrow, 2020). Furthermore, CEA can provide more localized food production in urban centers where the majority of the population is moving, lowering the transportation costs associated with traditional farming (Engler & Krarti, 2021).

Growing gourmet mushrooms with CEA is becoming more attractive since they require less growing materials, water, and energy than other crops. In general, mushrooms are gaining popularity and different varieties can be found in more of today's grocery stores and markets. This can be attributed to their large variety of nutrients and other natural phytochemicals that contain a large range of nutritional and health benefits (Cheung, 2010). Additionally, there are many different types of mushrooms, each of them having varying texture and flavor profiles. Due to their various health benefits and flavor profiles, the global mushroom market is expected to increase at a compound annual growth rate of 9.7% from 2022 to 2030 (*Mushroom Market*, n.d).

A Canadian start-up company, Adapt AgTech, is currently vertically farming 6 different mushroom strains in recycled shipping containers using CEA technology and plans to grow up to 14 different strains in the near future. The company has been experiencing issues with respect to some of their mushrooms' growth. For example, their pink oyster mushroom strain is reportedly growing discolored. Although pink oysters prefer a warmer climate compared to the other strains, they are all grown in the same container. It is for this reason they are not being grown optimally in their ideal environment. This results in a lower-quality mushroom that may not be able to be sold to restaurants, grocery stores, and markets.

The goal of this project is to devise a solution to growing multiple mushroom strains optimally in one area to produce high-quality mushrooms, using Adapt AgTech as a case study. This will be achieved by designing a growth chamber that will have its own microenvironment that is ideal for the type of mushroom growing inside of it. With the implementation of this design, if some mushrooms are observed to be growing poorly, for example their stems are too long or they appear discolored, the environmental conditions inside the chamber can be adjusted on the spot to properly adapt.

2. DESIGN CONSTRAINTS

Before beginning to design the growth chamber, it is crucial to establish the constraints we must design around. Using Adapt AgTech as our case study, we must consider the size of the shipping container our growth chambers will be in and the optimal environmental conditions of each type of mushroom being grown.

2.1 Size of Growth Chamber

We used the vertical farm mushroom shipping container from the company Adapt AgTech as a case study for our system. The goal is to incorporate a growth chamber on each shelving section shown in Figure 1. Therefore, one of the constraints for our system is the size of the growth chamber, as we aim to fit multiple within a shipping container farm. From the size of the shelving in Adapt AgTech's container, it is concluded that the growth chambers must be approximately 137.16 cm wide, 60.96 cm long, and 60.96 cm tall, as seen in Figure 2.

Figure 1: Adapt AgTech's vertical farm container layout

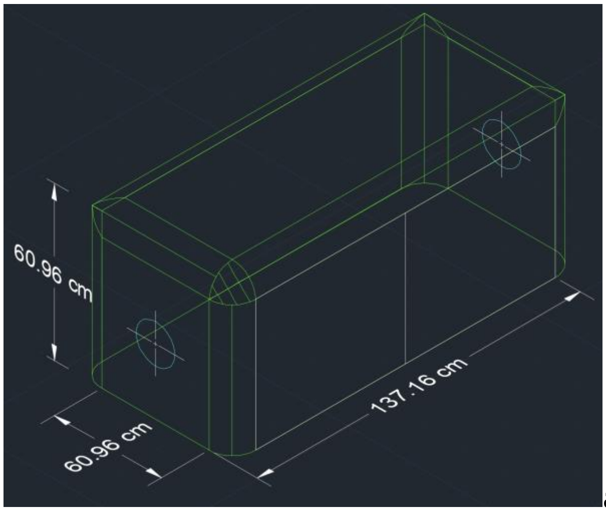

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Figure 2: Basic dimensions of unit growth chamber (SI Units)

2.2 Range of Environmental Conditions

The design must be able to support the growth of different types of gourmet mushrooms at various growth stages. The growth parameters of the mushrooms currently grown by Adapt have been identified in Tables 1, 2, and 3 below. The tables include parameters for the distinct growing stages of Pink Oyster, Lion’s Mane, Chestnut, King Oyster, Shiitake, and Maitake mushrooms. This data will be necessary for determining the approximate ranges of temperature, humidity, CO_2 levels, and lighting necessary for the growth chamber to accommodate.

Table 1. Optimal Growing conditions for each mushroom type grown during the <u>spawn run</u> in the container based on literature (Stamets, 2000).

	Incubation Temperature (°C)	Humidity	CO_2 Levels (ppm)	Lighting (lux)
Pink Oyster	24-30	95-100%	>5,000	n/a
Lion’s Mane	21-24	95-100%	5,000-40,000	n/a
Chestnut	21-24	95-100%	>10,000	n/a
King Oyster	24	90-95%	5,000-20,000	n/a
Shiitake	21-27	95%-100%	>10,000	50-100
Maitake	21-24	95%	20,000-40,000	n/a

Table 2. Optimal Growing conditions for each mushroom type grown during the pinning stage in the container based on literature (Stamets, 2000)

	Initiation Temperature (°C)	Humidity	CO_2 Levels (ppm)	Lighting (lux)
Pink Oyster	18-25	95-100%	500-1,000	750-1,500
Lion's Mane	10-15.6	95-100%	500-700	500-1,000
Chestnut	10-16	98-100%	1,000-2,000	100-200
King Oyster	10-15	95-100%	500-1,000	500-1,000
Shiitake	10-16	95-100%	<1,000	500-2,000
Maitake	10-15.6	95%	2,000-5,000	100-500

Table 3. Optimal Growing conditions for each mushroom type grown during the fruiting stage in the container based on literature (Stamets, 2000)

	Temperature (°C)	Humidity	CO_2 Levels (ppm)	Lighting (lux)
Pink Oyster	20-30	85-90%	500-1,500	750-1,500
Lion's Mane	18-24	85-95%	500-1,000	500-1,000
Chestnut	10-16	90-95%	1,000-5,000	100-200
King Oyster	15-21	85-90%	<2000	500-1,000
Shiitake	16-18	60-80%	<1,000	500-2,000
Maitake	13-16	75-85%	<1,000	500-1,000

From the literature represented in Tables 1, 2 and 3, the range of environmental conditions the growth chamber must attain are:

- Temperature range: 10-30 °C
- Humidity range: 60-100%
- CO_2 levels: 500-40,000 ppm
- Light range: 50-2,000 lux

3. DESIGN PARAMETERS

As with the cultivation of most plants, mushroom growth has specific environmental requirements which must be met to achieve the desired product. Additionally, the consideration of the container's dimensions add required constraints to the design process. This section is a review of different ways we can achieve the desired conditions of temperature, humidity, CO_2 levels, and lighting, as well as an analysis to incorporate the best materials and sensors for the chamber.

3.1 Temperature

The ideal temperature for mushroom growth is dependent on the variety of mushrooms being grown and their specific growth stage. Growing mushrooms at temperatures too high or too low can have negative impacts on their growth. If the temperature and humidity are above the desired range, the fruiting bodies of the mushrooms can develop lighter-colored caps that have a depression in the middle. If the temperature is high and the humidity is low, the caps will become thin, brittle, and umbrella-shaped with a thick mushroom stem. On the contrary, low temperature with high humidity leads to strong color and fruiting bodies. However, under these conditions the fruiting bodies grow slowly and fewer are produced. Additionally, a combination of low temperature and low humidity levels will cause a darker cap and thick stems, again with fewer fruiting bodies. It is notable to mention that with elevated levels of temperature there is potential for microorganism growth on the substrate. Furthermore, it has been observed that when temperatures exceed 30°C, green molds can multiply on the substrate before the mycelia begins to grow, subsequently inhibiting the growth of mushroom mycelia (Wan Mahari et al., 2020).

The growth chamber must be able to reach optimal temperatures for various types of gourmet mushrooms. From the design constraints section above, we concluded that the growth chamber must be able to reach temperatures ranging from 10°C to 30°C in order to accommodate all of the previously listed mushroom types at varying growth stages.

Different options:

1. Heating system: With only a heating system, the temperature of the shipping container our system will be placed in must be set to 10°C at all times in order to reach all possible desired temperatures. With this option, the growth chamber would have an incorporated heater.

