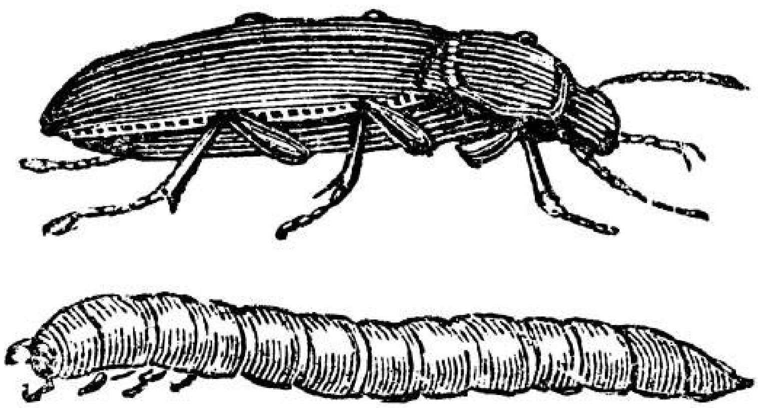
The Mealworm Farm Project

a low-cost household mealworm farm



BREE 495 - Engineering Design 3

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Winter 2019

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Abstract

Human food consumption is increasingly becoming a global issue as the rising demand for resources is virtually advancing every environmental issue - deforestation, climate change, erosion, land degradation, biodiversity loss, water pollution, water scarcity and food security. With the increasing worldwide demand for alternative protein sources and the rising costs of animal protein, the accessibility and consumption of sufficient, safe, nutritious, affordable and culturally acceptable food is becoming more challenging. Thus, our consumption patterns should change to improve human health and nutrition and reduce the environmental impacts of food production. Insect consumption, known as entomophagy, is presented as a sustainable protein alternative to counter food insecurity.

This paper suggests the introduction of a low-cost household mealworm farm to the market, that could provide protein sources at low costs and low environmental impacts to consumers, and increase the average consumer's emotional connection with their food. The design involves a multi-layer tray system for the rearing and harvest of the yellow mealworm (T.molitor L.) in a household setting. The yellow mealworm was chosen for this project due to its high protein and fat content, and its already existing farming expertise and promising option for mass rearing in western countries. The farm is climate controlled by being enclosed in a climate chamber containing the cooling unit and a heat pad inside each tray. A timer will go off when the larvae are ready to harvest after 14 days, to notify the user and make the farm more user friendly.

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List of Abbreviations

GHGs	Greenhouse Gases
ITIS	Integrated Taxonomic Information System
GWP	Global Warming Potential
EU	Energy Use
LU	Land Use
DIY	Do It Yourself
LCA	Life Cycle Assessment

1.0. Introduction

1.1. Background

In just a few generations, humans have exhausted earth's resources and transformed 30-50% of land to yield goods and services [1][2]. Human food consumption and the increased demand for resources is virtually advancing every environmental issue; the intensification of agriculture, in hand with population pressures, poverty, urbanization and lifestyle changes have reshaped our consumption and production of food in ways that have become detrimental to human and environmental health [3]. With a rapidly growing population of over 7 billion people, our dietary choices impact our environment and determines how our planet is used. Although the current global food production system is able to produce enough food to feed the human population, recent studies suggest that food production must increase from 70% to 100% to feed a population of 9 billion people by 2050 [4][5][6]. Therefore, human consumption patterns must change in order to improve human health and nutrition, and reduce the negative environmental impacts of food production [3].

Protein is essential to a healthy diet, however, with the increasing worldwide demand for alternative protein sources and the rising costs of animal protein, the accessibility and consumption of sufficient, safe, nutritious, affordable and culturally acceptable food is becoming more challenging [4][7][8]. Deriving protein from edible insects has been recognized as a potential solution with diverse applications, especially as an sustainable food and feed source rich in high quality protein and other beneficial nutritional ingredients such as fat, minerals, and vitamins [4][7].

Insect consumption, known as entomophagy, has been historically practiced by tribes, indigenous communities and developing countries in tropical regions of the world (Africa, Asia, Australia, and Latin America) as part of their regular diets and reared as feed sources for avian pets and reptiles in developed countries (The Netherlands, Europe, and The Americas) [4]. Most edible insects are harvested in the wild, with the most common insects consumed being Coleoptera (beetles), Lepidoptera (caterpillars), and Hymenoptera (bees wasps and ants); followed by Orthoptera (grasshoppers, locusts, and crickets), Hemiptera (cicadas, leafhoppers, planthoppers, scale insects, and true bugs), Isoptera (termites), Odonata (dragonflies), Diptera (flies), and other orders [4][7]. Currently, over 2,000 edible insect species have been identified and are consumed in 113 countries; it is estimated that at least 2 billion people worldwide practice entomophagy [4][7][9][10].

Insects provide food at a low environmental cost, contribute positively to health and livelihoods, and play a fundamental role in nature. They are rich in protein and good fats and are high in calcium, iron and zinc; making them healthy and nutritious alternatives to conventional livestock foods. Insects also have high feed-conversion efficiencies (i.e. they are very efficient at converting feed sources into protein), emit considerably lower ammonia and GHGs than conventional livestock and do not require a lot of space. Therefore, insect farming can be applied in both urban and rural areas; and depending on investment, insect farming can either be low-tech or highly sophisticated [4]. In general, insect farming or mini-livestock require low-tech activities and low-capital investments and thus “represent an innovative and novel food source rich in high quality protein as well as other beneficial nutritional ingredients such as fats, minerals and vitamins” [7].

Entomophagy is significantly influenced by cultural and religious practices; the earliest reference to entomophagy dates back to biblical times where is was, and still is considered taboo in many western and westernized societies [4][3]. In most Western countries, people view insect-eating (whole insects and insect containing foods) with disgust and associate the practice with primitive behaviour; this resulted in the neglect of insects in agricultural research [4][3]. As expressed by Vieira Alves et al., it is illogical that insect-eating is seen with prejudice, while eating lobster and shrimp (invertebrates that feed on decomposing material) is considered normal for human consumption [9]. However, the early domestication of large animals (cattle, sheep, goats and horses) and plants (wheat and rice) during the European colonization allowed Europeans the advantage of controlling food production, which resulted in the absence of insect food in the Western diet. In fact, food production is believed to have developed independently in nine areas of the world (Fertile Crescent, China, Mesoamerica, Andes/Amazonia, eastern United States, Sahel, tropical West Africa, Ethiopia and New Guinea) [4][9].

Despite traditional knowledge on insects and their harvest in the wild, industrial mass production of safe insects for human consumption (or mini-livestock) and processing into food/feed is still in its infancy in western societies. Therefore, the development of rearing, harvest and post-harvest technologies as well as regulations surrounding insect consumption is necessary to advance production in this sector [4][7][11]. In this project we will be designing a product for rearing insects in a household setting, specifically *Tenebrio molitor Linnaeus* (*T.molitor L.*), the yellow mealworm.

Currently, the yellow mealworm (*T.molitor*) is consumed in Africa, Asia, the Americas and Australia [4][10]. The yellow mealworm was chosen for this project due to its high protein and fat content, and its already existing farming expertise and promising option for mass rearing in Western Countries.

1.2. Vision Statement

Providing sustainable and viable protein alternatives in the form of insects at low costs to contribute to feeding a growing population, sustaining our environment and connecting people with their food.

2.0. Literature Review

2.1. Biology and Life Cycle of The Yellow Mealworm (*T. molitor*)

Insects are a class of animals within the group of arthropods that have chitinous exoskeletons, a three-part body, three pairs of jointed legs, compound eyes and two antennae [4]. *T.molitor L.* is of the order Coleoptera (beetles), which includes many other kinds of edible insects such as the aquatic beetles, wood-boring larvae and dung beetles that are typically eaten as larvae [4][12].

According to the ITIS, the species *Tenebrio molitor Linnaeus* was first given its scientific name by the taxon author Linnaeus in 1758. Commonly known as the yellow mealworm, grain/flour beetles, or ténébrion meunier (in french), *T.molitor L.* favour dark, moist and undisturbed areas; making them one of the largest beetles to infest food products (mainly in cereal and grain warehouses) causing up to 50% loss in production when infested [5][12][13][14]. Mealworm outbreaks can also affect residents a ½ mile away from the infestation site [14], and can be found in stored grains (oats, bran, …) in kitchen cabinets [15].

In order to come up with our design; we first needed to consider the life cycle of the mealworms and their optimal growing conditions. Mealworms feed on cereal grains and vegetables and do well in a dark, moist environment with a temperature range of 20 -28ºC at 60 - 80% RH [16]. Since mealworms are cold blooded, i.e. they do not have hearts and lungs to regulate their body temperature, poor climate conditions can affect their development and productivity [17]. Unlike mammals, mealworms do not have blood, instead they have a blue-green liquid, called hemolymph, that carries small organic materials from their digestive system to all the cells in their body [17]. In addition, due to their unique body mechanisms, mealworms do not produce methane (CH_4) [18]. Similar to other insect species, mealworms have a passive respiration system; where they continuously “breathe” in and out their bodies by exchanging air through a network of spiracles and tracheae located in their abdomen [17]. This respiratory network, like other cellular respiration reactions, carries oxygen to all the cells in their bodies that react with glucose and release carbon dioxide and water. The carbon dioxide is then released passively through the trachea, while water is excreted as urine [17].

The life cycle of the yellow mealworm is comprised of four stages as it undergoes complete metamorphosis from egg to larva to pupa and finally to adult or imago; due to this life cycle, *T. molitor L.* is termed a holometabolous [10]. The average life-cycle of a mealworm beetle spans around 3 months, but can be extended by maintaining lower temperatures at the cost of lower productivity [17]. The life cycle begins first, 4 to 17 days after copulation, when a female beetle lays an average of 500 eggs. The eggs are ovoid, elongated, milky white and shining (due to a sticky substance covering the egg), and are about 1.5 mm in length and 0.60 mm wide [10][13][19]. Embryonic development lasts between 4 to 6 days (this process can be accelerated at slightly higher temperatures from 25 to 27°C), after which small larvae (around 3mm long) hatch, turn yellowish-brown, and produce a hard, chitinous exoskeleton. This larval period lasts 6 to 9 months, and is the longest life stage of the mealworm, however it can be reduced to 3-4 months under optimum temperature and moisture conditions [16][20].

As mealworm larvae develop, they grow out of their old skin and shed their exoskeleton 9 - 12 times [5][18]. After 3-4 months of development, the mealworms are ready to be harvested, processed and consumed. Adult larvae closely resemble wireworms in appearance and weigh about 0.2 g and are approximately 2.5-3.5 cm in length [10][5][18]. When ready to pupate, larvae emerge to the surface of food products (substrate) and spend a few days as pre-pupate before turning into pupa (about 15 mm long, 5 mm wide, and remain stationary). When first formed, the pupa are white and then turn yellowish-brown and culminates into an adult beetle and the cycle is repeated. The pupa stage lasts 6 to 18 days but can last 5 to 6 days under optimum temperatures [10][13][19].

A recent study conducted by Oonincx, Dennis G. A. B., et al., and referenced by S. Feng, looked at the feed conversion, survival and development of mealworms and three other insect species on diets composed of food-by-products. In their study, the yellow mealworms developed in 12 to 32 weeks, with the larval period lasting for 3 months. The results concluded that dietary protein content was a determining factor in the development and survival of yellow mealworms. They found that when fed on low-protein diets, mealworms had an extended development period and lower survival rates compared to high-protein diets that had a shorter development period with higher survival rates [21].

3.0. Design Approach

3.1. Customer Needs Identification

The main purpose of our project is to supply customers with an environmentally sustainable, low-cost, and healthy protein alternatives that connects them more with their food. But do consumers actually want this product? To answer this question, an online survey was conducted to identify the needs of our customers based on their preferences of cost, health, environmental factors, and connectedness with their food. As a final question, the individual was asked whether or not they would be open to the concept of eating insects. Out of 97 responses, the following results were drawn:

- 58.8% of individuals reported that the environmental aspects of a food were influential or extremely important factors when choosing what food to eat.
- 81.5% of individuals reported that the health aspects of a food were influential or extremely important factors when choosing what food to eat.
- 54.6% of individuals reported that the emotional connection with a food was an influential or extremely important factor when choosing what food to eat.
- 84.5% of individuals reported that the price of a food was an influential or extremely important factor when choosing what food to eat.
- 49.5% of individuals were open or very open to the idea of eating insects, and 22.7% of individuals were somewhat open to the idea of eating insects.

It is important to note that this is a bias survey as it only had 97 responses and was targeted towards mcgill students. Nonetheless, it helped us identify our customer needs and gauge the consumer acceptance of insect consumption. It was interesting to see the contrast in responses to the last question presented: *How open are you to the concept of eating insects?* Where one person answered: “Somewhere between not-at-all and somewhat, I might like try a cricket or a tarantula. Probably will never be a part of my diet”, while another person answered: “I would be very open to trying it, and somewhat open to the idea of incorporating them into my regular diet if it was possible.”

With this data, we were able to conclude that there is a potential application for our product on the market, considering over 50% of respondents in every category valued the benefits we are trying to deliver, and 49.5% would be open to trying our solution and 22.7% would be somewhat open to trying our solution. This survey, in hand with further research helped us develop or design criteria and parameters.

3.2. Design Criteria

For our product to be viable and useful, the below criteria must be met. It is important to note that one of the main challenges for meeting these criteria was trying to find a compromise between cost, automation and aesthetics of the design.

Cost | Having an affordable product in an absolute priority. One of our goals is for consumers to use our product to save money on food, or to be able to afford high protein foods when they could not otherwise. If our product is too expensive, it will be useless. Based on existing designs on the market and customer preferences, we considered $300 - $400 to be the upper limit for how much our product would retail for.

