Developing a Household Level Smart Composter

MQP

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Abstract

The development of technology, policy, and infrastructure that support environmentally responsible management of food waste is increasingly important in mitigating global climate change. Households on the consumer level demonstrate a major source of food waste generation and thus are the project's target demographic. This project aims to create a smart composter that will promote decentralized, household composting behaviors to mitigate food waste related climate issues. It specifically targets the barriers–such as time, effort, space, and ick-factor–that deter young populations from contributing to composting efforts. The final design incorporates features inspired by industrial conical screw mixers, ensuring consistent mixing and high quality aeration. The addition of sensors and process controls help maintain optimal composting conditions, creating an efficient, hands-off composting experience.

Chapter 1: Introduction

The need to promote environmentally-friendly food waste management practices is increasingly important as the Earth experiences a rise in climate issues, including a rise in Greenhouse Gas pollution and direct impacts of overflowing landfills. Composting is an effective strategy that helps divert food waste from landfills [1]. The composting process involves microorganisms that break down food waste in three main phases, turning food waste into soil. This nutrient-rich soil product is beneficial for the plants and species living in it and its surrounding environment [2].

Typically, composting is carried out by individuals in backyard composters or piles. This process is known to be long (taking up to five weeks) and requires high amounts of effort to be successful. Few manual outdoor composters on the market are able to overcome these issues, leading to the development of what are referred to as "smart" composters – composters designed for indoor use that are able to create compost in short periods of time with minimal user input. However, many of these smart composters still require significant user input, are extremely expensive, and are not proven to actually produce viable compost for soil.

The goal of this project is to design a smart composting system that has the capability to create viable compost. By doing so, the aim is to address and overcome the barriers preventing young adults from composting. A full-scale engineering design process was conducted to create a working prototype of this smart composter. Key ideation strategies such as mind mapping and circle sketching were utilized in conjunction with pairwise comparisons and Pugh design matrices to select a final design from over 40 initial concepts.

The final design for the composter took inspiration from industrial conical screw mixers, which are typically used in particle mixing in the pharmaceutical industry. These mixers are specifically designed to create and maintain homogeneous mixtures– an important factor in ensuring even and consistent composting conditions inside a composter [3].

The various elements of the overall design were separated into multiple subsystems– aeration, mixing, compost chamber, heating, food deformation, food input and compost extraction. Analysis, testing, prototyping, and final design validation was conducted for each subsystem before it was incorporated into the final prototype assembly. The team ran multiple tests with the final assembly to confirm that the mechanical systems were functional. The mixing mechanism was determined to be successful in that it was able to achieve the desired rotational output.

Future work for this composter consists of running multiple full cycle tests to create and verify viability of compost. Additional automation through the use of feedback loops to adjust cycle parameters should also be incorporated. With these additions, the composting process can become more pleasant for users. In doing so, this project can have a significant positive impact on the environment.

Chapter 2: Background

The development of technology, policy, and infrastructure that support environmentally responsible management of food waste has become an increasingly important factor in global efforts to mitigate climate change [4]. Wasted food is associated with major greenhouse gas emission rates, the pollution of air and ground water, the decline of soil quality, and the indirect waste from growing and transporting food that was not consumed [5], [6]. Beyond the scope of environmental degradation, the mismanagement of discarded food materials has broader impacts on the economy and social and human rights issues such as systemic food insecurity [5]. The promotion and further development of proper food waste management systems represents a major opportunity for significant social, economic, and environmental progress.

According to the United States Environmental Protection Agency, discarded food materials account for 21.6% of the total municipal solid waste generated in the United States. Of this volume, only 6.1% is composted, with the majority of the remaining food waste being sent to landfill [7]. Food waste is generated at every level of the supply chain, from production, to storage, to transportation, to purchase [6], [8]. However, households on the consumer level are responsible for the highest food waste generation rate and therefore represent the greatest potential target for reducing rates of food waste in the United States [6]. Food management at this level is largely dependent on individual participation in food separation behaviors, either for collection by a centralized composting program or for incorporation into decentralized home composting systems [1], [8]. As such, when evaluating mitigation strategies for commercial food waste at the household level, it is relevant to first consider the existing composting technologies and infrastructure available on the residential level. Determinants of individual engagement in composting behaviors must also be considered to identify areas of weakness and opportunities to improve accessibility.

2.1 Smart Composting

Both centralized and decentralized composting systems exist for household use [1], [8]. The former involves intervention of a third party, such as a city government or other independent group, which organizes retrieval and disposal of resident food waste. Examples include a curbside collection program, or establishing a drop-off location. A decentralized composting system places responsibility for disposal solely on the individual, who might have a compost bin or a pile in their yard. Smart composting is an emerging technology which has been applied to both centralized and decentralized systems, though this report will mainly focus on the latter.