2. Cooling system: With only a cooling system, the temperature of the container will have to be set at 30°C at all times to reach all desired temperatures. With this option, the growth chamber would have an incorporated air conditioner.

3. Heating and cooling system: With both systems, the container's environment will be kept at a temperature between 10°C to 30°C and the growth chambers will be either heated or cooled depending on the growing stage and mushroom strain. With this option, the growth chamber would have to have an incorporated heater and cooling system.

Having both a heating and cooling system would increase the number of parts as well as require a lot of room in a rather confined space. Secondly, most air conditioning units are also relatively large therefore it is difficult to find an air conditioner that would fit inside the growth chamber. Upon assessing the three alternatives, a heating system presents the most efficient solution to achieving the desired temperature inside our growth chamber. Therefore, the container will be kept at 10°C and the growth chambers inside will each have their own heating system that heats according to the optimal temperature needed by the specific mushroom being grown inside. The following step is to determine the type of heating system our design will utilize.

Heating options:

1. Space Heater:
   These heaters are one of the most common types of home heaters. There are different types of space heaters, though the two that will be considered are electric space heaters and infrared space heaters. Infrared heaters emit heat that directly warms objects while electric heaters heat up the air. For this reason, infrared heaters tend to be more efficient as they provide instant warmth without needing to heat the whole space. Therefore, they could provide heat to the mushrooms quickly and efficiently. The downside of space heaters is that they tend to be fairly large units that would take up a large amount of space inside the box, which is a major drawback for our design as space must be prioritized for the mushrooms.

2. Heating Mats:
   These are sheets of plastic that have heating elements embedded inside. The mat heats up anything that is sitting above it (Pavlis, 2021). They are mostly used to heat up plant soil to facilitate germination. Basic mats heat up to a certain set temperature while other high-end mats are coupled with a thermometer and aim to achieve a user-set temperature at all times. These mats would provide bottom heat to the mushroom substrate which can be beneficial to some species, and they can also be found in a range of different sizes. A con of heating mats is that it only heats the substrate and not the surrounding air. This can be a

problem as to ensure optimal growth and fruiting the optimal temperature range must be maintained throughout the whole chamber. Some species may benefit from having a heating mat to heat the substrate but as a standalone heat source it is not sufficient to heat the whole chamber evenly.

3. Mini air heating PTC thermistor heater element with a fan:
   These heaters use PTC ceramic heating elements that can self-regulate and result in more efficient use of energy. These fan heaters heat up the air in a space by drawing up the ambient air and using a Positive Temperature Coefficient (PTC) ceramic heating element to heat it. The air then gets redistributed throughout the space using the built-in fan. This option can help distribute the warm air inside the growth chamber more evenly and efficiently (Netatmo, n.d). This heater can maintain a consistent temperature within a specific range, but is not able to maintain an exact temperature. As shown in the literature review above, most mushrooms are happy within a range of temperatures so this should not cause problems. Additionally, this heating option usually comes in smaller and cheaper units and is considered to be safe for indoor use as they do not produce any open flames. One drawback lies in the volume of noise radiated by the fan, although a fan is necessary for our system to create airflow, so it would be efficient to have a 2-in-1 system.

Due to its small size and high efficiency, the mini air heating PTC thermistor heater element will be chosen for our design. The infrared space heater would have also been a good option but because the box is relatively small and the space heaters are larger, we decided against it. The PTC thermistor heater has a 100 mm square fan which heats the air flowing into the chamber. This is another reason we chose this option, it serves as a heater and air flow inside the chamber so less components are needed for the already small space. The controller we will install will be able to decide on its own when to switch the heater and/or fan on, as well as the speed of the fan and the power of the heater, allowing for elevated precision and control (*more details in section 3.6*). These types of heater-fans are affordable and can be found on amazon (see Figure 3).

Figure 3: 110 V Mini air heater with constant temperature insulation PTC Thermistor Heater with fan (12 V/250 W). Retrieved from: https://www.amazon.ca/dp/B07NYX5DKD

The locations of the inlet and outlet fans are an important factor to ensure correct airflow mixing throughout the tank. For our design, we are constrained to placing the fans on the sides of the box. This is due to practical limitations to ease the cleaning of the growth chamber by its users. If the ventilation were to be placed at the top, it would be impractical to perform maintenance operations on the chambers. After discovering the inlet and outlet must be placed on the side, we had to determine the best y-direction placement of the fans, meaning parallel-top inlet/outlet, parallel-bottom inlet/outlet, or diagonal inlet/outlet as depicted in Figure 4.

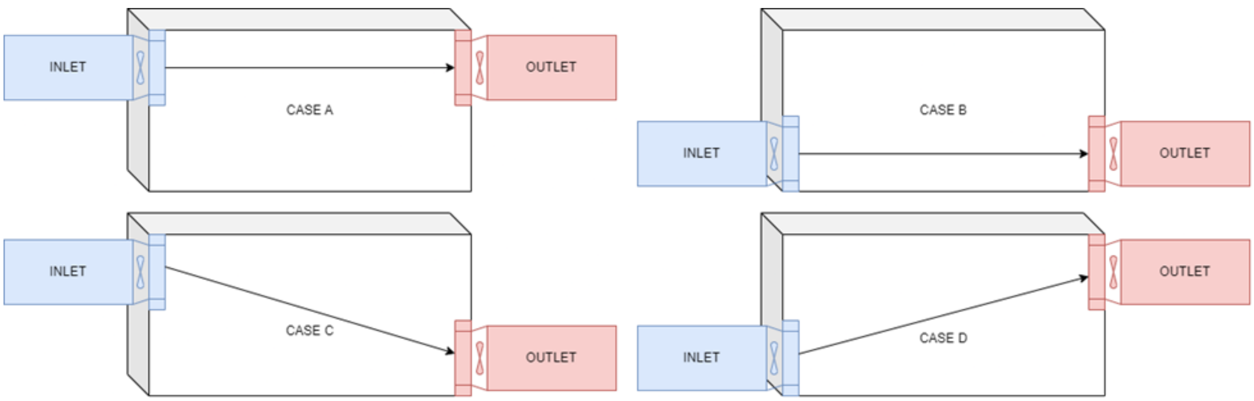

Figure 4: Possible ventilation placement solutions.

The literature suggests a more effective way of cooling a box-shaped environment is to place the outlets at the top and inlets at the bottom (Bahri & Hasini, 2018) shown in CASE D of Figure 4, and as the computational flow analysis depicts in Figure 5. Furthermore, this applies when the surrounding environment produces greater amounts of heat, resulting in the use of ventilation to expel hot air out of the system (RQS, 2020). In our case, we are attempting to bring heat into our system and expel the CO_2 produced by the mushrooms in the chamber. Since CO_2 is 1.5 times heavier than air at 20°C (Linde GmbH, 2017), the CO_2 will accumulate at the bottom. This is why a CASE C placement (inlet at the top and outlet at the bottom) for the fans appears to be most appropriate for our design.

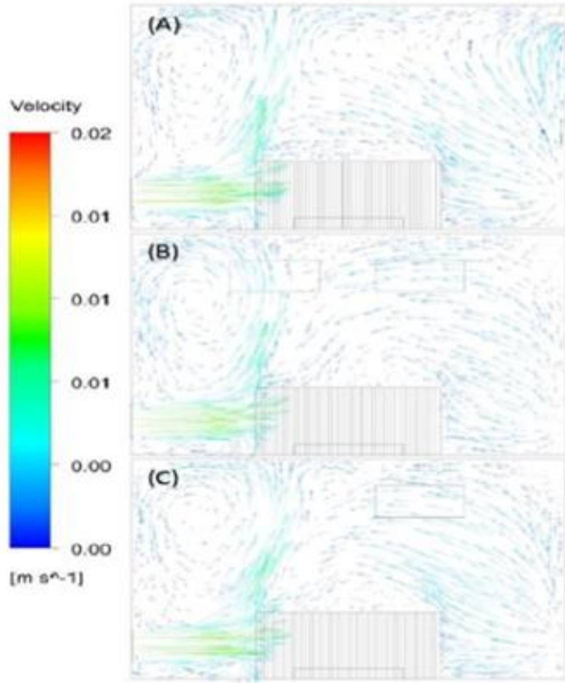

Figure 5: Air flow distribution for 3 different outlet placements. Retrieved from (Bahri & Hasini, 2018).