Labour/Maintenance | Having a design that requires low levels of maintenance is another important aspect to consider when designing for a mealworm farm. Allowing the design to have low labour requirements makes it easier for the consumer to adopt the product. In contrast, the user may be intimidated when high labour requirements are associated with the design and we risk losing the customers' interest. The ease of maintenance is also important from a food safety perspective; having the consumer neglect maintaining the farm could lead to food safety issues and mealworm cannibalism. Labour on the customer should be minimal, however, since this project aims at increasing the connectivity of the customer with their food, a certain degree of labour is expected.

User Friendliness | Having a user friendly design ensures the farm operates smoothly throughout its life cycle. A user friendly design must be easy to operate and use (i.e. it is easy to load trays on and off the farm structure), be easy to clean, produce minimal to no noise, and be safe (i.e. it is designed to prevent cutting, contained debris, and contained heat).

Durability | The design must be structurally sound and durable. The durability of the the design highly depends on the material used in manufacturing the farm components and their respective material properties.

Food Safety and Hygiene | One large concern for many consumers is the cleanliness of insects. Culturally, in western societies, insects have been labelled as "unclean" animals causing consumers to be skeptical of them being edible. Ensuring that there is as little chance as possible of food contamination is incredibly important. This can be ensured by having an enclosed environment to reduce the risk of contamination.

Aesthetics | Since eating insects is usually perceived as being primitive, dirty or disgusting, having an aesthetically pleasing design plays a significant role in the acceptance of the product to the market.

3.3. Design Parameters

In order to meet the above design criteria, the following design parameters must be taken into consideration:

Climate Control - Temperature and Humidity | As mentioned in section *2.1. Biology and Life Cycle of The Yellow Mealworm (T.molitor)*, mealworms are cold blooded animals and depend on their surrounding environment to control their body temperature. Therefore, in order to ensure the safe and rapid development of mealworms and sufficient harvesting productivity, mealworms must be kept under the optimal growing conditions of 20 - 28ºC temperature range at 60 - 80 % RH [16], in dark lighting conditions**.**

Ease of Harvesting | Hand picking mealworm larvae is an incredibly time consuming and frustrating harvesting technique that can potentially cause damage to the mealworms. Making harvesting easy, safe and interactive can help reduce the time of harvesting and make the process enjoyable for the user; hence increasing their connection to their food. Therefore, ensuring the final design has a harvesting notification is essential to making harvesting easy. Another way to simplify the harvesting process would be providing the user with tools to sort mealworms and separate them from their substrate.

Ease of Use and Reliability | The final design must be reliable, both structurally and operationally. Therefore, the materials selected for the design must be durable and structurally sound. The farm should also be able to operate smoothly without any software malfunctions or component damage, and produce a continuous and sufficient quantity of mealworms to meet protein requirements.

Food Safety and Hygiene | It is of the utmost importance that the mealworms produced by the farm adhere to food safety guidelines and standards; however, industry standards and guidelines related to insect consumption, and specifically *T.molitor*, are largely undefined. Nonetheless, the main risk associated with insect consumption relates to microbial contamination that can arise due to poor mealworm living conditions; this can be mitigated by ensuring proper climate control and sanitary conditions. The main concern of this parameter is ensuring that the user does not get sick from consuming the mealworms. While certain minorly harmful bacteria are present in mealworms, their subsequent freezing and processing is believed to reduce the risk associated with microbial contamination. Additionally, we need to ensure that proper climate control helps eliminate or decrease odours coming from the mealworm trays.

3.4. External Search

3.4.1. Existing Designs and Benchmarking

Currently, two distinct designs exist on the market for personal mealworm cultivation. One is a more sophisticated patent protected design, $The\ Hive^{TM}$, designed by LivinFarms - a pioneering technology company in the alternative protein sector [22] - which involves a controlled climate with sensors, a harvesting notification system, and an automated harvesting system that harvests your mealworms in 4 hours. This makes the product unaffordable to our target consumer at a price of $699. The other is a more basic DIY approach that requires harvesting the mealworms manually, with no electronics involved. There are various DIY mealworm farm designs on the internet, such as the one created by *Vela Creations* - content creators that make guides, books, and articles with a DIY approaches to the unique problems of homesteading off grid - [23]. Other DIY designs involve a similar tray stacking system, without any electronic components to maintain optimal growth conditions for the mealworms. This has the benefit of being considerably cheaper, at a cost as low as $30; however, there is a sacrifice in terms of mealworm yield and productivity since the mealworms are not kept under ideal temperatures year long. Our goal will be to combine these designs, by using the temperature control mechanism of $The\ Hive^{TM}$, and the affordable and simple design practices of a typical DIY project. *Table 1* below is a benchmarking table that compares the 2 existing designs against the selected features.

Table 1: Benchmarking of Existing Designs.

Feature	LivinFarms	Vela Creations
Cost	$699	$30
Mealworms per Harvest	200 g - 500 g	454 g - 680 g
Labour/Maintenance	Moderate	High
User Friendliness	High	Low
Durability	High	Moderate
Food Safety and Hygiene	High	Moderate
Size	N/A; Compact desk-top design	0.14 m^2; Large tower design
Aesthetics	High	Low

3.4.2. Applicable Patents

LivinFarms' The Hive ™ is a patent protected design that is commercialized in Asia. Livin Farms Hive, their previous design, was first released on kickstarter as their first desktop farm for edible insects to empower people to grow their own food. The Livin Farms Hive designs greatly inspired our final design as it ranked exceptionally well on *Table 1* when benchmarked against our projects' design features. *Figure 1* illustrates the design of the Livin Farms Hive retrieved from their kickstarter website [24], while *Figure 2* illustrates the patent protected The Hive ™ design retrieved from their user manual [25]. Figures 1 and 2 can be found in *Appendix B - Patents and Existing Designs*. In addition to the existing designs, we found a few patents related to the personal cultivation of mealworms. These patents are discussed below. It is worth mentioning that the researched patents illustrate the more advanced insect industry in Asia compared to North America; many of the patents were written by chinese and korean inventors.

CN203913010U - Yellow Mealworm Imago Collection Disk [26]

This patent was invented by 彭锴, a chinese inventor. He created a mealworm imago separation technique that simplifies traditional mealworm separation methods. *Figure 3* in *Appendix B - Patents and Existing Designs* illustrates his design; a rectangular solid collection disk with slightly smaller dimensions that a traditional mealworm breeding disk allowing to be placed inside the breeding disk seamlessly. The frame of the design is made of wooden or plastic structures and while the tray bottom has a grated network grid layer with 10 meshes clamped onto the frame. 彭锴 claims that this collection method was at least 100 times less time consuming than traditional breeding methods. The design is simple to operate and reduces the risk of damaging the mealworm bodies when harvesting.

CN205005743U - Yellow Mealworm Breeding Device [27]

Invented by 欧阳力剑 and 杨光杰, this design breeds mealworms to be used as juvenile salamander feed. The device looks similar to traditional mealworm bulk production methods as it also involves a stackable tray system, however the design aimed at tackling two main features; ventilation and light conditions. Mealworms do not like light, and since high humidity in the environment can cause food mildew, ventilation and light conditions become an important factor to consider when breeding mealworms. *Figure 4* in *Appendix B - Patents and Existing Designs* illustrates the overall farm structure made of wooden shelving and a cross section of one of the egg trays.

CN101449670A - Yellow Mealworm Larva Breeding Method [16] and KR101660379B1 - Method for Stimulating Rapid Growth of Tenebrio molitor Larvae [20] are two other patents that helped inform our decision making process and set our design criteria; both patent addressed the optimal growing conditions of the mealworms and presented convenient methods of operation that are free of pollution and have high efficiency when enclosed cultivation is performed.

3.4.3. Applicable Standards

In countries where entomophagy is common practice, there are no set regulations that challenge the production, marketing, and consumption of edible insects. This makes it easy for insect consuming countries to progress in this industry [11]. However, in western societies, entomophagy is still in its infancy, and safety regulations represent a significant barrier to the use of insects in both food and feed. Although entomophagy is gaining interest in North America, there is no specific set standards that apply to edible insects. The FDA set a current legal basis for the market by publicizing its opinion on the matter; in order for insect to be allowed for market they had to be bred for the use as human foods, be labeled with the common name of the insect, its scientific name, and the potential risks of allergies. Importing insect products in the US is legal, however insect products had to follow FDA standards including bacteriological tests and good manufacturing practice certification in order to meet standards [28].

It is worthwhile to mention that, as of 2017, the EU approved the use of insect protein for fish feed. This makes the regulations over the use of insects in animal feed less challenging to overcome. Nevertheless, insects must still be raised according to the conventional livestock regulations (i.e. that insects cannot be fed on organic side streams or any waste product) [11]. As entomophagy becomes a subject of increased interest in Europe and North America, edible insect products that include dried whole insects, insect powder, and insect containing snacks are making their way to the Canadian market [29]. Despite its traditional practice and knowledge in Asia, Africa and Latin America, entomophagy is not practiced by the Canadian population, and hence there are no applicable standards for edible insects [28]. Nonetheless, edible insect production for food must meet the same safety and hygiene standards as other foods available in Canada; most importantly standards related to bacterial pathogens as it is used to indicate the overall sanitation conditions of the food production process [29].

4.0. Design Constraints

4.1. Anti-Nutrient Properties & Microbial Risks

Anti-nutrients are natural or synthetic compounds that interfere with the process of nutrient absorption [30]. Chitin, found in the exoskeleton of insects, is a structural nitrogen-based carbohydrate that can potentially affect protein digestibility negatively [11][31]. Finke (2007) examined seven insect species and found 2.7-49.8 mg of chitin per kg fresh weight and 11.6-137.2 mg/kg in dry matter [11][32]. Although chitin is considered indigestible by humans [33], bacteria that can digest chitin and chitosan using chitinolytic enzymes in the human gastrointestinal tracts have been found [11][34][35][36]. Chitin is notably high in fibre; and in Japan, chitin extracts from shellfish have been approved and are readily used in cereals as a source of fibre. In addition, chitin has also shown to positively affect the immune system of poultry, reducing the need for antibiotic use [4]. Another concern is the potential toxicity of insects. However, studies on the levels of toxins in edible insect species have found that values fall well below the toxicity levels acceptable for human consumption [11]. Overall, there is limited data on the anti-nutrient properties of edible insects, and more research is required in this sector.

Insects, like many meat products are rich in nutrients and moisture and thus provide a favorable environment for microbial survival and growth [4]. This raises concerns on the microbial risks of entomophagy. Traditional processing practices (that include boiling, roasting, and frying) are usually applied to improve taste and palatability; this comes with the added benefit of ensuring that consumers receive a safe food product. Refrigeration is also recommended for fried and boiled insects. In tropical countries however, insects are usually consumed whole [4]. Research shows that the main risk of microbial contamination in insects comes from their gut microbiota [11][37].

In 2017, the FDA analyzed untreated fresh edible insect samples from the Belgian market and found that all the samples had an aerobic mesophilic microorganism, yeast and mould count higher than the Good Manufacturing Practice limits for raw meat [11][38]. Starving insects 24-48 hours prior to slaughter/refrigeration has been suggested as a way to reduce harmful gut bacteria, however Wynants (2017) and Larouche et al. (2017) suggest that this approach had no significant impact on the levels of gut microbiota [11]. As practiced with other meat sources, these risks can be mitigated by introducing appropriate processing steps that can reduce the risk of bacteria-borne diseases. A simple blanching step for example can be added during processing to reduce microbial levels to below acceptable limits [11][39]. Other simple methods for preventing contamination include acidifying insects with vinegar, which has shown to be successful [4].

Studies on organic and metal contamination levels in whole edible insects and insect-based foods in Belgium found that, when the same standards of preparation are applied, consuming edible insects presented the same level of microbial/contaminant risk compared to other conventional meat sources [11]. In order for edible insect species to be considered as a viable food and feed source, further work is needed to establish food and feed safety standards for edible insect production in addition to proper processing, handling, and storage to prevent contamination and spoilage [7].

4.2. Mass Production & Regulations

For edible insects to be considered a viable food source, it must be possible to mass produce them on a large-scale in a sustainable, safe and efficient way [11]. Conventional large-scale livestock and fish production facilities are considered economically viable due to their high productivity and efficiency in the short run; however, these facilities also come with high environmental costs. One such challenge in livestock production is manure disposal [4]. The success of the insect farming industry will largely depend on its ability to set up reliable and consistent production chains that are able to produce high quality food and feed with high nutritional value [4]. *Figure 5* in the *Appendix C - Mealworm Literature* illustrates a schematic process for the production of food and feed products derived from insects [7].

Conventional livestock and agricultural systems have low manual labour expenses due to the advanced level of automation they have, however, this is not the case with the production of edible insects [7][11]. The necessity for high manual labour makes insect protein production expensive, with prices comparable to that of other meat sources. Fore example, in the Netherlands, mealworms cost 32.33 €/kg based on rehydrated weight, and in Nigeria, the *Cirina forda* caterpillar species, the most widely marketed edible insect, sells at approximately two times the price of beef [7][11]. Thus, to make the mass production of edible insects attractive as an alternative protein source to beef and poultry, the production costs of edible insects must be reduced through the development of rearing, harvest and post-harvest technologies. In addition, edible insects can gain credibility as a food and feed source by developing safety and quality metrics/standards [7][11]. Centralizing information, literature, methods and practices can also aid in establishing marketing strategies to target consumers and industries, which in turn can aid in creating a list of edible insect species approved by society as a food source [4].