The purpose of a smart composting machine is to maintain the ideal physiochemical conditions necessary to produce quality compost without requiring user input [9]. The term “smart” refers to the system’s ability to self-regulate. Since it requires almost no user input, smart composting is seen as a more hands-off approach to traditional composting. The machine can sense conditions such as temperature and humidity, and adjust (e.g. add heat/water) when these values drop below the desired level.

This section will discuss how smart composting differs from traditional methods, the criteria assessed within a smart composting machine, and a review of the existing market and literature.

2.1.1 Smart vs. Traditional Composting

The main difference between smart composting and traditional composting is that the latter requires the user to decide when the compost needs maintenance, and to then perform that maintenance. With a smart composter, the user simply loads in their organic material, shuts the lid, and waits until the process is complete. Another notable disparity between the two is cost for the user. Traditional composting is often free, with the user simply storing their organic waste in a container they already own, or in a pile in their backyard. To account for the parts and labor required to put a smart composter together, it comes with a price tag. The most popular model currently on the market, the Lomi, is listed at $499 [10]. This of course does not include the extra cost of electricity to run the machine, a unique aspect of smart composting. In addition to the added cost, the location of a smart composter is limited by proximity to a power source, while a traditional compost bin can be placed wherever the user wishes. However, the use of electricity allows the composter to make use of sensors which regulate conditions important for quality compost.

2.1.2 Composting Criteria

All things that grow decompose naturally; composting simply speeds up this process by facilitating the ideal environment for the microorganisms responsible for decomposition, like bacteria and fungi [9]. This involves regulating factors such as temperature and humidity, and maintaining a proper ratio of carbon-rich (“browns”) to nitrogen-rich (“greens”) material. The result of the composting process is a soil-like mixture which is packed with nutrients and very beneficial for gardening, horticulture, and agriculture.

The functionality of a smart composter involves a microcontroller which controls sensors as well as the features that respond to the readings from those sensors. The goal is to establish a feedback loop which maintains the ideal environment mentioned earlier. Criteria being sensed may include temperature, humidity, carbon to nitrogen ratio, aeration rate, pH, and electrical conductivity. There is variance among sources regarding the ideal conditions for each of these, as there is not a universally established “best case scenario” for compost. However, it is understood that each of these properties have a significant effect on the quality of compost produced. The consideration of the effects varies based on the desired end use of the compost. For example, a composting system intended to create soil for a garden will be more concerned about electrical conductivity than one simply meant to condense food waste.

As mentioned, sensors for each criterion trigger an associated response when outside of the ideal window. Recommended temperature values range anywhere from 0 to 70°C [9], [11]. Possible responses to values outside this range include heating, rotation, and/or aeration processes. If the humidity sensor reads outside the accepted range (somewhere between 25-75%), water input, rotation, and/or aeration is proposed [9], [12]. Suggested solutions to a pH below 6 involve enacting aeration and/or rotation processes [11]. An unsuitable carbon to nitrogen ratio (outside of 15-35:1) can be satiated by adding carbon rich material, such as charcoal [9], [13]. Electrical conductivity is greatly influenced by salt levels in food, so the suggested strategy to lower the value is to monitor how much salt is going in, or to add water to existing compost [14].

2.1.3 Market and Literature Review

Several smart composting machines already exist in the market, the most notable being the aforementioned Lomi seen in Figure 1. This machine begins by grinding the compost, followed by a heating and cooling cycle. It regulates temperature, moisture content, and oxygen level throughout these processes [15]. The user interface features three modes: "Eco-Express", "Lomi Approved", and "Grow". "Eco-Express" is intended for food waste, and ideal for a user looking for quick turnaround and low energy use. The user can select "Lomi Approved" if they are looking to process bioplastics, compostable commercial goods, and packaging in addition to food waste. The final setting, "Grow", uses low heat in order to preserve soil-friendly microorganisms and bacteria. Other commercial systems similar to the Lomi include the Tero and Reencle.

Figure 1: The Lomi smart composting machine [16]

There are also several composters constructed for the purpose of research and experimentation. O. Sepúlveda-Cisneros et al. designed a system composed of an Arduino microcontroller; various sensors; a bioreactor; and mixing, crushing, ventilation, and spraying systems [9]. The parts used in this system are shown in Figure 2 below.

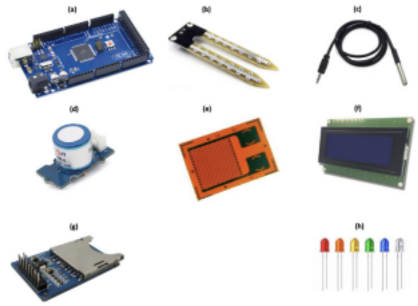


Figure 2: Components used in O. Sepúlveda-Cisneros et al. smart composter design [9]

Attempting to combat excessive food waste in Morocco landfills, Mustafa et al. proposed a smart composter with a rotating drum feature (Figure 3) [17]. This project also included an application which allowed the user to send instructions to the machine if the measured values of the compost were not suitable.