3.2 Humidity

Humidity is of great importance in mushroom growth considering mushrooms are composed of 80-90% water. If the relative humidity is too low, the substrate will become dry and inhibit growth. Alternatively, excess humidity may also decrease mushroom yield as it causes the condensation of water vapor on the surface of the mushrooms. This can accelerate undesired microbial growth and discoloration (Wan Mahari et al., 2020). More specific physical impacts on mushrooms from various humidity levels were mentioned in section 3.2.

We have analyzed different solutions to raise the RH inside the chamber. The first solution we thought of was a regular ultrasonic plant humidifier that would be placed inside the box, however, since space is a constraint, this would have been ineffective due to its large size.

Therefore, the ideal option would be placed outside the growth chamber to increase space. An alternative option is to utilize an ultrasonic humidifier that would blow the mist inside the box while the water tank would be on the outside. These types of humidifiers are called foggers and are usually made for reptiles. In this system, the fogger is located on the outside of the chamber and is connected to a tube that leads into the chamber. These humidifiers include an atomizer which is a small metal plate that vibrates at high frequency and causes water to break up into small droplets. This atomizer is placed at the bottom of the water reservoir. There is also a small fan located on the top of the water reservoir which is meant to help distribute mist more evenly inside the reservoir. In our design, we also want to include a float valve inside the reservoir to regulate the water level. Our reservoir will be connected to a water source to avoid having to constantly refill it, therefore as water is used up by the fogger the float valve will open up to allow more water to enter. When the water reaches a certain point, the float valve closes to prevent overfilling.

Since the fogger will not be placed directly in the chamber, a tube is needed to connect them together. One option for this is flexible plastic tubing such as PVC or polyethylene as it is lightweight, easy to work with and can be found in a range of sizes. Another option is to use a more durable material such as silicone or rubber tubing. These materials are most resistant to damage and can withstand higher exposure to temperature, though are generally more expensive. The sizing of the tube is also important as if it is too small, the flow of humid air can be restricted and if it is too large, it may allow for too much moisture or energy loss. A larger tube means a larger surface area that the humid air comes into contact with, which can cause more moisture to condense and stick to the surface of the tube, further reducing the amount of moisture reaching the chamber.

Another requirement essential for our design is the ability of the fogger to power on when it is connected to power, meaning no manual input from users. These humidifiers are known as "mechanical control" humidifiers. Essentially, the user mechanically sets a power level (low-mid-high) and whenever power is switched on, the mist will start being produced. This is essential because the mister will be switched on by the Raspberry Pi through a power on-off system.

3.3 CO_2 Levels

It is important to monitor carbon dioxide levels when growing mushrooms. During the spawn run, experts usually suggest CO_2 levels be maintained from 10,000 to 20,000 ppm. During the fruiting phase, the ideal level is 500-800 ppm. If the levels increase above 1,000 ppm mushroom yield will decrease as a result. It is especially important to monitor CO_2 levels during the pinning stage, when mushrooms initiate the fruiting process, as they pin under high levels resulting in the extension of their stems in search of oxygen. Consequently, if there is too much CO_2 the mushrooms will continue to grow longer in the pursuit of oxygen. In the early pinning stage, most varieties of mushrooms will require between 1,200 and 1,500 ppm CO_2 concentrations. If the cap is smaller than the body, there is a strong chance CO_2 concentrations are too high and legging, meaning extensive growth of the stem, is occurring. Contrarily, if the stems are found to be too short, the level of CO_2 may have been lowered too early during pin growth (*Monitoring CO_2, 2022).*

When the mushrooms are in their fruiting stages it will be most important to exhaust the CO_2-filled air. From section 2.2, it was found that the exhaust will have to be able to decrease the amount of CO_2 in the growth chamber to 500 ppm. One of the simplest and most cost effective ways to decrease the CO_2 levels is by passive ventilation. This is done by creating a hole in the chamber to allow the exchange of air. However, this method may not be sufficient to decrease the concentration to 500 ppm. Another option is by using fans to create an airflow in the chamber. An exhaust fan can be installed to pull air out of the chamber, this is usually the method used to exhaust CO_2 in larger grow rooms. Since our chamber is small, we will need an exhaust fan that is not too strong because it can lead to a decrease in humidity levels and can cause the chamber to cool down too quickly which is detrimental to the mushroom growth. Air must be exchanged approximately 6 times an hour for mushroom growth spaces (Reynders, 2020).

$$Air\ Flow\ Rate\ = Volume\ of\ Growth\ Chamber\ \times\ \#\,of\ exchanges\ per\ hour/60\ minutes$$
$$Air\ Flow\ rate = \ 18\ ft^3 \times 6\ exchanges\ per\ hour/60\ minutes$$
$$Air\ Flow\ rate = \ 1.8\ cubic\ ft\ per\ minute\ (CFM)$$

3.4 Lighting

Light is an important environmental factor for fungal species. Contrary to plants, fungi do not use light as a source of energy, but as a source of information to stimulate important metabolic pathways (Tish & Schmoll, 2010). Commonly observed effects are the induction or inhibition of sexual development and conidiation to the circadian clock resetting and the suppression of spore release (Corrochano, 2007). During the mycelia growth stage, no light is required. However, light is essential during the fruiting development stage and can affect certain mushroom characteristics like color. When mushrooms are in a dark environment, they would rather produce only stipes and not caps. Therefore, if there is an insufficient amount of light in the growing room, one can observe the production of mushrooms with small caps and long stems. However, it has been shown that excessive light can bring about mushrooms that are shorter and darker (Wan Mahari et al., 2020). Various light testing has been conducted to study fungal photoresponses. The absorption of blue light (440-470 nm) proved to significantly develop the dry-weight of fruiting bodies, up to 50% compared to traditional white light (Huang, Meng-Yuan et al., 2017). Finally, blue LED light treatments resulted in significantly higher fungi dry-weight formation than under red or white LED treatments.

We will be incorporating this knowledge into our design by installing a monochromatic blue LED light with a photoperiod of 8 hours day/16 hours night. The light intensity should be set at the specific ranges listed in Table 2 and Table 3, as the optimal range varies by mushroom strain and growth stage. The blue LED will be installed outside the growth chambers in the surrounding space of the container (see Figure 6) This is because having the LEDs inside the growth chambers would expose them to high levels of humidity which leads to their degradation and a decrease in performance (Kim et al., 2015).

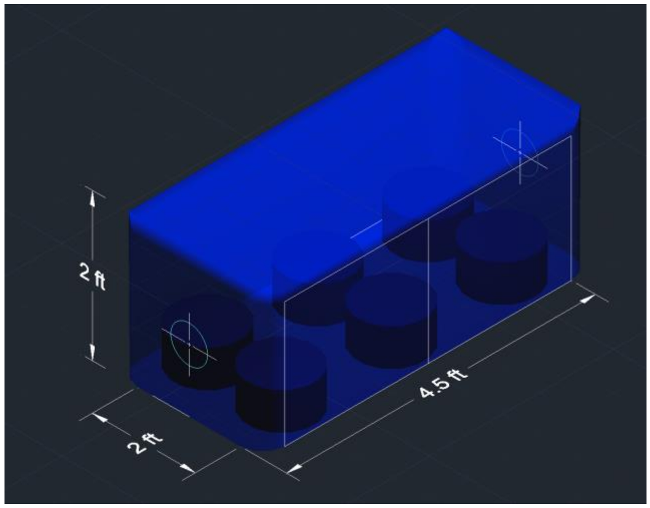

Figure 6: Realistic depiction of growth chamber under monochromatic Blue LED light. (Imperial Units)

3.5 Structural Material

The materials used to build the growth chamber were ultimately chosen based on budget, utility and life cycle assessment considerations. The structural components needed to fulfill these specific design requirements had to pass a Pugh chart screening test, and subsequently approved by the design team management. Design criteria of interest are the price, the material’s durability, its resistance to water and humidity, its weight, its impact on the environment, its ability to be modified and manufactured, its transparency, and finally its resistance to cleaning chemicals and scratches. All these criteria have been closely compared for Wood, Acrylic, Plastic, Polycarbonate, and Glass. The PUGH chart (Figure 7) indicates the most suitable material would be either plastic or acrylic. The main advantage of using PET plastic is its price, however, the box will appear less professional and of lower quality. On the other hand, acrylic is more expensive and more durable than plastic and has clear transparency which allows for light to pass through. It is also more physically aesthetic than a plastic box. Taking all of this into consideration, the material chosen for our growth chamber is Acrylic.