4.3. Consumer Acceptance & Cultural/Social Behaviour

Our food choices are potentially influenced by a variety of factors, and thus, dietary change has proved difficult to implement effectively; although consumers generally have positive attitudes and a growing interest in sustainability, there is often a gap between consumer attitudes and their behavioral patterns [3][8][40]. Urbanization in western countries has left people disconnected from nature; although this is changing, the westernization of urban areas can change insect consumption in developing countries. Take the case of locust consumption in the Fertile Crescent as an example, where the consumption of loctus disappeared in areas characterized by strong westernization [4]. This makes sense, since most western societies view insect eating with disgust and relate it to primitive behaviour [4]. These feelings of disgust originate from the culture and beliefs embedded in these societies which significantly impact food consumption patterns [4][41][43]. As stated by Mela (1999), “culture, under the influence of environment, history, community structure, human endeavour, mobility and politico-economic systems, defines the rules on what is edible and what is not” [42]. Therefore, our beliefs and attitudes in hand with marketing, demographic, economic, social, cultural, and religious factors influence our dietary choices [3][8].

Food consumption patterns don’t only reflect our nutritional needs and appetite, but also our personal preferences of taste, odor and texture, as well as culture and ethics [44]. Studies found that ambivalence and optimistic bias are two possible reasons why dietary changes lack success [8]. Ambivalence refers to having mixed feelings about consumption of certain diets - despite them being unhealthy - due to personal preferences, while optimistic bias is when individuals are over-optimistic and underestimate the overall perceived risk a particular hazard can have on them relative to others [3][8].

The main challenge standing in the way of making edible insects a sustainable and viable protein alternative is the need to reduce and eliminate the western-driven stigma around entomophagy [45]. By doing so, opportunities for research on mass production, optimization and efficiency of insect farming can be pursued [45]. Although progress has been made in this area, and western societies are getting more comfortable with the idea of entomophagy, consumer acceptance of insects as human food is still low [11]. This is because behavioral patterns are often poorly reflected through consumer attitudes; food choices are often influenced by price, quality, convenience, brand familiarity, and other cultural norms, while ethical factors and consequences are only considered by a minority of consumers [3][8]. However, the use of insects as animal feed has showed significantly more support; thus this could be a gateway to increasing consumer acceptance of insects as a food source [11].

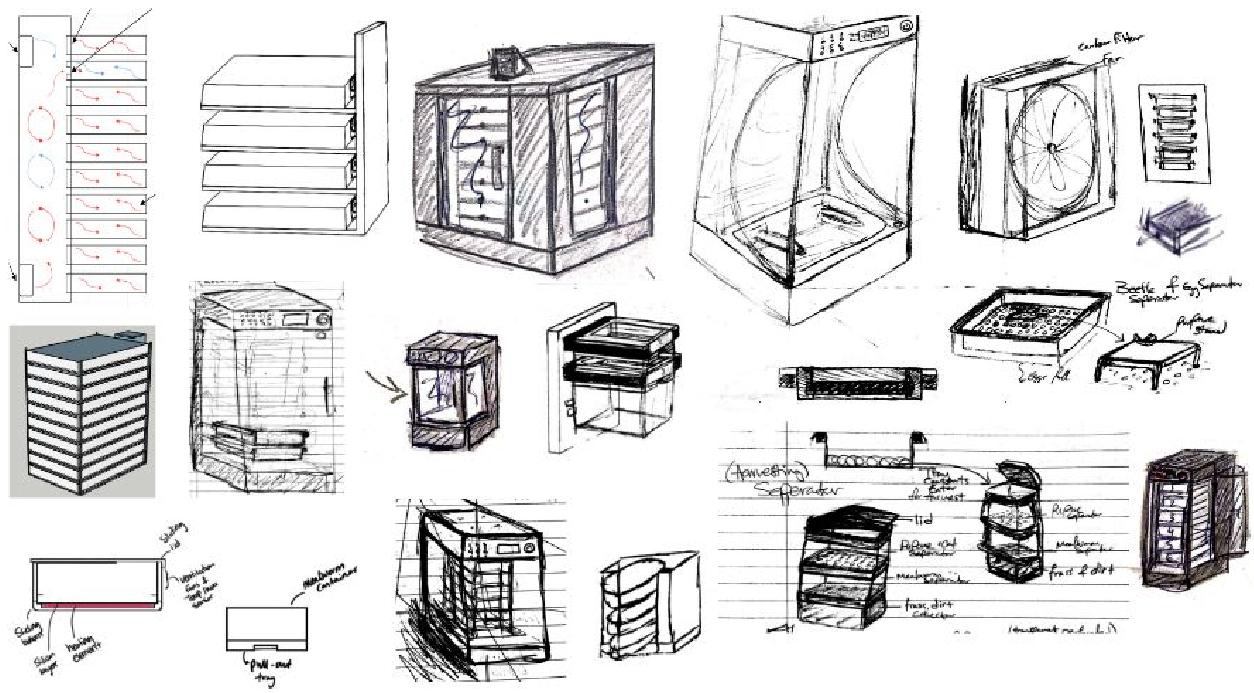
Our future food consumption patterns will continue to reflect our overall lifestyles, income levels, values, and consideration of human health and the environment. In order to implement changes, consumers must be convinced that their behavior can have an effective impact in fighting issues such as environmental degradation and social inequality [3][8]. According to studies, ethical and sustainable dietary changes could be stimulated by increasing involvement, perceived consumer effectiveness, certainty, social norms, and the perceived availability of sustainable products [3][8].

5.0. Design Selection

Using the existing designs and applicable patents, we brainstormed and evaluated various alternative designs based on the selection criteria/features that were identified from the design criteria and parameters. In order for our design to meet those criteria, the design required a spawning area for mealworms, a climate controlled and ventilated enclosure that reduces odour, and finally it had to connect people to their food and maintain a continuous quantity/quality of mealworms; making the design reliable. *Figure 6* below illustrates the various design sketches and concepts generated when coming up with the final design. *Section 3.4.* of this report greatly informed our concept generation as our design was first inspired by *The Hive*™. It is worth mentioning that the final design was also inspired by the conceptual design of a regular dehydrator and a computer desktop.

When selecting our design, the final generated concepts were arbitrarily weighted based on the selection criteria, and compared. After identifying the strengths and weaknesses of the chosen concepts, the designs were combined to come up with the final design, which utilizes the stackable tray system of traditional breeding methods, as well as the mesh screen separation technique found across DIY projects and patents. Our final design has also utilized the concept used in the Livin Farms Hive kickstarter design, where the mealworms are transferred onto the next tray via automatic gates found at the bottom of the tray. For our design, a drawer separation technique was used instead to lower cost; cost was one of the main criteria that we needed to meet, so design features related to the functionality and maintenance of the product had to be compromised. The farm will be climate controlled by having an enclosed climate chamber with a cooling unit (fan) and a heat pad in the larvae trays. A timer will go off when the larvae are ready to harvest after 14 days, to notify the user and make the farm more user friendly.

Figure 6: Concept Generation Sketches.



6.0. Design Implementation

6.1. Operational Flow

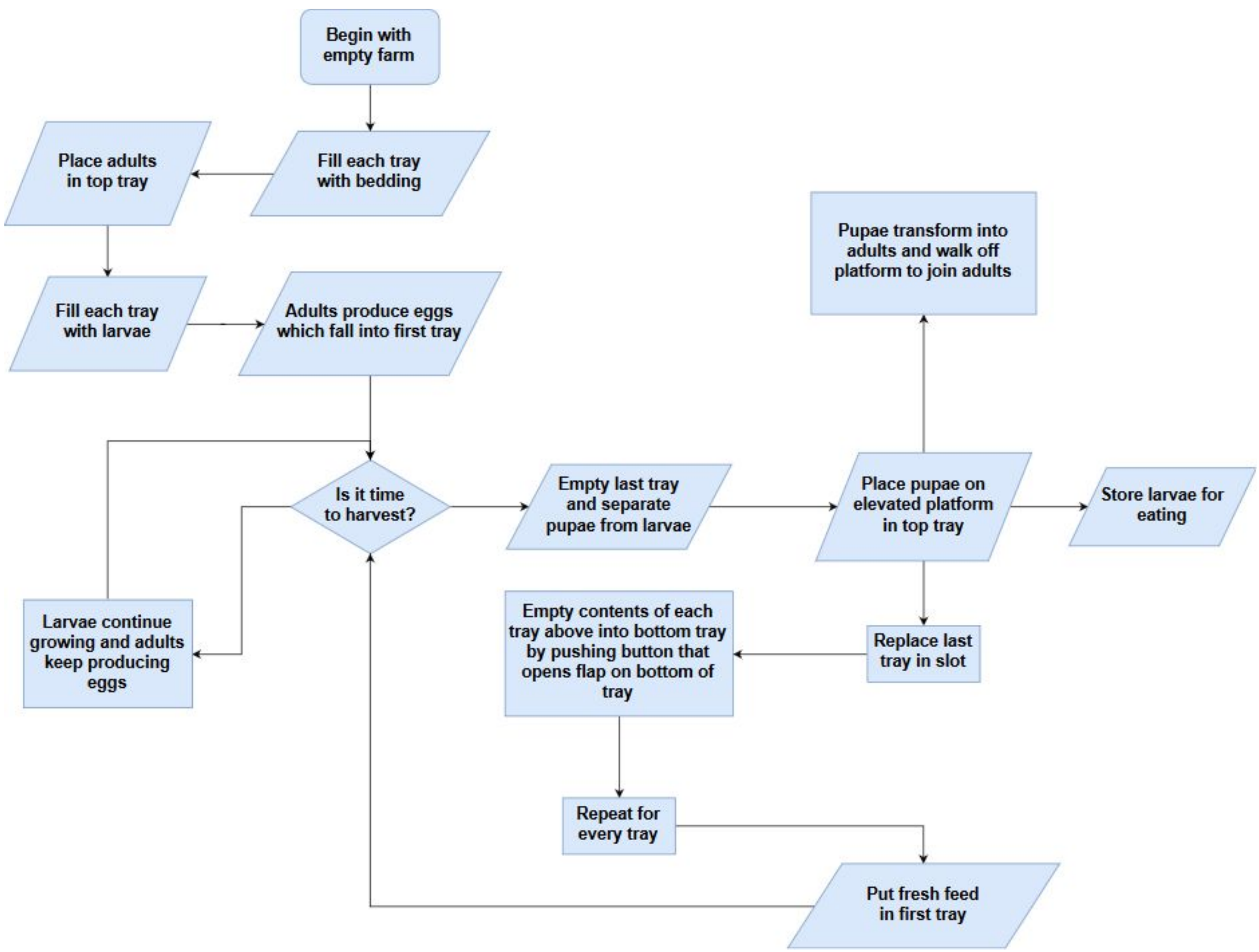
Our overall design aims at separating the different stages of the mealworms in different trays, controlling the temperature if each individual tray, and controlling airflow through a central system. The farm is organized as follows:

- The beetles and the pupa are contained in the top tray (Tray # 1). The pupa are placed on an elevated platform to separate them from the beetles and prevent cannibalism. Once the pupa metamorphosis into beetles, they will walk off the platform and join the other beetles on the tray.
- Larvae are located in the six trays (Trays # 2-7) below Tray # 1 that contains the beetles. The youngest larvae will be placed in Tray # 2 below the beetles, while the oldest larvae will be contained in Tray # 7, the bottom tray. Since larvae grow at different rates, the harvest tray (Tray # 7) will contain some pupa which will replenish the colony.

- Eggs will be located in Tray # 2 immediately below the beetle tray (Tray # 1). Tray # 1 will have holes 2.0 mm in diameter to allow the eggs and some frass to pass through, but not the beetles or pupa.

Please refer to *Figure 7* below for an operational flow diagram of the farm. Since this product is intended to be made for the everyday consumer, we have also prepared a brief instructional manual section that would help the consumer understand how to operate the farm; this can be found in *Appendix A - User Instruction Manual*.

Figure 7: Operational Flow Diagram



6.2. Heating System

Tenebrio molitor thrives in temperatures between 20 and 28ºC [16][20]. Since we want this product to produce as reliable and consistent yields as possible to the consumer, there will be a heating system that keeps the body temperature of the mealworms within this temperature range. We will do this through heating pads within each tray that will maintain a surface temperature of approximately 28 degrees, and transfer heat through conduction to the growing substrate. This system exploits the fact that mealworms tend to bury themselves in the growing medium (because of their sensitivity to light), meaning it is unnecessary to heat the surrounding air within the chamber through convection, and can be achieved with much less energy through conduction, which is a more efficient form of heat transfer. Each heat pad will be controlled by the microcontroller and a relay, which disconnects the relay when the internal temperature of the chamber is above 28°C (sensed by a temperature sensor within the first larvae tray).

6.2.1. Heat Transfer Analysis and Simulation

The main form of heat transfer we are concerned with here is conduction heat transfer from the heat pad to the substrate. We also need to consider heat loss through contact of the substrate with the surrounding tray which will be cooler than the heat pad, as well as convection heat loss of the substrate with the cooler surrounding air.

We will be assuming steady state heat transfer, so we will have no energy accumulation, and thus as the first law of thermodynamics states:

$$Energy\ Input\ +\ Energy\ Output\ =\ 0$$

Using Fourier's law and the formula for convective heat transfer:

$$Energy\ Input\ =\ -k_s * A_s * \nabla T_{hp}$$

Where:

$k_s = local\ heat\ flux\ density\ of\ the\ substrate$

$A_s =\ Surface\ area\ of\ contact\ between\ substrate\ and\ heat\ pad$

$\nabla T_{hp}\ =\ temperature\ gradient\ between\ heat\ pad\ and\ substrate$

$$Energy\ Output\ =\ -4 * k_t * A_s * \nabla T_t\ + h\ * A_s * (T_a - T_s)$$

Where:

$k_t =\ local\ heat\ flux\ density\ of\ the\ tray$

$\nabla T_t\ =\ temperature\ gradient\ between\ substrate\ and\ the\ tray$

$T_a =\ temperature\ of\ the\ air\ in\ degrees\ celsius$

$T_s =\ temperature\ of\ the\ substrate\ in\ degrees\ celsius$

We assumed the substrate was oatmeal, using this we found:

$$k_s = 0.0641\ \frac{W}{m*K}\ [46]$$

$$k_t =\ 0.48\ \frac{W}{m*K}\ [47]$$

The Nusselt number for a hot surface in a cold environment for free convection in a horizontal plate is [48]:

$$\overline{Nu_L} = 0.54 * {Ra_L}^{1/4},\ 10^4 < Ra_L < 10^7$$

$$\text{Where; } Ra_L = \frac{uL}{\nu}$$

It is unclear without doing an in depth fluid dynamic analysis what *u* would be, but for the purposes of this calculation, we have assumed it to be 0.3 m/s, a velocity that is felt as a slight draft during summer in a cold climate [49]. The kinematic viscosity of air is $1.562 * 10^{-5} \frac{m^2}{s}$ at 25°C [50] and the characteristic linear dimension is 55cm (from tray geometry).

$$Ra_L = \frac{0.3*0.55}{1.562*10^{-5}} = 1.0563 * 10^4$$

$$Nu_L = 0.54 * (1.0563 * 10^4)^{\frac{1}{4}} = 5.47$$

The thermal conductivity of air at 25°C is $k_a = 0.02551 \frac{W}{m*K}$ [50]. From this:

$$h = \frac{Nu_L * k_a}{L} = \frac{5.47*0.02551}{0.55} = 0.254$$

After obtaining the heat transfer coefficient, we were able to create a simulation in Fusion 360. Please see *Section 7.1.* for the results.

6.2.2. Heating Pads

The heat pads will be of similar design to propagation heat pads used for root germination. Currently these retail to the general consumer at around $22.95 CAD [51]. If this project were to become a retailed product, a heat pad specifically designed for this application would be used, which we approximate would bring the cost of a heat pad down 50% making each heat pad cost around $11.47 each. The heat pads be designed to have a surface temperature of around 25°C in order to provide a suitable environment for the mealworms

6.3. Ventilation System

The ventilation system for the farm will be a natural ventilation system. We are aiming for a system that delivers a minimum of 6 air changes per hour. This is based on the standard for patient rooms in hospitals [52]. To choose an appropriate fan to deliver this desired amount of air changes we used the following equation:

$$ACPH = \frac{60*Q}{Vol} \text{ [53]}$$

Where:

$ACPH = Air\ changes\ per\ hour$

$Q = Air\ exchange\ rate\ in\ \frac{cm^3}{minute}$

$Vol = Volume\ of\ air\ inside\ structure\ in\ cm^3$

The volume of air inside the structure is 241280 cm^3 , therefore:

$$Q \geq \frac{6*241280}{60} \geq 24128\ \frac{cm^3}{minute}$$

So we will need a fan that has a minimum air exchange rate of $24128\ \frac{cm^3}{minute}$.

6.3.1. Carbon Filter and Odour Control

A big concern in the design is odour control. To deal with this problem we will place a carbon filter on the inlet of the fan, due to their ability to remove volatile organic compounds, odors, and other gaseous pollutants from the air [54]. The dimensions of the carbon filter will be 10cm x 10cm, dimensions picked to match the dimensions of the fan. We have found a supplier in china [55] that is selling 1m x 2m x 10mm rolls for $13.2 each, meaning the cost per carbon filter per unit would be $0.066.

6.4. Electronics

6.4.1. Sensors and Harvest Notification System

In order to help keep the conditions of the farm at an optimal temperature and humidity, we will be placing a DHT11 temperature and humidity sensor in the farm which will monitor the temperature and humidity. This sensor will be connected to a microcontroller which, when it detects a temperature above 28°C it will disconnect the contact in the relay, thus turning of the heat pads. The sensor will be placed in the top tray, which will give an estimate of a typical temperature in the trays. The sensor will also collect humidity data, which it will use to notify the user by an LCD display when the humidity is below 60 % RH (the lower range of the ideal mealworm humidity [16], telling them to put carrots or potatoes in the trays. This will of course not be an accurate description of all the trays, but will serve more of an aid to remind the user to make sure the mealworms have enough moisture in the air. Ultimately though, it will be the responsibility of the user to ensure that each tray has sufficient humidity by adding in vegetables.

Our design involves a considerable amount of user interaction, so we believe that is important to give as many aids as possible so that the user maintains the farm correctly and has a good experience. One of the more complicated aspects for the user of the design is the harvesting system. The system will operate on a timer of 14 days between harvests. This means that every 14 days a notification will appear on the LCD screen that will tell the user to harvest the mealworms, with detailed instructions on the harvesting procedure.

6.6. Design Drawings and Material Selection

6.6.1. Tray Design

Our final tray design will involve a removable drawer with a heat pad that the user will pull when harvesting to transfer the tray contents into the tray below, or, in the case of the harvest tray, the user will remove the tray from the structure and separate the pupae and larvae, freezing the larvae for consumption, and placing the pupae on the elevated platform in the beetle tray to replenish the colony. See *Figures 8, 9, 10, and 11* for engineering sketches and Fusion 360 renderings of the larvae tray and beetle tray in *Appendix E - Final Design Sketches*. Please note, the holes in the adult tray are enlarged for display purposes; the true diameter will be 2.0 mm, which will allow the eggs (0.60 mm in diameter) to pass through.

To deal with the issue of the heat pad cord getting tangled when the drawer is removed, the male end of the cord connection will be held in place in the tray structure, and the female connection connected to the heat pad in the drawer will connect to the male end via a magnetic connection. This way the heat pad will disconnect when the drawer is pulled out, and connect when the drawer is placed back in the tray.

An important calculation was how large the trays needed to be in order to supply enough yield. We are aiming for the farm to supply 49 g protein/week, half the weekly protein requirement for an average adult male [56]. To achieve this we are making the following assumptions based on previous scientific research. A typical Tenebrio molitor individual is 15% fat, 20% protein [57], 100 - 110 mg [58], and has a growing density of 2.55 larvae/cm2 [59]. This information tells us that there are 22mg protein/mealworms (= 110mg*0.2) and that 2228 worms will need to be harvested each week (= 49,000/22) in order to meet our requirements. From this we can calculate the area required:

$$Area\ Required\ =\ Harvest\ Requirement\ (larvae/week) * weeks\ (weeks)/Growing\ Density\ (larvae/cm^2)$$

$$Area\ Required\ =\ 2228\ larvae/week * 2(week)/(2.55\ larvae/cm^2)$$

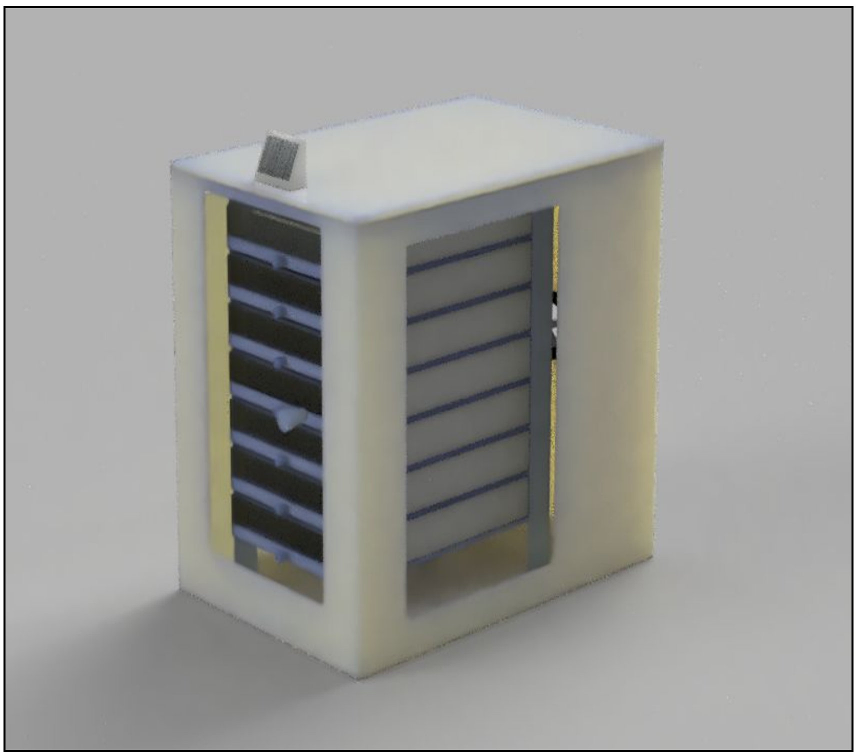
$$Area\ Required\ = 1747.5\ cm^2$$

Since 55cm*32cm = 1760 cm^2, we can achieve the required area by making the dimension of each tray $= 55\ cm\ x\ 32\ cm$. To avoid overcrowding the mealworms and ensure air circulation inside the tray, we will make the tray 7cm high. This gives us the final dimensions for the tray $= 55\ cm\ x\ 32cm\ x\ 7\ cm$.

6.6.2. Farm Structure

The overall farm consists of a stackable structure that holds and supports the trays, which are enclosed inside another structure, the climate chamber, where the cooling fan operates. This was chosen so that we could increase the air-flow within the enclosed environment, without the added investment of purchasing a fan for each tray. We have also decided to add two clear acrylic plastic pieces for the door and a viewing area on the side. The viewing area was added to the design to increase aesthetics and user connection with their food, so that the user can view the mealworms in action. A rendering of the final farm structure design is shown in *Figure 12* below. See *Figure 13* in *Appendix E - Final Design Sketches* for an engineering sketch of the structural design.

Figure 12: Rendering of the Farm Structure Design on Fusion 360.



6.7. Manufacturing and Assembly

While many parts can be bought by other sources (such as the electronic components), the trays and the structure will have to be manufactured. For this we propose rotational molding. There are several advantages of rotational molding that make sense with this product. Rotational molding has a comparatively low up-front cost, cost-effective, good for hollow parts (which many of the parts, mainly the external structure, are), and eco-friendly [60]. It has the drawback of having long manufacturing times, but it is unlikely that this product will need to be able to be manufactured at a very large rate initially.

6.8. Bill of Materials

Table 2 below shows the costs of materials used in the design. For an in depth look at part prices, see *Section 8.5.1.*

Table 2: Material Cost Breakdown.

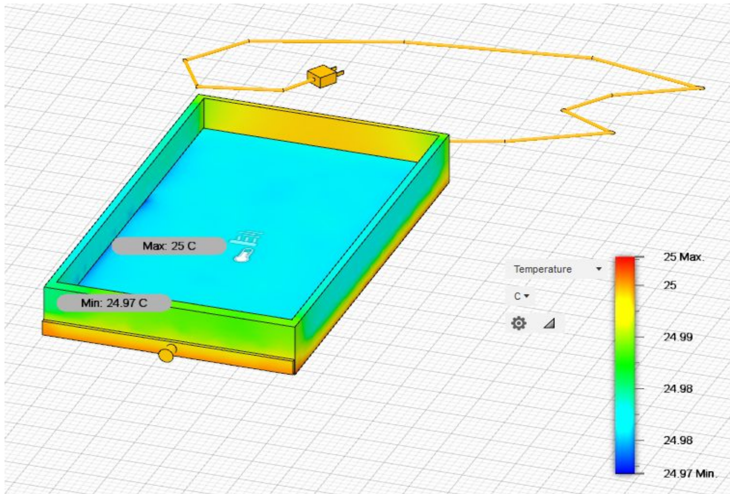
Material	Density	Cost/kg	Cost/cm^3
HDPE Plastic	0.97 g/cm^3 [61]	$3.09 [62]	$0.003
Acrylic (clear)	1.2 g/cm^3 [63]	$2.50 [63]	$0.0025

7.0. Simulations and Experiments

7.1. Heat Transfer Modeling on Fusion 360

Fusion 360 is an "Integrated CAD, CAM, and CAE software" that is useful for a variety of applications including CAD design, renders, and simulations [64]. We used this software to perform a thermal analysis on our tray design with a heat pad performing a thermal load of 25°C. Oatmeal was not available as a material, so we used particle board as the substrate which has a similar thermal conductivity of 0.078 $\frac{W}{m*K}$ [65], compared to the thermal conductivity of oatmeal which is 0.0641 $\frac{W}{m*K}$ [52]. *Figure 14* below illustrates the simulation results. As expected there is a very even temperature distribution throughout the tray, and the substrate is adequately heated to be an ideal temperature for the mealworms.

Figure 14: Results of Fusion 360 Simulation with Heat Pad in Tray.



7.2. Experimental Methods and Statistical Analysis

The experiment was performed in order to find the feed requirements and amount of waste/frass produced by the mealworms. However, since mealworm frass was very tiny and is easily mixed with wheat bran and oat bran, it was difficult to quantify the amount of waste produced. 4 trials were conducted with 10 mealworms per trial for a 1 week period. The mealworms were placed in aluminum dishes (usually used for soil sampling) and were also fed on 3 different diets: wheat bran, oats, and mixed (oats and wheat bran). Each mealworm was weighed separately - before and after - to obtain the change in weight of the mealworms. The room temperature of the lab was at 22 degrees Celsius. Results are shown in *Table 3* in *Appendix D - Experimental Data*. These results indicate that the average change in mealworm weight was equal to the average change in dish weight i.e. that everything the mealworms gained in weight was lost from the original food input; however this could also indicate that the balance used to weight the mealworms might not have been accurate enough.

For this experiment, a 95% two-sided confidence interval (upper limit, lower limit) for the data set was performed using a t-distribution. Since a small sample size was analyzed, the x-bar was used to find the sample mean and estimate the true population value. The sample standard deviation was calculated, and the confidence limits (interval estimate of the upper and lower limits) for each trial was found to give an indication of how much uncertainty there is in our estimate of the true mean. A significance level of 0.05, 9 degrees of freedom and a sample size of 10 were used. The results are shown in *Table 4* in the *Appendix D - Experimental Data .* The results indicates that the average margin of error is +- 0.016.