Problem/Situation: Box Material Selection

	Criteria	Baseline	Wood	Glass	Acrylic	Plastic (PET)	Polycarbonate	Totals	Rank
			Alternatives 1	2	3	4	5		
1	Financially affordable	2	0	−	+	+	+	2	2
2	Durable / Shock Resistant	5	+	−	0	0	0	0	5
3	Resistant to water & Humidity	5	−	+	+	+	+	3	1
4	Not too heavy	3	−	−	0	+	+	0	6
5	Environmentally Responsible / Recyclable	2	+	0	−	+	−	0	6
6	Easily manufactureable	5	+	−	+	0	+	2	2
7	Light can pass through (transparent)	5	−	0	+	0	−	-1	9
8	Resistant to cleaning chemicals + Scratches	3	−	0	0	0	0	-1	8

Figure 7: Pugh chart, for material selection

3.6 Sensors & Software

When growing mushrooms, air moisture content is a key factor in influencing growth, quality, and yield. The majority of small mushroom farms use manual spraying techniques which can be costly and is less effective at keeping relative humidity constant throughout the day (Cikarge & Arifin, 2018). With the advancements of AI and technology, new solutions that would have been very expensive in the past are now inexpensive and accessible on the market. These solutions have been proven to be very effective in maintaining optimal RH, with very few fluctuations. A very common proposed solution found in the literature is humidity automation with the help of a microcontroller (see Figure 8) (Anta, Sandra, & Hendrawan, 2021; Cikarge & Arifin, 2018; Najmurrokhman, Kusnandar, Komarudin, Daelami, & Adiputra, 2019). The projects developed in the literature all include an Arduino microcontroller setup with temp/RH sensors. The controller follows a “Fuzzy Logic” code that will activate an ultrasonic humidifier based on the sensor’s feedback. Fuzzy logic means there is more flexibility in the output than just 0 and 1, black or white, or pump on or off in our specific case. Depending on the sensor’s feedback, the output can be any real number from 0 to 1, gray and black or white levels, or the pump can be actioned at 20, 50, 70%... full power (in our case). (Anta et al., 2021; Cikarge & Arifin, 2018; Contributors to Wikimedia, 2022).

For our system, two sensors will be used for automatic parameter regulation. As our design has size constraints, we will be using the minimum amount of sensors possible to optimize space usage. Two sensors per box will be in charge of monitoring CO2 levels, temperature, humidity, and lighting. The SCD30 will be reporting CO2 concentration in ppm, the temperature in degrees Celsius, and relative humidity in %. From the SCD30 data sheet (Sensirion, 2020), SCD30 has a

± 30ppm, ±3%RH, ±0.4 °C accuracy. The TSL2561 will be measuring the light intensity at all times inside the box with a lux range of 0.1 to 40000 lux.

The association of the two sensors is crucial for our design as the system must operate autonomously and properly react to the sensors' feedback. As mentioned previously, the light requirements for mushroom growth do not need to be precisely monitored. However, it is still important to supervise the light inside each chamber in case a problem with the lighting arises. The light sensor will be in charge of determining whether the light works properly and displaying the LED intensity decrease over time. LED70 rating denotes how many hours the bulb will last before it hits 70% of its initial light offering (Eugen, 2021). This is a variable we will want to track closely in order to send an alert when it is time to change the LEDs in the system.

All of the sensors will be connected to a raspberry pi (Pi) and the analog data will be processed and converted to digital data. A wifi connection will establish the link from the Pi to a cloud remote server that will store the data and display it on an interactive Graphical User Interface (GUI). The GUI will be accessible anywhere in the world through an online website requiring authentication for added security. The server will automatically analyze the processed data from the Pi and output regulation controls to the Pi that will be in charge of activating fans, heater, and humidifier (see Figure 9). The proper mathematical regulations still need to be figured out and tested in order to reach the required user-set parameters.

A camera, depicted in Figure 8, will be added to the system to automatically generate time-lapses in order to manually supervise the chamber. This feature would be a great addition as sensors are not capable of measuring everything that happens inside the growth chamber. For instance, if a bug infestation was harming the culture, a camera could display it on the GUI and warn the supervisor to manually clean the chamber.

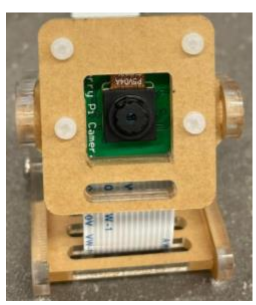

Figure 8: Freenove 5MP Camera, for monitoring mushroom growth (refer to section 5.7)

Figure 9: SCD30 sensor, for the monitoring of temperature, relative humidity, and CO_2 levels

4. SOCIAL, ENVIRONMENTAL AND ECONOMICAL CONSIDERATIONS

Food production is integral to ensure the seamless operation of any functioning society in modern times. The ever-increasing demand for gourmet mushrooms has led companies, such as our former client Adapt Agtech, to create an on-the-go vertical mushroom cultivation farm. As with any project, engineers should aim to implement the most sustainable design possible, without compromising their client's needs and objectives. Upon analysis, various factors and obstacles surface, revealing numerous complexities. As engineers, we encounter the task of constructing an efficient growth chamber, while considering the unique environmental, economic, and social concerns presented by the project.

4.1 Environmental Considerations

As the first pillar of sustainability, it is of utmost importance to ensure the environmental consequences of our growth chamber. The first aspect of consideration lies in the materials and components chosen for its construction. To achieve this, we have created a Pugh chart for the assessment of materials. As indicated in Figure 7, the material chosen was acrylic. This decision was made on the account of its durability and ability to withstand the presented conditions. Additionally, this will assure its long-lastingness while offering a sturdy, premium feel to the chamber. Choosing long-lasting materials such as acrylic allows for the reduction of waste, which will be further intensified in our decisions for other elements as well. Once the acrylic is no longer of use it can be repurposed or recycled, further intensifying the materials longevity and environmental benefits. Furthermore, our growth chamber increases the efficiency of the container as a whole by controlling environmental conditions with sensors. This would entail setting a specified temperature for the specified mushroom and reducing the amount of heat needed through the compartmentalization process. Utilizing our sensors to control relative humidity and temperature levels decreases the amount of energy input required for a mushroom farm. As well, in the selection process of all components of the box we ensured each one was as environmentally responsible as possible. This process entailed researching the longevity, recyclability, and durability of the materials, as well reading reviews from previous customers. Another element taken into consideration is the replicability of the components. In the case of failure in any electrical part or sensor, we have ensured the simplicity of the replacement process and the system remains intact. By enhancing this aspect of our design, we aim to increase its lifespan and environmental consciousness.

One negative environmental consequence lies in the production of CO_2 which is accompanied by mushroom growth. Although this is not a direct result of the construction of our design, it is notable to mention that there is an associated link.

4.2 Economic Considerations

The second pillar of sustainability refers to the economic viability of a project and its design. This was greatly considered in the Pugh chart and throughout the design process. The importance of this pillar cannot be easily disregarded as if the client concludes our design is too costly, it will be disregarded entirely. The client already has expenses to overcome, such as the cost of the mushrooms themselves. Therefore, we aim to reduce initial costs without compromising the quality of the overall design. Nonetheless, our product's goal is to solve the container's issues with efficiency to allow our product to return on the investment cost.

This product is designed around the constraints and requirements given by one company's individual circumstances, although can easily be applied elsewhere. As there is interest in the market for such designs, we can reach out to other companies as well and seek to do similar work or present the value of our automated growth chamber.