7.3. Java Simulation

We attempted to make a java simulation of the operational process of the entire farm to try and test our design without having to construct a prototype or wait for the long process of the mealworm going through its lifecycle. This proved more difficult than originally anticipated due to the unavailability of some information such as a protein curve for the mealworm, and also the difficulty of replicating the variability in biological growth that the operation relies on (such as having a mixture of larvae and pupae in the bottom tray). If anyone wishes to obtain the code completed, they can contact Samuel Dalton at samuel.dalton@mail.mcgill.ca.

8.0. Design Considerations

8.1. Risk Factor Matrix

A risk factor matrix was created following the framework presented by the United States Department of Energy to evaluate and numerically rank risk factors that might affect the design from 1 to 3; where 1 is the least likely/dangerous risk and 3 is the most likely/dangerous risk. To ensure all risks are addressed appropriately to the full functionality of the design, the framework also identifies risk contributors and mitigation procedures to ensure appropriate measures are taken. *Table 5* below shows the risk factor matrix for our final design.

Table 5: Risk Factor Matrix.

Risk Factor	Risk Rank	Risk Contributors	Mitigation Procedure
Low humidity	2	- Low temperatures - Dry air	- Temperature control - Add vegetables
Tray deterioration due to heat	1	- Material failure from high point-source heat	- Choosing a durable material resistant to high temperatures - Temperature control
Heat pad overheating	3	- Hardware Malfunction	- Choosing reliable manufacturers
Sensor malfunctioning	3	- Hardware Malfunction	- Choosing reliable manufacturers
Software glitches	2	- Poor coding	- Choosing a good software company
Component Damage (screen, fan, filter, trays) due to product wear and tear	1	- Mishandling	- Warranty in place
Mealworm cannibalism	2	- Poor living conditions - Beetles climbing onto elevated platform	- Add vegetables - Temperature control
Electronics short circuiting	2	- Poor manufacturing	- Choosing reliable manufacturers
Heat pad malfunctioning	2	- Poor manufacturing	- Choosing reliable manufacturers

After evaluating inherent risks in our design, we concluded that the two most likely/dangerous risks were overheating of the heat pads and sensor malfunctioning which could compromise the farm yield and the optimal mealworm growing conditions. Simple ways to mitigate those issues requires us to choose reliable manufacturers that properly follow engineering standards.

8.2. Life Cycle Assessment Considerations

Conducting a LCA plays an important role in the selection of the final design as it allows us to quantify the environmental, social, and economic impacts a design/product has throughout its life cycle; from raw material extraction to the product end life when it is disposed, recycled, reused, or reclaimed. For our project, a LCA would consider several things: the amount of energy being consumed at each stage; the amount of CO2 emissions released due to extraction, manufacturing, production and transportation; the amount of water being used or recycled at each stage; the impact of extraction, manufacturing, and production on local communities; the cost of extraction, manufacturing, and production; how ethical the methods of extraction, manufacturing, and production are; the amount of land required/degraded at each stage, and finally, the global warming potential (GWP) of mealworms. A LCA would also consider the impact the product has after it has reached the consumer, and after disposal; therefore it would also consider the amount of feed required for mealworm cultivation as well as the feed specifications and the related impacts of the feed production (i.e. water used, CO2 emissions and land required for oats and wheat bran). Additionally, it would consider the amount of energy consumed by the whole farm throughout its life-span.

Oonincx and de Boer conducted a LCA to quantify the environmental impacts of mealworm production. Their results illustrated in *Table 6* in *Appendix C - Mealworm Literature* show the absolute and relative GWP, energy use (EU), and land use (LU) for the production of 1 kg of fresh mealworms. For *1 kg of fresh mealworms*, the GWP was 2.7 kg of CO2-eq, EU was 34 MJ, and LU was 3.6 m2 per year. In contrast, for GWP, EU, and LU *per kg of edible protein from mealworms*, the GWP was 14 kg of CO2-eq, the EU was 173 MJ and the LU was 18 m2 . These values also contribute mainly to the production and transportation of feed grains and carrots [18]. Results also showed that the energy used to produce 1 kg of mealworm protein was lower than that for beef, comparable to pork, and slightly higher than chicken and milk [18]. Mealworm larvae also compared favourably with pigs and beef cattle in their GHG emissions as they produce considerably less greenhouse gases (by a factor of about 100 compared to pigs and beef cattle). They also were found to compare favourably with pigs in ammonia emissions (with about a tenfold difference compared to pigs) [4][18]. *Figure 15* in the *Appendix C - Mealworm Literature* illustrates these findings.

8.3. Environmental Impact

The need to increase food production to sustain a growing population has placed heavy pressure on the already limited resources of our planet. Currently, livestock production accounts for 70% of all agricultural land-use and in order to meet the increasing demand for livestock products and animal protein, innovative solutions are needed. Insects provide an opportunity to help meet this rising demand as they provide a number of advantages at a low environmental cost [4].

As the demand for meat rises, so does the need for grain and protein feeds [4]. Therefore, feed-conversion efficiencies are an important aspect to consider when rearing livestock. Insects have high feed-conversion efficiencies (i.e. they are very good at converting feed mass to body mass, represented in kg of feed per kg of weight gain), this is because insects are cold-blooded and depend on their environment to control metabolic processes such as body temperature [4][11]. Feed-to-meat conversion rates depend on the class of animal and the production practices used in its rearing [4]. According to Oonincx, Dennis G. A. B., et al. (2010), diet composition was found to be the main determinant of feed conversion efficiency for a given insect species. Their study found that yellow mealworms had high feed conversion ratios (>3.8) on all diets compared to conventional livestock that were reported to be 2.3 for poultry meat, 4.0 for pork and 8.8 for cereal beef. Thus it was concluded that yellow mealworms were as efficient as poultry in converting their feed to food for human consumption [66].

Insects also require considerably less land and water compared to conventional livestock; in fact, mealworms were found to be more drought-resistant than cattle [4]. For every 1 ha of land required to produce mealworm protein, 2.5-10 ha would be required to produce a similar amount of milk, chicken, pork, and beef protein [4][18]. Agriculture uses water directly to grow crops for human consumption and indirectly to grow feed for livestock production; therefore, as the demand for meat rises, so does the need for grain and protein feeds [4][11]. This in turn leads to deforestation and increased fertilizer use due to an increase in cropped lands [11][18]. Miglietta (2015) examined the water footprint perspective of commercially produced insects, taking into account the entire production system, and found that the water footprint per ton of mealworms was larger than that of pigs and chickens. However, when taking into account the edible percentage of the animal, the re-examined data showed that mealworms had a lower water footprint than other conventional livestock [67]. This is because insects are considered to be 80-100% edible while other livestock are 40%–50% edible [68]. Finally, insects emit relatively few GHGs and low amounts of ammonia compared to conventional livestock [4].

Insects can also be reared on organic side streams as a means of reducing environmental contamination, while adding value to waste. Despite these benefits, one of the largest barriers of adopting insects as an alternative protein source in western societies remains: consumer acceptability. Nevertheless, food consumption patterns and lifestyle changes in a globalized world can change quickly; this was seen with the rapid acceptance of raw fish as sushi [4].

8.4. Social Impact

8.4.1. Health and Nutrition

The global average meat consumption (per capita) is rising, largely due to the increase of income and the decline in meat prices [5]. This can be seen as a positive since meat is a energy and nutrient dense food source. This increase in meat consumption, however, has come at a cost to human and environmental health. In western countries, meta analysis generally shows that participants consuming high amounts of red and processed meats have moderately higher levels of total mortality rates than those with low meat intakes [5]. Studies suggest that eating high amounts of processed meats are associated with an increased risk of diabetes, high blood pressure, weight gain, and other chronic diseases in adults. According to the IARC, processed meats were the cause of 34,000 cancer related deaths worldwide [5]. This becomes a problem for many low income individuals as cheap processed meats are their only option due to affordability and convenience.

Insects are a food source rich in protein, fats, energy, minerals and vitamins, with the energy content (per fresh weight) being comparable with other fresh meat protein sources [11]. Mean estimates show energy levels in insect species to be around 400– 500 kcal per 100 g of dry matter [71]. Mealworms are considered to be a healthier alternative as they have a high protein to fat ratio, and contain beneficial micronutrients. Fresh mealworms are generally 15% fat and 20% protein [69]. However, it is important to note that the nutritional value of edible insects can be highly variable, even within the same insect species, values can change depending on the metamorphic stage of the insect, habitat conditions, and diet. In addition, nutritional composition is also influenced by processing practices before consumption, such as drying, boiling or frying [4]. *Table 7 and Table 8* in *Appendix C - Mealworm Literature* summarize key nutritional information about the yellow mealworm for food cultivation purposes. This illustrates the health benefits of the yellow mealworm, and it's potential benefits if included in a consumer's diet.

Attempts to compile data on the nutritional value of edible insect species were pursued, however, in the current literature, only a few studies analyse the nutritional value of edible insects, and in countries where entomophagy is practiced, insects comprise of only a part of local diets; limiting the local knowledge of entomophagy. These data are also variable and not comparable due to insect variations and different analysis methodologies [4]. Despite data variations, Rumpold and Schlüter (2013) compiled the nutritional compositions for 236 edible insect species based on dry matter [72]. The insects were found to still be a highly significant food source, that is rich in high quality protein, provides sufficient amounts of energy, meets amino acid requirements, is high in monounsaturated and/or polyunsaturated fatty acids, and rich in micronutrients, including minerals and vitamins [4]. *Table 9* in the *Appendix C - Mealworm*

Literature, retrieved from the FAO/INFOODS database, compares the average protein content among insects, reptiles, fish, and mammals [73].

8.4.2. Food Safety

Food safety is paramount in food production, processing and preservation. Issues of food safety with regard to insects include: microbial safety, toxicity, unpalatability, and inorganic compounds [4]. In order to commercialize the use of edible insects for food or feed, optimal preservation methods need to be determined, human hazards should be avoided, and the rearing system design must mitigate disease and minimize sensitivity to potential diseases. Therefore, risk guidelines and sanitary standards need to be developed and implemented for each species [4]. It is important to note that animal welfare and health issues arise when working in intensive animal production with high animal densities. Like many intensive production practices, insects are typically reared in small and confined spaces; to ensure animal welfare and mitigate health issues, farmed insects should be provided with adequate space [4]. Mealworms, like other insects tend to cluster. Therefore, in order to minimize mortality and increase productivity, optimal conditions are pursued in rearing facilities [4].

As mentioned in *Section 4.1.,* Insects are rich in nutrients and moisture and thus provide a favorable environment for microbial survival and growth [4]. And "although it has been stated that no significant health problems have arisen from the consumption of edible insects (Banjo, Lawal and Songonuga, 2006b), consumer confidence is arguably strongly correlated with the perceived safety of a given product." [4] With respect to zoonotic infections and health issues, there is insufficient research done on the risk of disease transmission from insects used as food or feed to humans. However, due to the significant taxonomic difference of insects compared to humans and conventional livestock, the risk of zoonotic infections are considered to be low. Nevertheless, careless use of waste products, unhygienic handling of insects, and the direct contact of the reared insects with outside contaminants could potentially increase the risks of zoonotic infection [4]. Therefore, Insect farming at a household level is able to mitigate potential microbiological hazards and zoonotic infections since it provides greater control over hygienic practices and provides safe feed sources for insects. Hence, a well designed rearing facility plays a significant role in ensuring food safety of edible insects.

8.5. Financial Analysis

8.5.1. Parts List and Final Cost

Table 10 below illustrates a list of parts used for the structure and their respective price.

Table 10 : A Parts List

Part	**Volume (cm^3)**	**Material**	**Cost**	**Cost (CAD)** [80]
Chamber	21769.8473	HDPE Plastic	65.31 (USD)	86.94
Door and Knob	1561.0266	Acrylic (Clear)	3.90 (USD)	5.19
Transparent Viewing Sheet	1800	Acrylic (Clear)	4.5 (USD)	5.99
Fan	N/A	N/A	$3.00 (CAD) [79]	3.00
Microcontroller	N/A	N/A	$2.49 (CAD) [78]	2.49
Heat Pads (x6)	N/A	N/A	68.82 (CAD) [51]	68.82
Tray Structure	2149	HDPE Plastic	6.45 (USD)	8.59
Larvae Trays (x6)	12,729.25	HDPE Plastic (Clear)	38.19 (USD)	50.84
Adult Tray	1466.4152	HDPE Plastic (Clear)	4.40 (USD)	5.86
Carbon Filter	N/A	N/A	$0.066 (USD)	0.088
LCD Screen	N/A	N/A	$30.00 (USD) [77]	39.93
DHT22 Temperature Sensor	N/A	N/A	$2.53(USD) [75]	3.37
Relay	N/A	N/A	$4.01(USD) [76]	5.34

Total Parts Cost: $286.45
Estimated Manufacturing and Labour Cost per Unit: $20
Proposed Retail Price: **$350**

8.5.2. Maintenance Costs

Table 11 below illustrates an overview of maintenance costs for the user.

Figure 17: Maintenance Cost of the Farm.