4.2.1 Cost Breakdown

The cost assessment for building the mushroom growth chamber is based on the initial prototype design production cost, and excludes labor and power tools used to produce the container. Assuming the final outcome is to be scaled twice as big as the prototype, structural materials cost should increase accordingly. Furthermore, we acknowledge that the initial model was constructed as a simple DIY (Do It Yourself), while our proposed final product should yield a more commercial-grade system resulting in higher manufacturing costs.

1. *Structural materials*

6 Polycarbonate lexan sheets 3-mm thick (including custom cuts): $243 (prototype)
2 8-ft aluminum angle bar: $35.56
9 Epoxy 25-ml tubes: $120.40

1 5-ft hollow polymer rod (window holders): $9.27
1 5-ft insulating strip: $11.35

2. *Environmental control components*

Exhaust Fan (120 mm computer fan): $10.25
Heater Fan: $32.33
Humidifier Fan: $10
Raspberry pi: $40
LED lights: $10
Mist maker: $15.90
Float Valve: $15.20
12 V Power Supply Adapter: $12.60
Camera for Raspberry Pi: $10.95
Adafruit: $16.80
Sensors Module for RH and CO_2: $71.30
Logic Level Power Converters: $10.60

Total Cost: $660.61 (before tax)

4.3 Social Considerations

The third and final pillar of sustainability refers to the social considerations necessary that accompany any given design. In a similar manner to the other pillars, this element is integral as it is of great necessity for it to be accepted by users and those affected by it. We approached this product's design with various social factors in mind at all times. Key factors include low maintenance, accessibility, maneuverability, and overall ability to use this system with ease. With the implication of remote sensing and control of the chamber's environment, we have simplified many aspects for users.

The first element we designed to ease any interaction with the opening of the box is with its doors. We designed a double door system which will slide open horizontally, saving the users space and preventing damages in a potentially already crowded environment. To prevent further hazards, we have attached rubber ends to the doors so they will not cause harm if contacted.

A crucial component in this regard is employee satisfaction. We aimed to design a chamber that requires as little interactions and complications as necessary. Through utilizing various sensors, employees are not required to service the mushrooms in any regard except for the removal of spore buildup. All environmental control elements can be performed locally on the raspberry pi, or remotely by deploying the web application.

5. PROTOTYPE

Throughout the design process, two prototypes were constructed for the growth chamber. The size of the initial prototype presented us with difficulty regulating relative humidity, temperature, and CO_2 levels within the box. However, it allowed us to achieve a better understanding of the dynamics of the combination of components we are utilizing to regulate these environmental conditions. Our final prototype can be seen in Figure 10. This prototype includes several components: a humidifier (atomizer disk, and a 12V fan), a 2 components heater (a 12v fan and a 12V 10A radiator board), an exhaust fan, an SCD30 (CO_2, Temperature and Humidity sensor), and a TSL2590 (light) sensor.

5.1 Structural & Functional Elements

After the construction of our second prototype, we now have an understanding of the functionality of the design as a whole. Numerous experiments and extensive amounts of time testing allowed us to identify parts of the design which operate better than others.

The prototype chamber casing is made of 3 mm polycarbonate Lexan sheets. The advantages of using this material include its lightweight properties, its transparency, and its resistance to the environmental conditions in which the mushrooms will be grown. The sheets were manufactured based upon design dimensions, although the width was reduced in half for the prototype design (60.96 x 60.96 cm). The side sheets have 10 cm airflow inlet/outlet circular apertures drilled to provide air circulation for preventing the buildup of carbon dioxide and ensuring the growing environment remains oxygenated. The front windows were designed to be slidable to ensure space optimization inside the grow room corridor. To construct this, two hollow polymer rods with ~3 mm slits were placed at the top and bottom ends to be bonded onto the structure with a layer of transparent epoxy glue. The quick-setting epoxy provided a strong and lasting cementing agent to permanently bond all sides of the structure and window holders, withstanding tensile strength stresses up to 4400 psi (275.8 Mpa). An insulating strip was placed around the windows to cover open spaces and assure hermetic sealing. In addition, triangular shock absorbing aluminum strips were bonded on each extremity of the box. The strips were originally 243.84 cm long, and machined cut into 60.96 cm units at the Macdonald campus Shop.

Figure 10: Full view of the growth chamber and its components

5.2 Humidifier

Located on the top left corner of the box, the second prototype of our humidifier, displayed in Figure 11, is composed of a plastic tupperware, fitted with a small fan, an atomizer, a float valve, and a piece of tubing to produce and transfer humidity. The speed and efficiency of the humidifier greatly exceeded our expectations. Although we attached an inlet to grant users the option to connect it to a water source to avoid constantly refilling manually, the recommended water level (750 mL) will last at least 6 hours before needing to be refilled. As with all components of the design, the humidifier is attached to the raspberry pi, allowing us to achieve optimal relative humidity levels within the chamber by automatically activating and deactivating the fan and the atomizer.

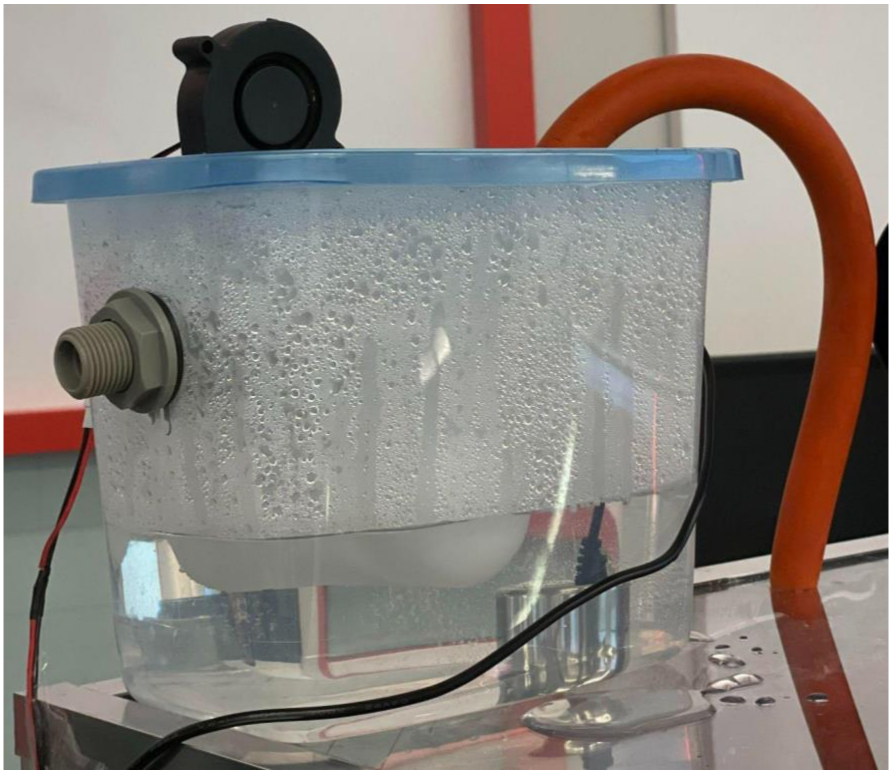

Figure 11: Humidifier, which produces and transfers humidity into box

5.3 Fan / Heater

Located on the left side of the box as displayed in Figure 12, the fan heater regulates temperature throughout. For the simplification and optimization of the electrical components, we adjusted the electrical wiring of this component to connect to a multipurpose 12v adapter and run through a relay before connecting it to the raspberry pi. This process allows us to cut electricity flow to control and deactivate it so the box may remain at the specified optimal temperatures. This component functions as expected and surpasses our initial vision, as it doubles as both a fan and a heater.

Figure 12: Outside view of fan heater, whose purpose is to regulate temperature within the chamber

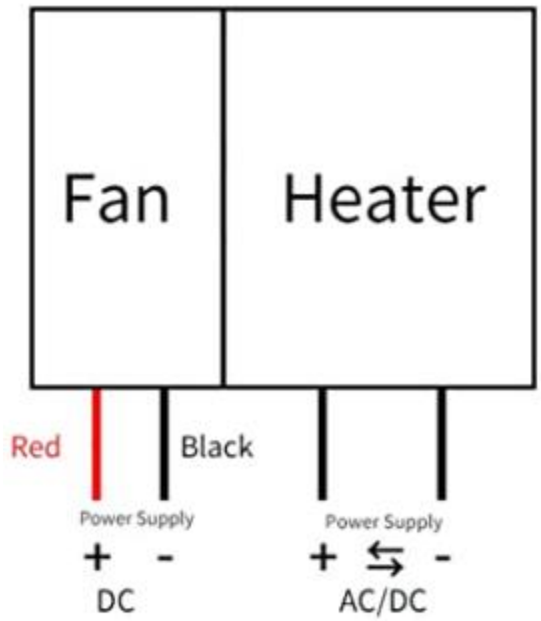

Figure 13: Schematic explaining the composition of the heater.

As displayed in Figure 13, this electrical component is made of two parts attached together, the fan and the heater. This is a very convenient way to regulate air flow and temperature simultaneously, as each component can be controlled individually by the Raspberry Pi. This means that either the fan alone can be turned on, or both the heater and the fan. The Raspberry Pi can decide whether to just fan (to reduce temperature) or fan and heat (to increase temperature).

A safety consideration has been taken into account while developing this component of the system: what if the heater switched on without the fan? What about the potential fire hazard? This consideration has been thoroughly tested, and two safety mechanisms are implemented in the system to avoid fire hazards. The first one is that the system has been set up so that the fan must always be on when the heater is on. This allows the temperature downregulation of the heater. As well, the heater may not be on for more than 60 seconds without a 5 minute cooldown period to avoid overheating. The second safety measure is an automatic built-in threshold of the heater. When overheating is detected (one that may cause a safety hazard), the heater switches off by itself until the temperature of the element reaches a normal temperature again. This is to avoid damage to the heater. After rigorous testing, this situation never occurred as the raspberry pi managed to regulate the temperature of the element successfully, thus avoiding fire hazards.

5.4 Raspberry pi

A Raspberry Pi, displayed in Figure 13, is a small computer which allows us to control the electronic components of our design. It is very versatile and allows us to regulate the growth chamber.

Figure 13: Raspberry Pi, allows users to control all necessary components of the growth chamber through a web application

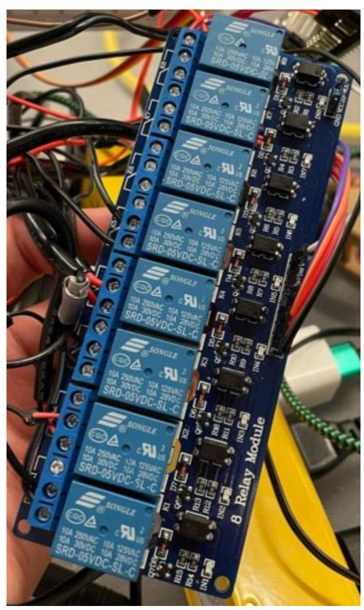

Figure 14: Relay, for the congestion of electricity flow to allow the raspberry pi to control attached components.

The relay board, displayed in Figure 14, is attached to different GPIO pins of the Raspberry Pi, each pin controls a specific relay switch. A GPIO pin is designed to send either 3.3V or 5V through the pin. When the relay board detects a 5V input from the Raspberry Pi, the specific switch is closed and electricity flows, meaning the component is ON. When a lower voltage than 5V is detected, the component's switch reopens and the electricity doesn't flow anymore, the electric component is switched off. The raspberry pi is configured to automatically play with the GPIO pins to control the devices depending on the live data it receives from the sensors.

5.5 Exhaust Fan

In the final version of our prototype, we utilized the exhaust fan displayed in Figure 15. The reality of utilizing this system is that it causes a change in temperature and relative humidity levels. However, we believe this process will not have a significant negative impact on the mushrooms grown as the time internal for which conditionals are no longer optimal is very short.

Furthermore, it was difficult to measure CO_2 levels that would normally be accumulating in our chamber as we have not started growing mushrooms yet. Therefore, we were not able to test how often the exhaust needs to be activated so the chamber remains approximately at 1000 ppm. However, we did observe that upon activating the large exhaust, humidity and temperature decreased dramatically. Therefore, it will be important to use a fan that removes less air and is only on when CO_2 levels rise past the threshold.

Figure 15: Exhaust fan, used for expelling CO_2

5.6 Horizontal-Opening Sliding Doors

As displayed in Figure 16, the doors are equipped with 2 separate knobs for easy access to the interior elements of the chamber. These doors were specifically designed to avoid injuries and allow for full accessibility of the interior. This was achieved by constructing a track for the top and bottom of the independent polyester doors. Additionally, the side edges have been fitted with rubber endings in the event of user contact, which double as a preventative measure to ensure the chamber is better sealed.

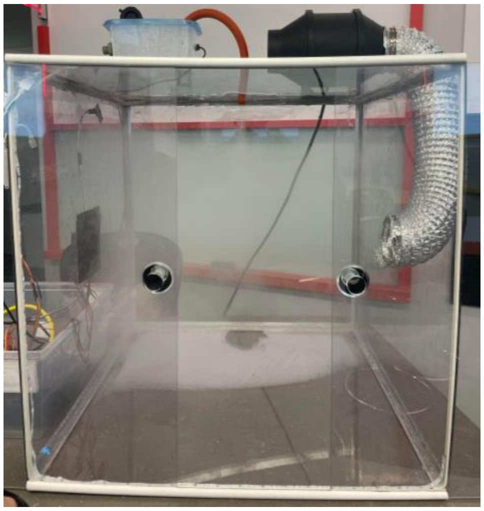

Figure 16: Sliding windows, allowing for simple and convenient access to the interior elements of the chamber

5.7 Optional Camera

The Raspberry Pi Camera depicted in Figure 8 is a small and versatile camera module designed specifically for Raspberry Pi boards. To connect the Raspberry Pi Camera to a Raspberry Pi 3B+, users need to locate the Camera Serial Interface (CSI) port on the board and insert the ribbon cable with the blue side facing towards the HDMI port. Once connected, the camera interface needs to be enabled using the sudo raspi-config command in the terminal. After enabling the camera interface, users can use various software libraries and applications to capture still images and videos. The Raspberry Pi Camera is supported by popular software packages like the official Raspberry Pi Camera Module Python library, OpenCV, and other third-party libraries.

The Raspberry Pi Camera can be easily configured with MyCodo to generate live images and timelapses directly on the dashboard. Users can set up the camera as an input source in MyCodo and configure the desired settings for live image capture and time lapse creation. This allows users to view and monitor live images and create time-lapse videos directly from the MyCodo dashboard.

5.8 Data Generation on My Codo

The sensors inside the growth chamber take live measurements of temperature, CO_2 levels and relative humidity levels. Real time data is played on the graph below in Figure 17.

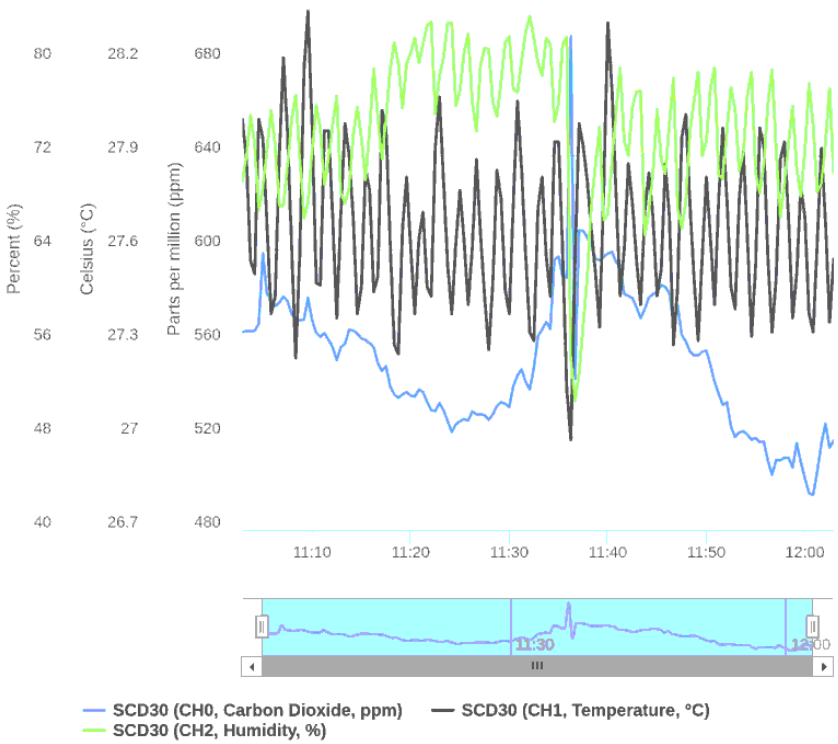

Figure 17: Graph generated from regulating relative humidity, temperature, and CO_2 levels