Item	Daily Electricity Consumption	Quantity/Harvest	Cost (CAD)	Cost/Harvest (CAD)
Heat Pad x 6	2.448 kWh [i]	N/A	0.1/kWh [83]	3.43
Fan	0.480 kWh [ii]	N/A	0.1/kWh [83]	0.672
Oatmeal	N/A	1.157 [iii]	3.37/kg [82]	3.90
	Total Maintenance Cost/Harvest			**$8.002**

[i]: Daily Electricity Consumption of a Heat Pad = 24 hr operation * 17 Watts [51] = 0.408 kWh ; **Daily Electricity Consumption For six Heat Pads =** 6 * 0.408 kWh **= 2.448 kWh**
[ii]: Daily Electricity Consumption of the Cooling Fan = 24 hr operation * 20 Watts [79] **= 0.480 kWh**
[iii]: Density = Weight / Volume ; Feed Volume Required = 54 cm * 30.4cm * 2 cm = 3283.2 cm^3;
Therefore, using Oatmeal (Quaker Quick Oats or Large Flake Oats) as feed with Density = 0.34 g/cm^3 [81][82], **Total weight = 1.157 kg /harvest.**

8.5.3. Economic Returns and Benefits

As calculated previously, the following costs are associated with the farm:

$$Investment\ Cost = \$350\ CAD$$

$$Maintenance\ Cost = \frac{\$8.00}{Harvest} = \frac{\$4.00}{Week}$$

(The harvest period is 14 days)

We are supplying 49 grams of protein per week of mealworms as stated previously. We will use ground beef as an example to compare the price of using our farm vs. buying commercial meat.

$$Price\ Ground\ Beef/kg = \$12\ CAD\ \ [84]$$

$$Grams\ protein\ per\ kg\ of\ ground\ beef = 143\ g\ \ [85]$$

$$Meat\ required\ for\ 49\ g\ protein\ =\ 0.34\ kg$$

$$Cost\ of\ buying\ meat\ =\ \$4.08\ CAD$$

There is marginal economic difference between buying conventional meat and using the farm. It is comparable to meat prices however, and will deliver other health and environmental benefits.

9.0. Conclusion

Protein is essential for providing a healthy diet, but with the rising costs of animal protein, the increased demand for protein in middle classes, population growth, food insecurity, and increased environmental pressures, it is difficult for many people to find affordable and healthy high protein food sources. Insect consumption, also known as entomophagy, has been recognized as a potential solution. This is because insects have high feed-conversion efficiencies, emit considerably lower ammonia and GHGs than conventional livestock and do not require a lot of space. Therefore, insect farming can be applied in both urban and rural areas; and depending on investment, insect farming can either be low-tech or highly sophisticated. Insects are also rich in good fats and are high in calcium, iron and zinc; making them healthy and nutritious alternatives to conventional livestock foods [4].

Our design seeks to solve or limit various health, environmental, and cultural issues that could possible increase in the future, mainly limited access to healthy and affordable sources of protein. While still in the early stages of development, it is possible that our design could help solve these issues while still being economically viable. The design involves 7 trays that separate the life stages of the mealworm to avoid cannibalism. Each tray is temperature controlled by heat pads and ventilated by exposure to a climate chamber containing a cooling unit. This allows the mealworm to grow at it's ideal growing temperature. A timer will go off once the larvae are ready for harvest after 2 weeks (14 days) to help make the farm user friendly. The current design estimates the cost of the farm to be $350 which is within our price range goal of $300-$400.

In general, insect farming or mini-livestock require low-tech activities and low-capital investments and thus "represent an innovative and novel food source rich in high quality protein as well as other beneficial nutritional ingredients such as fats, minerals and vitamins." [7]. Insects also provide livelihood opportunities for low income individuals as they can increase the quality of traditional diets and provide cash income to vulnerable people. Despite the benefits of entomophagy, more research needs to be done on the anti-nutrient properties and microbial risks of edible insects. In addition, to successfully produce insects at an industrial scale, practices for the mass production, processing, distribution and consumption of edible insects still need to be developed, along with food and feed regulations that can ensure food and feed safety and pave the way for consumer acceptance of insects as food.

10.0. Acknowledgments

We would like to thank Dr. Robert Kok for being our mentor, Dr. Chandra Madramootoo for advising us throughout the design project, Dr. Grant Clark for providing us with laboratory space to conduct our experiments. We would also like to thank the McGill University library for access to research journals, as well as Autodesk for their fantastic software.

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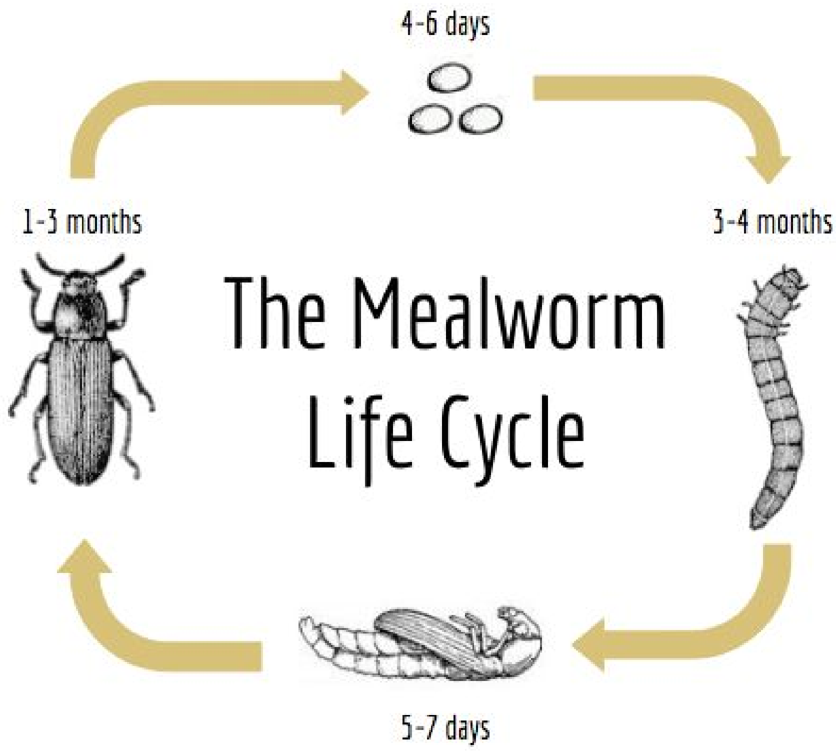
Appendix A - User Instruction Manual

Hello bug lover! Welcome to the mealworm farm project. You're almost on your way to producing a healthy source of protein for you and your family/friends. First let's get a little for familiar with Tenebrio molitor (T.molitor), the yellow mealworm.

The yellow mealworm undergoes complete metamorphosis! This means it has four life stages, each illustrated below.



When you receive your farm, it will come with seven bags of mealworms. In order to set up your farm, first make sure there is about 2 cm of substrate in each tray (we recommend a mix of oatmeal & wheat bran). Next follow these simple steps:

1. *Empty Bag # 1 (Beetles) in Tray # 1. This will be where the you beetles will reproduce and expand your colony! Notice that this tray has holes that allpw the eegs to fall down onto the next tray.*

2. *Empty Bag # 2 - 7 (Larvae at different development stages) in Trays # 2 - 7 respectively.*

The setup is now complete! Turn on The Farm^{TM}, follow the instructions that appear on the LCD screen and you are ready to go!

Some things to keep in mind:

Remember, it is your responsibility to make sure the mealworms have enough moisture to stay hydrated. You will need to feed your mealworms vegetable scraps (carrots, potatoes, etc…) every 2-3 days as vegetables contain moisture. The system will warn you if the tray is not getting enough moisture. Similarly, you will need to remove these excess vegetable scraps before they get moldy as this will not be healthy for the mealworms or for you

The harvesting cycle spans 2 weeks (14 days). A timer will start once you set up the farm, and after 14 days your mealworms will be ready to harvest! When ready to harvest, follow the following steps:

1. *Remove Tray # 7 (Harvest).*
2. *Separate the larvae and the pupa.*
3. *Place the pupae in the elevated platform in Tray # 1 (Beetles).*
4. *Seperate the larvae and store them in a container and freeze them overnight to induce mortality.*
5. *Discard of the substrate, wipe the tray with a dry cloth and securely return it inplace.*
6. *Now, pull the drawer of Tray # 6 (Larvae) to transfer the mealworms and substrate to Tray # 7 (Harvest), then securely return it inplace.*
7. *Repeat this for Trays # 5 - 2 repepectiely. This means you will be following this procedure from the bottom up!*
8. *Place fresh substrate in the Tray # 2 (Larvae).*
9. *Press "Finish" on the LCD display and the timer will start counting down to the next harvest.*
10. *Cook and enjoy your tasty larvae!*

Appendix B - Patents and Existing Designs

Figure 1: Livin Farms Hive Design. [24]

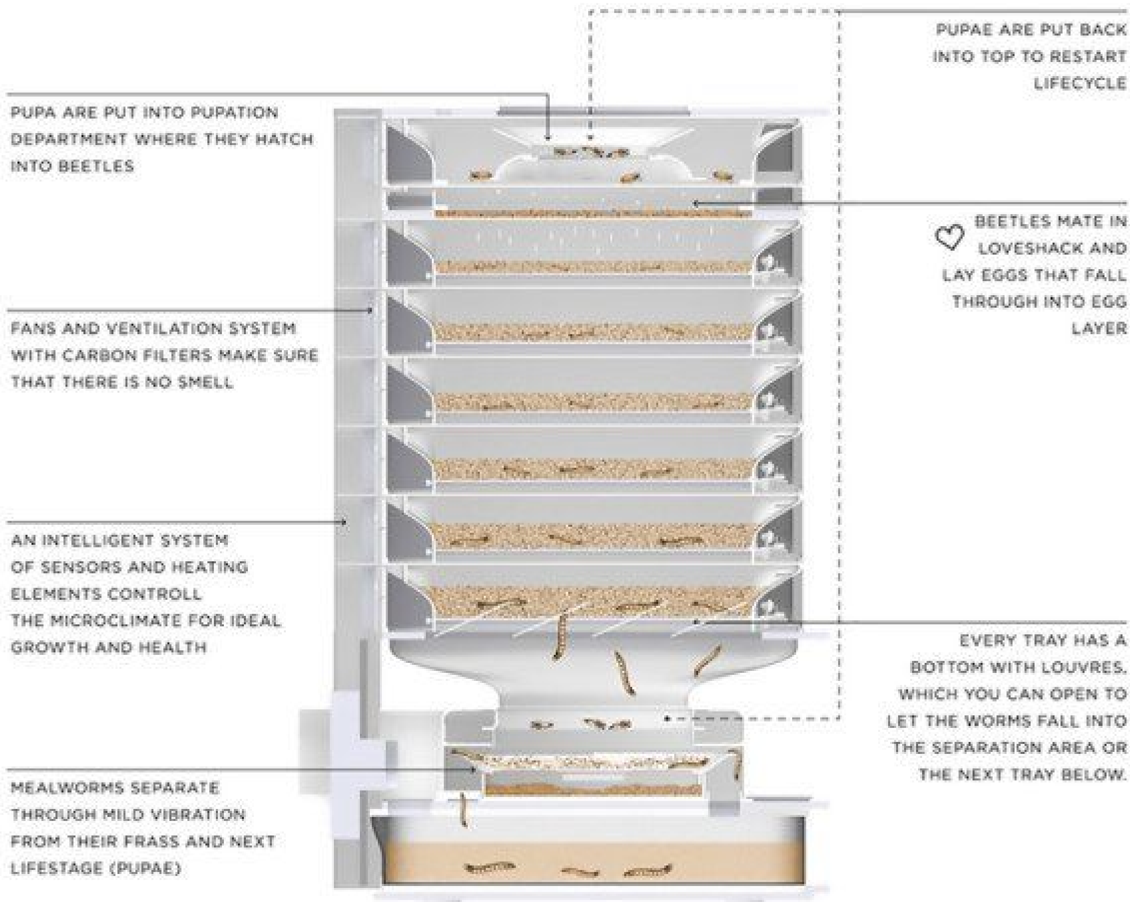


Figure 2: LivinFarms The Hive ™ [25]

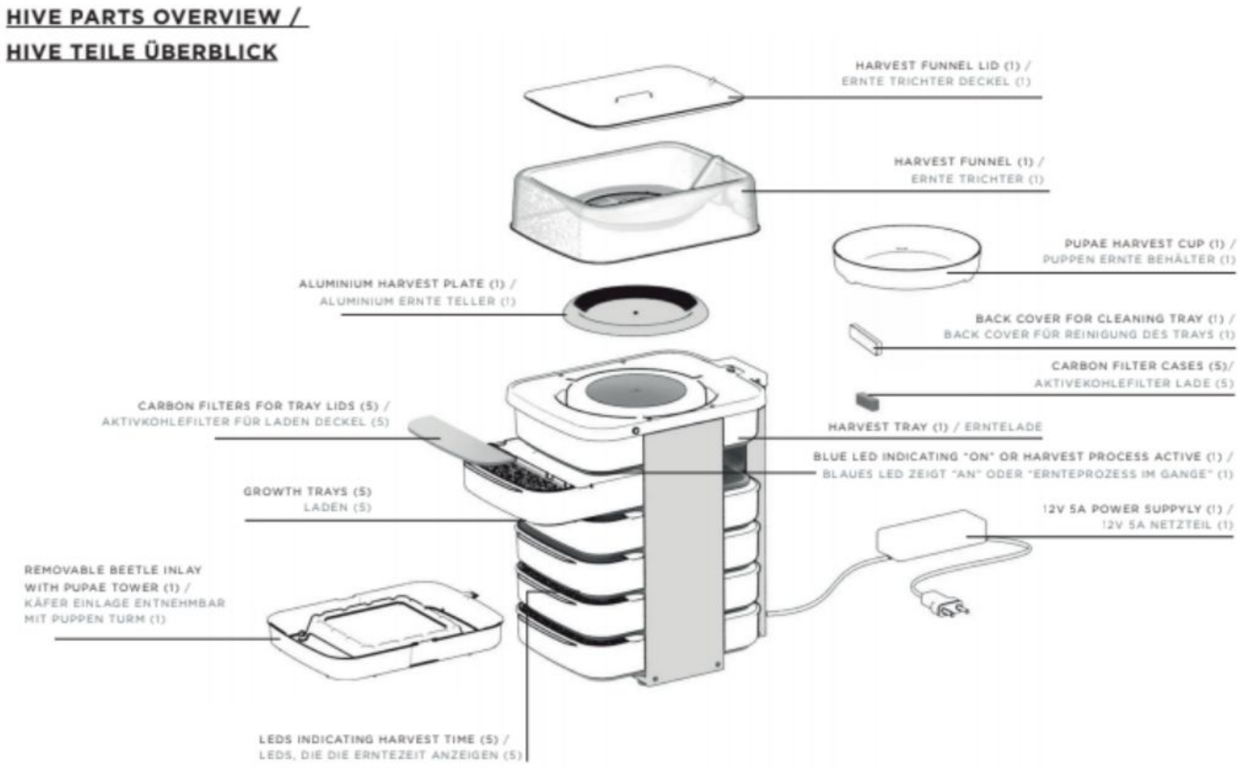


Figure 3: Yellow Mealworm Imago Collection Disk [26]