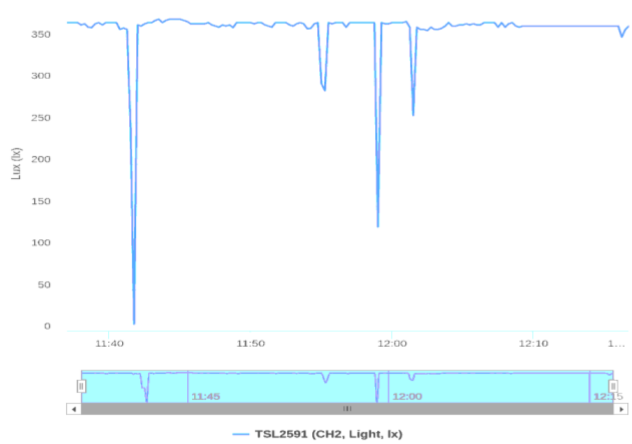

Figure 18: Light variation inside the box during the capstone presentation. (April 11th from 11:30am to 12:30 am)

The graph in Figure 18 demonstrates the light variation throughout our project's presentation to the class. The light sensor has been obstructed (as visible on the graph) to demonstrate the automatic light switching of the LEDs inside the box. More details on the way this was accomplished will be available in the "Functions" section.

Figure 19: Output configuration of the electric components

This setup configuration is used to declare each component with the Raspberry Pi. Each electronic component has been assigned a raspberry pi GPIO so that the Pi can individually control each component.

5.9 MyCodo Functions and Configuration

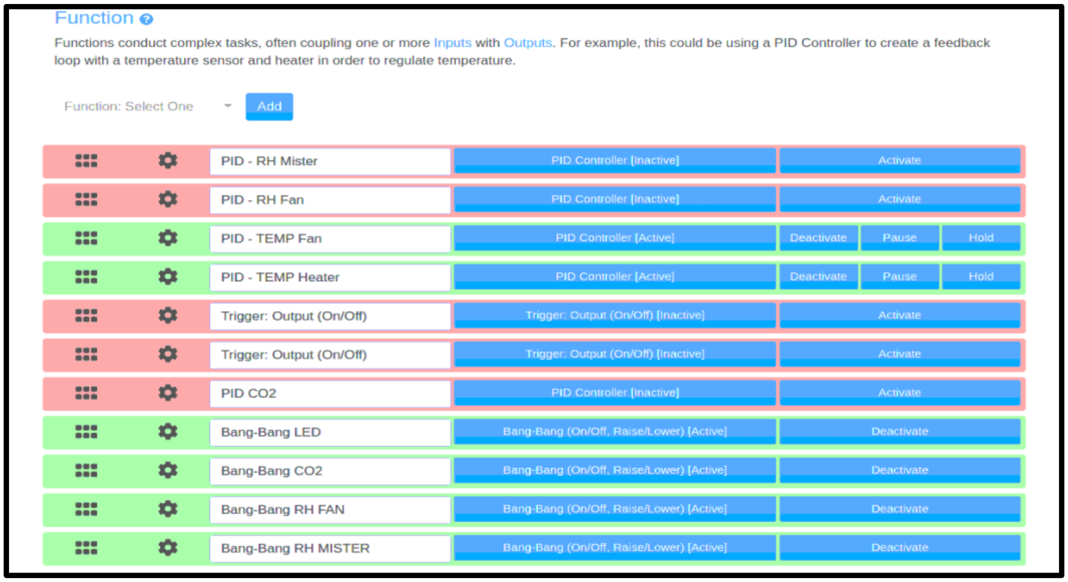

Figure 20: Function configuration page

This set-up page in Figure 20 will be controlling how the system reacts to the environmental conditions provided by the sensor. Two different types of functions have been used after manual and extensive testing, Bang-Bang hysteresis and PID control.

5.9.1 BANG-BANG Hysteretic Function

The Bang-Bang Hysteretic (On/Off) (Raise/Lower) function is a type of control system used to regulate a single output based on a single input. The function has two directions, Raise and Lower, and can be used for heating or cooling applications. The “Bang-Bang LED” function, visible in Figure 20, was used in combination with a LUX threshold, to automatically switch on the lights whenever the environment was too dark. In simpler terms, whenever the LUX amount was below the threshold (set at 50 lx), the pi would send the signal to switch the lights on. This was demonstrated during the capstone presentation on April 11th (see Figure 18).

To use the function, you need to select an input and an output, and set a setpoint and a hysteresis value. The setpoint is the desired value for the input, and the hysteresis value is the range around the setpoint within which the output should be turned on or off. For example, if the setpoint is 25°C and the hysteresis is 2°C, the output will turn on when the input is below 23°C (setpoint - hysteresis) and turn off when the input is above 27°C (setpoint + hysteresis). If you select the Raise direction, the function will turn the output on to increase the input value towards the setpoint. If the input value rises above the setpoint plus hysteresis, the output will turn off to maintain the desired temperature. This direction is suitable for heating applications.

On the other hand, if you select the Lower direction, the function will turn the output on to decrease the input value towards the setpoint. If the input value drops below the setpoint minus hysteresis, the output will turn off to maintain the desired temperature. This direction is suitable for cooling applications.

In summary, the Bang-Bang Hysteretic (On/Off) (Raise/Lower) function provides a simple and effective control system for regulating a single output based on a single input, with options for heating or cooling applications.

5.9.2 PID Controller

This section details the process of a PID controller for which the reader should refer to figures 21 & 22 of the report.

The PID Controller is a feedback mechanism used in various industries to regulate a measurable condition, such as temperature, to a desired setpoint and maintain it with minimal overshoot and oscillation. The controller uses three different terms, namely proportional, integral, and derivative, to calculate the output and adjust it to achieve the desired setpoint.

The proportional term is proportional to the difference between the current and desired values and produces an output that is directly proportional to the error. The derivative term considers the rate of change of the error and adjusts the output to prevent overshoot. The integral term calculates the sum of all the past errors and adjusts the output to reduce the steady-state error.

The controller estimates the error between the setpoint and real output while continuously monitoring the system output. In order to lower the error and get the system closer to the setpoint, the controller then modifies the output based on the PID calculations.

While the controller is running, the PID parameters, including the proportional, integral, and derivative gains, can be changed to fine-tune the control loop. Any modifications made while the controller is paused, however, won't take effect until it starts up again.

A properly tuned PID controller will retain the setpoint with minimum sway and achieve the setpoint rapidly with little oscillation and overshoot. In many different industries, including manufacturing, process control, and automation, PID controllers are frequently utilized in temperature, pressure, flow, and level control systems.

The proportional, integral, and derivative terms are used by the PID controller to calculate the output and modify it in order to reach the desired setpoint. The error between the setpoint and the current value is proportional to the proportional term (P).
The output is calculated as follows:

$$P = Kp * error$$

where Kp is the proportional gain, and error is the difference between the setpoint and the current value.

The integral term (I) is proportional to the sum of all past errors and is used to eliminate any steady-state error. The output is calculated as follows:

$$I = Ki * \int(error\ dt)$$

where Ki is the integral gain and the integration is carried out over time.

The derivative term (D) is proportional to the rate of change of the error and is used to reduce overshoot and oscillation. The output is calculated as follows:

$$D = Kd * d(error)/dt$$

where Kd is the derivative gain and d(error)/dt is the derivative of the error with respect to time.