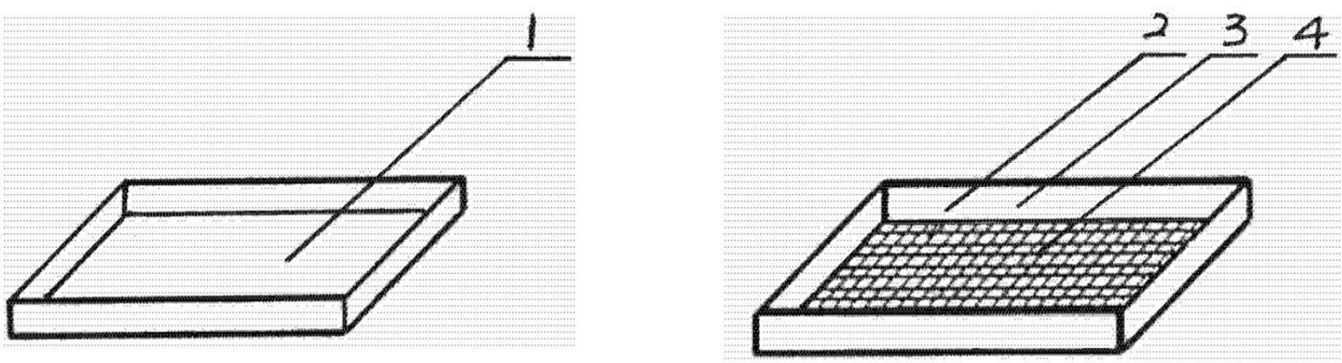
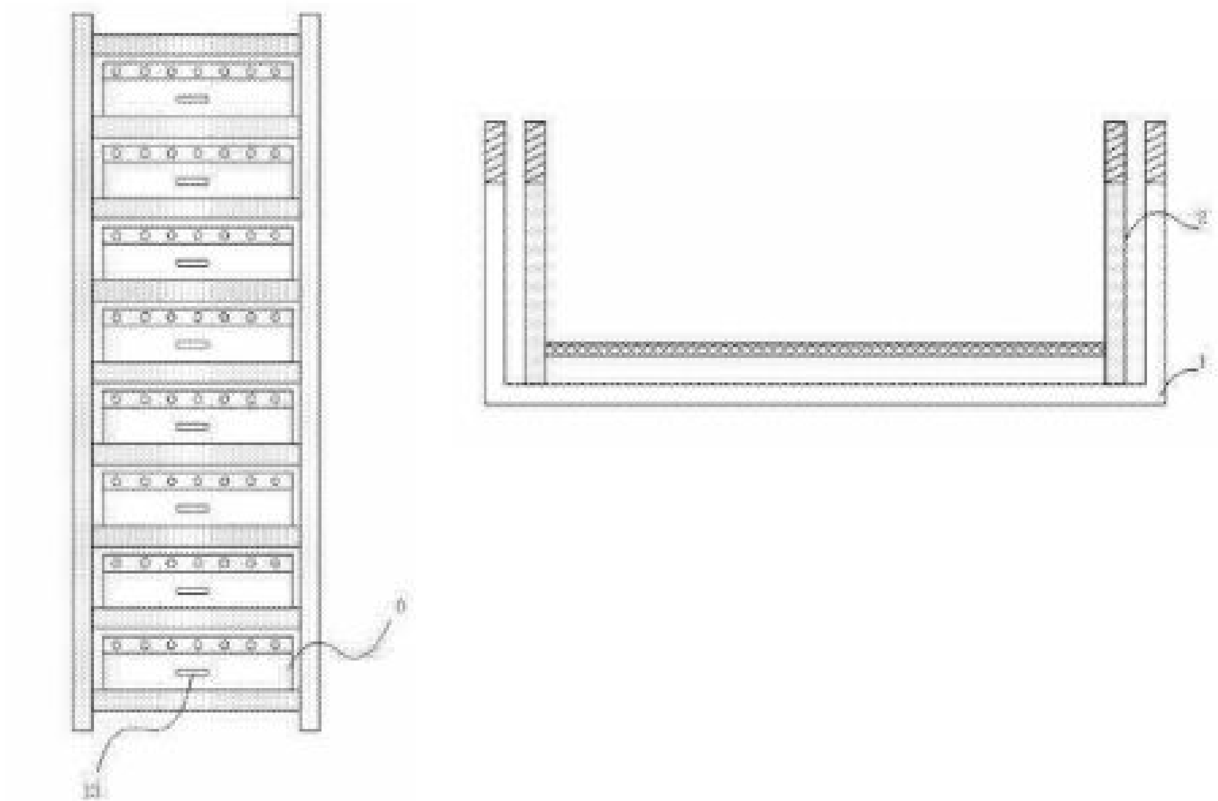


Figure 4: Mealworm Breeding Device [27]



Appendix C - Mealworm Literature

Figure 5: Schematic process for the production of food and feed products derived from insects.[7]

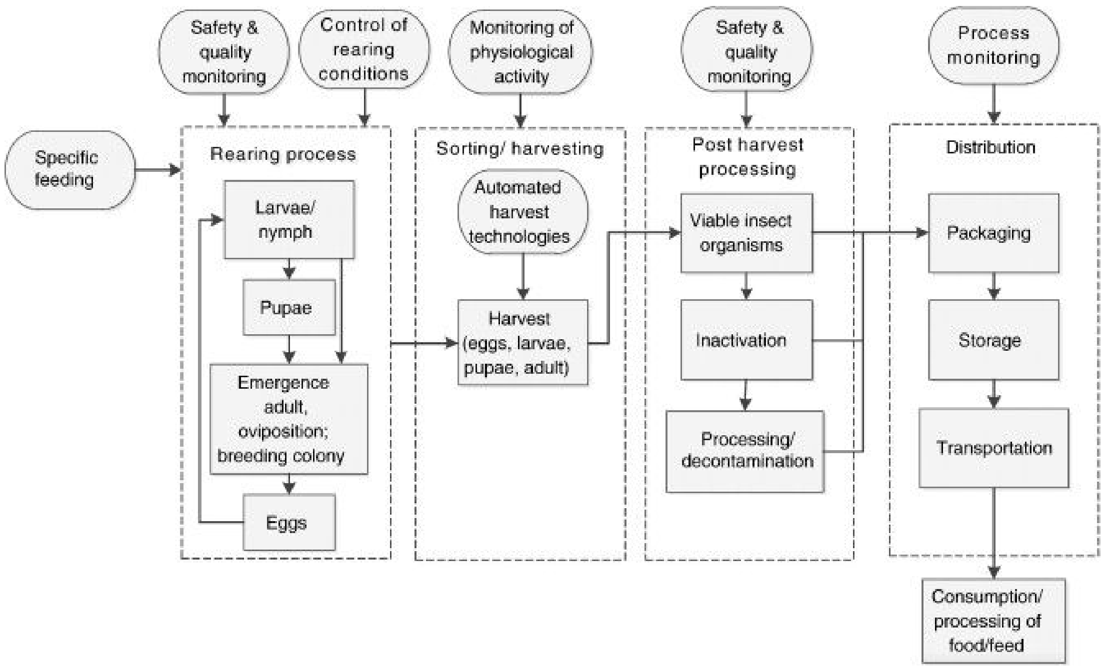


Table 9 : Average Protein Content of Insects, Reptiles, Fish, and Mammals.[]

Comparison of average protein content among insects, reptiles, fish and mammals

Animal group	Species and common name	Edible product	Protein content (g/100 g fresh weight)
Insects (raw)	Locusts and grasshopppers: *Locusta migratoria, Acridium melanorhodon, Ruspolia differens*	larva	14–18
	Locusts and grasshopppers: *Locusta migratoria, Acridium melanorhodon, Ruspolia differens*	Adult	13–28
	Sphenarium purpurascens (chapulines – Mexico)	Adult	35–48
	Silkworm (*Bombyx mori*)	Caterpillar	10–17
	Palmworm beetles: *Rhynchophorus palmarum, R. phoenicis, Callipogon barbatus*	Larva	7–36
	Yellow mealworm (*Tenebrio molitor*)	Larva	14–25
	Crickets	Adult	8–25
	Termites	Adult	13–28
Cattle		Beef (raw)	19–26
Reptiles (cooked)	Turtles: *Chelodina rugosa, Chelonia depressa*	Flesh	25–27
		Intestine	18
		Liver	11
		Heart	17–23
		Liver	12-27
Fish (raw)	Finfish	Tilapia	16–19
		Mackerel	16–28
		Catfish	17–28
	Crustaceans	Lobster	17–19
		Prawn (Malaysia)	16–19
		Shrimp	13–27
	Molluscs	Cuttlefish, squid	15–18

Figure 15: GWP, EU, and LU of 1 kg of fresh mealworms. [18]

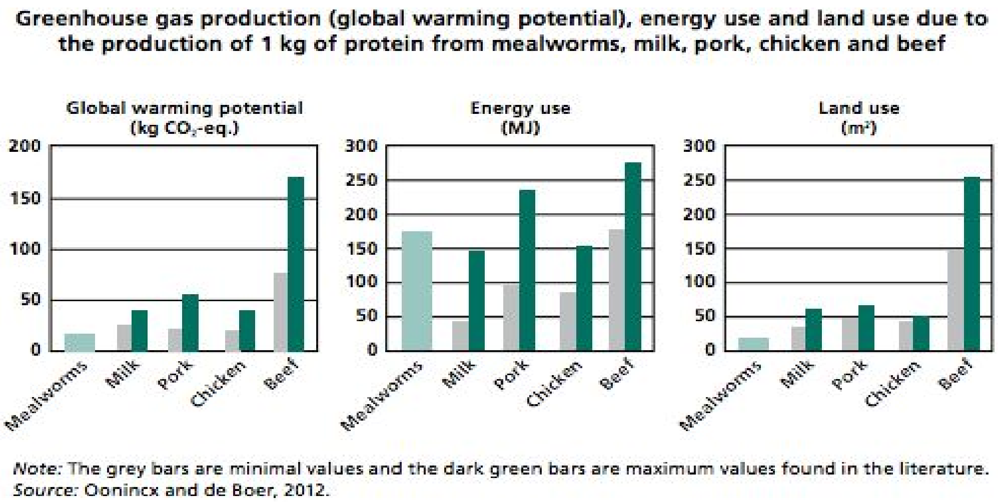


Table 7: Nutritional values of mealworms.[24]

Source: Finke, M. D. (2002), Complete nutrient composition of commercially raised invertebrates used as food for insectivores. Zoo Biol., 21: 269–285. doi: 10.1002/zoo.10031

Mealworm Nutrition Values (per 85 grams fresh mealworms)		
Nutrient	**Value**	**Unit**
Calories	175	kcal
Carbohydrates	13	g
Protein	16	g
Total Fat	16	g
Omega 3 Fatty Acids	0.25	g
Omega 6 Fatty Acids	5.98	g
Ash	11.4	g
Cholesterol	126.7	mg
Fiber	7.4	g
Vitamin A	85	IU
Vitamin B12	0.4	ug
Vitamin C	1.02	mg
Vitamin D	21.3	IU
Vitamin E	0.4	IU
Thiamin	0.204	mg
Riboflavin	0.69	mg
Niacin	3.5	mg
Folate	0.13	mg

Mealworm Nutrition Values (per 85 grams fresh mealworms)		
Nutrient	**Value**	**Unit**
Vitamin B5	2.227	mg
Biotin	0.0255	mg
Choline	156.74	mg
Calcium	14.365	mg
Chloride	158.95	mg
Chromium	0	mg
Copper	0.5185	mg
Iodine	0.01445	mg
Iron	1.751	mg
Magnesium	68.085	mg
Manganese	0.442	mg
Molybdenum	0	mg
Phosphorus	242.25	mg
Potassium	289.85	mg
Selenium	0.02125	mg
Sodium	45.645	mg
Sulfur	0	mg
Zinc	4.42	mg

Table 8: Nutritional Aspects of various invertebrates [74]

Mineral	Superworms	Giant mealworm (larvae)	Mealworm (larvae)	Mealworms (adult)	Waxworms	Silkworms	Crickets (adult)	Crickets (nymph)	Earthworms
Calcium (mg/kg)	177[c]	184[c]	169[c]	231[c]	243[c]	177[c]	407[c]	275[c]	444[b]
Phosphorus (mg/kg)	2,370	2,720	2,850	2,770	1,950	2,370	2,950	2,520	1,590
Magnesium (mg/kg)	498	864	801	606	316	498	337	226	136
Sodium (mg/kg)	475	489	537	632	165[a]	475	1,340	1,350	965
Potassium (mg/kg)	3,160	2,970	3,410	3,400	2,210	3,160	3,470	3,520	1,820
Chloride (mg/kg)	1,520	1,750	1,870	1,910	640	620	2,270	2,220	910
Iron (mg/kg)	16.5	21.5	20.6	21.8	20.9	16.5	19.3	21.2	50.4
Zinc (mg/kg)	30.7	44.5	52.0	46.2	25.4	30.7	67.1	68.0	17.7
Copper (mg/kg)	3.6	6.4	6.1	7.5	3.8	3.6	6.2	5.1	1.5
Manganese (mg/kg)	4.3	3.6	5.2	4.0	1.3[c]	4.3	11.5	8.9	1.3[a]
Iodine (mg/kg)	<0.1[c]	<0.1[c]	0.17	0.22	<0.1[c]	<0.1[c]	0.21	0.28	0.38
Selenium (mg/kg)	0.14	0.13	0.25	0.16	0.11	0.14	0.19	0.10	0.40

[a]Value is 67–100% of the NRC requirements for rats for growth.
[b]Value is 33–67% of the NRC requirements for rats for growth.
[c]Value is 0–33% of the NRC requirements for rats for growth.

Table 6: The Absolute and Relative GWP, EU, and LU of 1 kg of fresh mealworms

Table 2. Environmental impact of inputs in a mealworm production system.

	GWP (kg CO_2-eq)		EU (MJ)		LU (m^2)	
Carrots (kg)	0.38	14.27%	4.31	12.80%	0.51	14.39%
Mixed grains (kg)	1.11	41.98%	10.47	31.09%	3.03	85.14%
Gas (MJ)	0.70	26.26%	11.71	34.77%	0.00	0.02%
Egg trays (kg)	0.00	0.12%	0.04	0.13%	0.00	0.01%
Electricity (MJ)	0.45	17.06%	7.13	21.17%	0.01	0.24%
Water (M^3)	0.00	0.03%	0.01	0.04%	0.00	0.00%
Animal (kg)	0.01	0.29%	0.00	0.00%	0.00	0.00%
Farm	0.00	0.00%	0.00	0.00%	0.01	0.20%
Total	2.65	100.00%	33.68	100.00%	3.56	100.00%

Absolute and relative contribution global warming potential (GWP), energy use (EU) and land use (LU) for the production of one kg of fresh mealworms based on economic allocation.
doi:10.1371/journal.pone.0051145.t002

Appendix D - Experimental Data

Table 3: Experimental Data on Mealworm Weight.

Change in Mealworm Weight (g)

Mealworm	Trial 1 (old on bran)	Trial 2 (new on bran)	Trial 3 (new on mix)	Trial 4 (new on oats)
1	0.000	0.060	0.000	0.030
2	-0.060	0.010	0.040	-0.030
3	0.020	0.000	0.040	0.020
4	-0.050	0.020	0.070	0.030
5	-0.030	0.010	0.020	0.030
6	0.060	-0.040	-0.020	0.050
7	0.010	0.020	0.030	0.050
8	0.020	0.020	0.050	0.060
9	-0.010	-0.020	0.000	0.010
10	0.020	-0.010	0.000	0.010
Average Change	-0.002	0.007	0.023	0.026
Avg Dish Weight	8.150	8.105	8.145	9.010
Avg Feed Weight	3.110	3.000	3.270	4.120
	Total Weight			
Before	11.335	11.189	11.495	13.205
After	11.333	11.196	11.518	13.231
Average Change in Weight	-0.002	0.007	0.023	0.026

Table 4: Statistical Analysis of Experimental Data.

	Mealworm Weight (g)							
	Trial 1 (old on bran)		Trial 2 (new on bran)		Trial 3 (new on mix)		Trial 4 (new on oats)	
Mealworm	Before	After	Before	After	Before	After	Before	After
1	0.080	0.080	0.050	0.110	0.080	0.080	0.060	0.090
2	0.090	0.030	0.080	0.090	0.060	0.100	0.080	0.050
3	0.070	0.090	0.070	0.070	0.060	0.100	0.050	0.070
4	0.120	0.070	0.110	0.130	0.020	0.090	0.070	0.100
5	0.090	0.060	0.080	0.090	0.080	0.100	0.050	0.080
6	0.060	0.120	0.090	0.050	0.070	0.050	0.030	0.080
7	0.070	0.080	0.090	0.110	0.080	0.110	0.030	0.080
8	0.040	0.060	0.070	0.090	0.020	0.070	0.040	0.100
9	0.080	0.070	0.090	0.070	0.060	0.060	0.040	0.050
10	0.070	0.090	0.040	0.030	0.040	0.040	0.040	0.050
X bar	0.077	0.075	0.077	0.084	0.057	0.080	0.049	0.075
STDEV Sample	0.021	0.024	0.021	0.030	0.023	0.024	0.017	0.020
t 0.975 (alpha = 0.05)	2.262	2.262	2.262	2.262	2.262	2.262	2.262	2.262
Upper Limit	0.125	0.129	0.124	0.152	0.109	0.134	0.087	0.119
Lower Limit	0.029	0.021	0.030	0.016	0.005	0.026	0.011	0.031
Margin of Error	0.015	0.017	0.015	0.021	0.017	0.017	0.012	0.014

Appendix E - Final Design Sketches and Renderings

Figure 8: Engineering Sketch of a larvae tray.

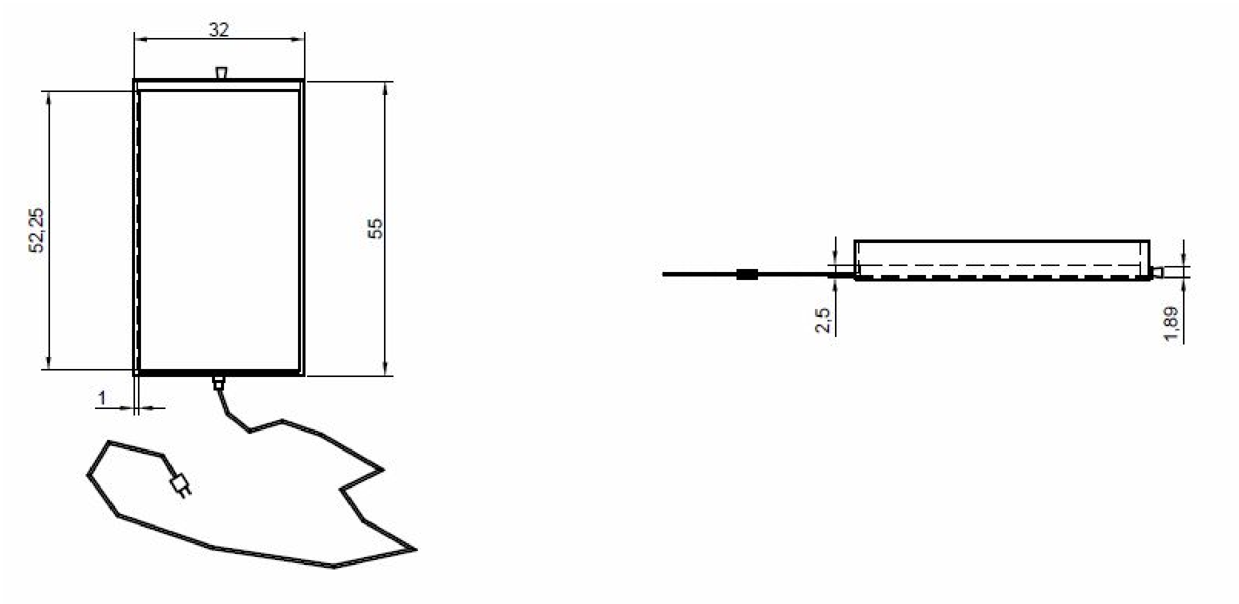


Figure 9: Engineering Sketch of a beetle tray.

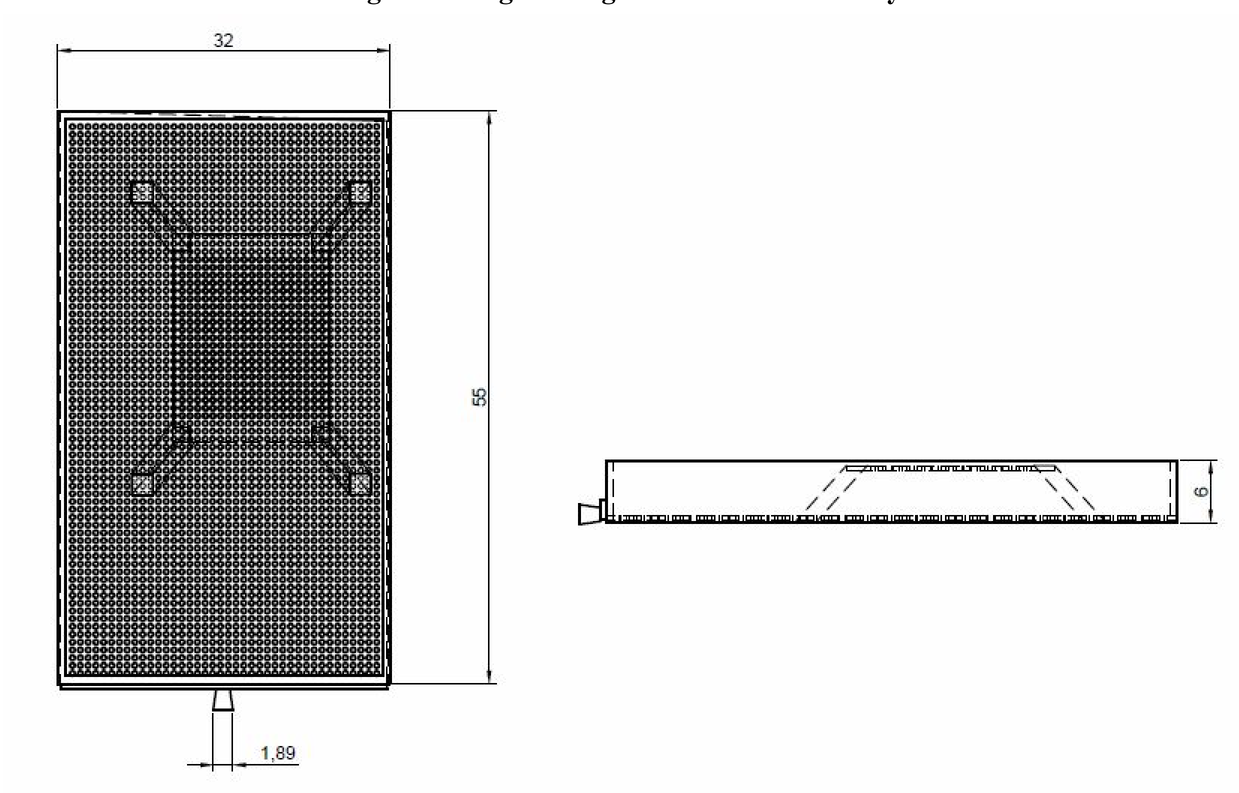


Figure 10: Rendering of a larvae tray on Fusion 360.

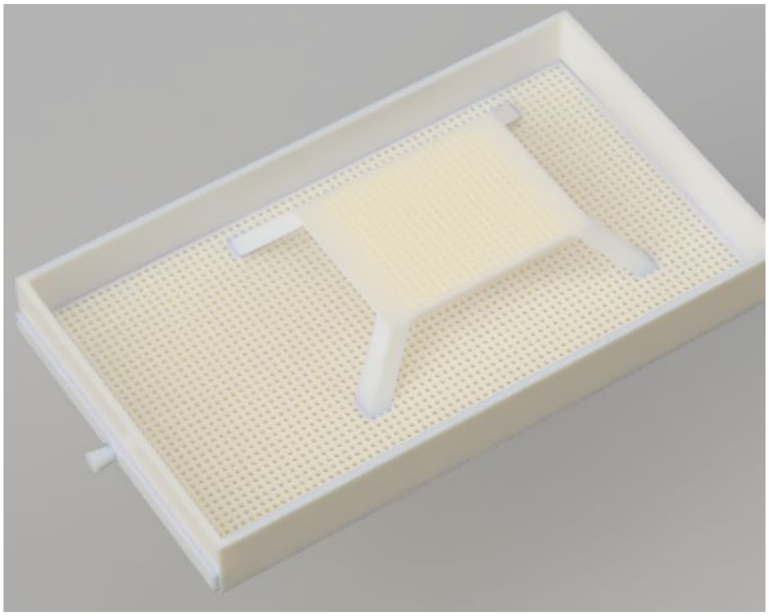


Figure 11: Rendering of a beetle tray on Fusion 360.

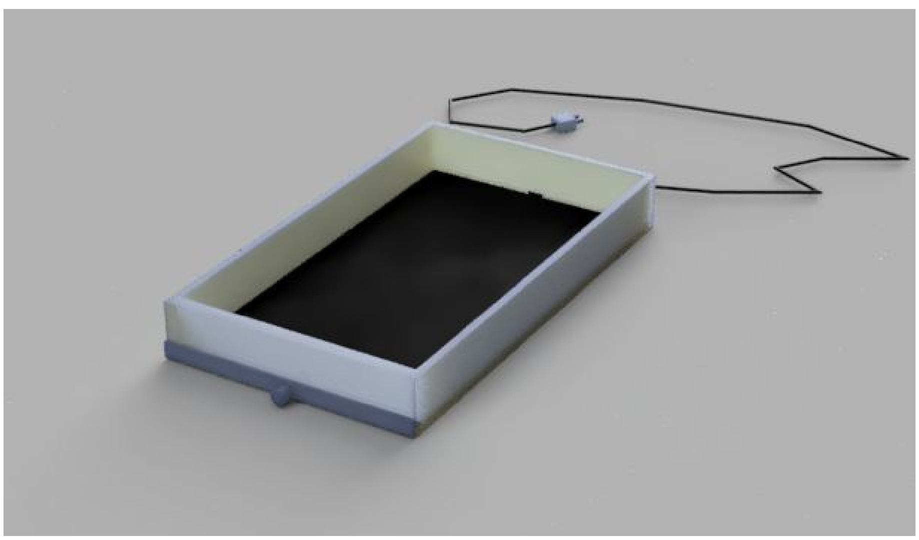


Figure 13: Engineering Sketch of final Structure