The final output of the PID controller is the sum of the three terms:

Output = P + I + D

The gains (Kp, Ki, Kd) need to be tuned for each application to achieve the desired response. Increasing the proportional gain will increase the response of the system but can lead to overshoot. Increasing the integral gain will reduce steady-state error but can lead to slow response and instability. Increasing the derivative gain will reduce overshoot but can lead to high-frequency noise.

The tuning process typically involves adjusting the gains until the system responds as desired, with minimal overshoot and oscillation, and maintains the setpoint with little deviation from it. The tuning process can be done manually or using automated methods such as the Ziegler-Nichols method. It is worth noting that MyCodo has an automatic PID tuning using the latter method. In the case of our project, the “PID Auto tuning” has been used to determine the best P, I and D values.

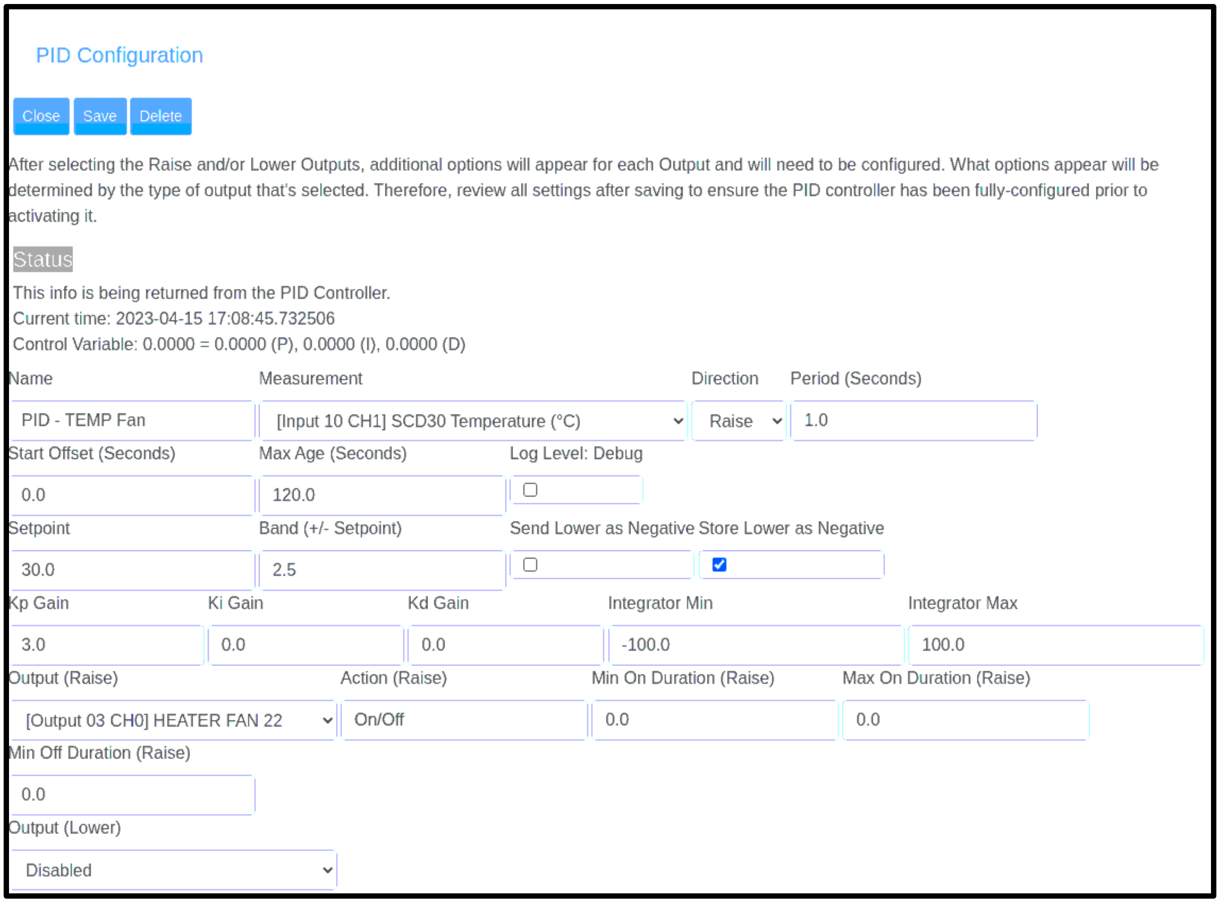

Figure 21: An example of a PID configuration page from MyCodo, regulating the temperature inside the system

$$u(t) = \overbrace{K_p e(t)}^{\text{Proportional}} + \overbrace{K_i \int_0^t e(\tau)\,d\tau}^{\text{Integral}} + \overbrace{K_d \frac{d}{dt} e(t)}^{\text{Derivative}}$$

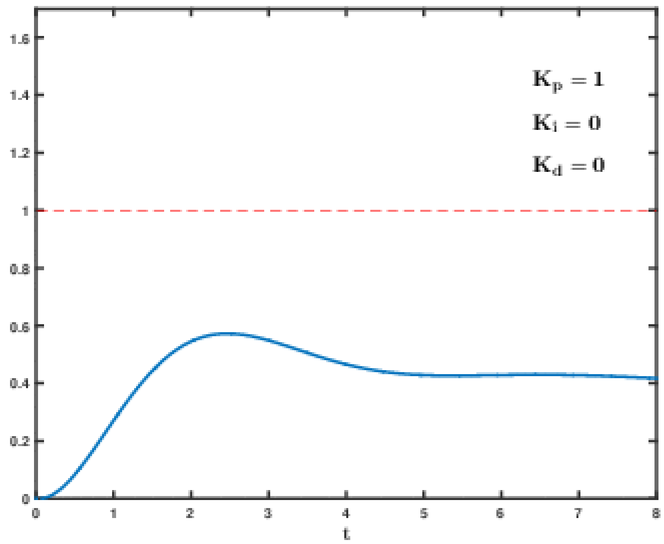

Figure 22: Visual representation of a PID controller. Taken from the MyCodo documentation (https://kizniche.github.io/Mycodo/Functions/#pid-controller).

This image is animated and will only display correctly in .DOCX format of the report.
See this link: https://kizniche.github.io/Mycodo/images/PID-Animation.gif if the image is not displaying correctly.

6. FUTURE IMPLEMENTATIONS / CONCLUSION

This report outlines research conducted to design and produce an automated growth chamber for the cultivation of gourmet mushrooms in a vertical farm. The process was initiated by assessing the design constraints given by a company's operation in a container. Subsequently, extensive research was conducted on various design parameters, being temperature, relative humidity, carbon dioxide levels, lighting, structural materials, and the required sensors and software required for the environmental control and monitoring system. A PUGH chart was produced, allowing us to choose acrylic as the material for the construction of the growth chamber. Taking environmental, economic, and societal factors into consideration, we were prepared to construct our prototype.

Our previous report mentions incorporating a camera for the complete remote monitoring of mushroom growth. We have successfully added this component and have achieved this goal. Additionally, we now have the web application which we have been utilizing for advanced monitoring and regulating of the environmental conditions. The structural acrylic sheets initially proposed were replaced with polycarbonate Lexan sheets due to machining convenience, being less brittle of a material and avoiding crack damages from drilling inlet/outlet apertures. Assembling the container proved to be challenging as the combination of the 3 mm thickness of the panels and lower rigidity of the material produced an unintended bending formation. Thicker 12.7 mm Lexan sheets would have maintained a uniform upright structure, but at the expense of raising the prototype material cost.

Overall, the construction of our prototypes was a success as we were able to regulate all previously outlined environmental conditions within the growth chamber. However, we would like to explore alternative exhaust options to avoid losing optimal development conditions for a brief period of time. Additionally, in our final version of the design we will take advanced measures to ensure the chamber is completely sealed off and minimize opportunity for needless energy loss. Finally, we will further experiment with the location of the sensors and humidity outflow, including test trials with live mycelium inoculated substrate. Environmental control and monitoring components, which were the main premise to the design project's success, accomplished the intended results in maintaining adequate humidity and temperature levels while reducing irregular micro-climate formations within the grow room.

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