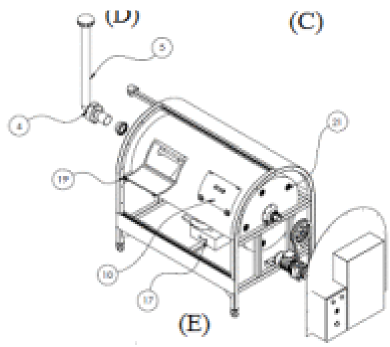


Figure 3: Assembly drawing of the smart composter designed by Mustafa et al. [17]

Finally, K. Gunasegaran et al. were inspired to design a smart composting system in response to the food waste crisis on Penang Hill, one of the most densely populated regions in Malaysia [18]. In addition to a turning plastic drum and an automated programming system, the authors also experimented with microbial solutions. Their system is shown in Figure 4.

Figure 4: Smart composting machine designed by K. Gunasegaran et al. [18]

Though there is no shortage of innovation in smart composting, the challenge comes in persuading people to participate.

2.2 Barriers and Determinants of Household Level Composting Behaviors

As the single most frequently landfilled material in the United States, attention to food waste represents a significant opportunity to make progress on environmental preservation efforts. While there have been efforts nationwide to adopt different food waste recovery either with large centralized collection programs or smaller decentralized community or home strategies, there is an apparent gap between consumer intention to engage in these programs and actual engagement with environmentally friendly behaviors [1], [8], [19]. To improve rates of participation, it is necessary to investigate the factors that limit individual consumer engagement with these behaviors.

A New York study on this found that the Theory of Planned Behavior is a useful framework to predict the behavior of individual residential source separation habits [8]. Under the Theory of Planned Behavior, there are three constructs that can be used to predict individual intentions of adoption. These include the individuals' attitudes or beliefs about the behavior, their perceived behavioral control or perceived ability to perform the behavior, and the social pressure that they may have to perform the behavior [8]. The following section discusses the determinants and barriers of individual engagement in household level responsible food waste management behaviors under the framework of the Theory of Planned Behavior.

2.2.1 Attitudes and Individual Perceptions of Composting Behavior

An individual's underlying beliefs and attitudes about composting or the degree to which they have invested personally in environmental issues can influence their intention to engage in responsible food waste management practices in their home, such as separating food waste for composting [8]. These attitudes can be informed by feelings of moral responsibility, previous exposure to and knowledge of the issue, the opinions of the individuals' social group, or feelings of anxiety about a perceived threat imposed by the issue [8], [19], [20]. Several studies have indicated that education and informational awareness campaigns that reinforce positive attitudes about responsible waste management are positively correlated to increased engagement with these behaviors [21], [22]. However, to maximize the effectiveness of a campaign like this, the communication strategy used in terms of content included and mode of information transfer are important. A study of strategies to increase household source-separation of food waste in Sweden revealed that distribution of written information about the potential environmental gains of source separating food waste did not significantly increase rates of source separation [23]. These results were attributed to a failure to account for the education level and potential language or cultural barriers of their target group [23]. The National Waste Awareness Initiative suggests that this type of information campaign could be improved by incorporating elements of personalization and visualization as well as simple but efficient language use to make messaging more accessible to different groups [22].

While information campaigns can help to form positive attitudes about pro-environmental behaviors, these alone will not necessarily influence an individuals' intent to adopt a pro-environmental behavior, especially when perceived behavioral control is low [8]. In fact, in situations where an individual perceives an action to be beyond their personal capacity, they will tend to distance themselves from the problem regardless of personal underlying attitudes about the issue, either by denying personal responsibility or by deflecting responsibility onto an external group [19], [20]. In a study investigating the psychological barriers that limit climate change mitigation action, it was found that in these scenarios, an individual might tend to adopt a belief that they are powerless and that their individual action or inaction is inconsequential and therefore deny any responsibility to change [20]. Alternatively, an individual trying to justify their inaction, might adopt the belief that the pro-environmental behaviors that they are already engaging with negate the need to adopt other pro-environmental behaviors, such as composting [20]. An extension of that study investigating the psychological barriers to individual behavioral changes that support biodiversity conservation found that people also have a tendency to attribute the responsibility of action to external groups, such as the government [19]. This study also found that these tendencies are directly correlated to the individual's perceived proximity to the threat of environmental degradation or climate change, with individuals more likely to divert responsibility to external powers when the threat is distant, and more likely to feel powerless and ignorant of how to initiate action when the threat is close [19]. At this point, the individuals' personal perceptions about the challenges of engaging in pro-environmental behaviors are limiting the possibility that that individual will adopt these behaviors in the future. As such, when developing strategies to improve participation in household level composting behavior, it is imperative that the factors that limit an individual's perceived behavioral control are minimized.

2.2.2 Perceived Behavioral Control of Household Level Composting Behaviors

The factors that influence perceived behavioral control of composting behaviors are those that relate to the confidence that an individual has in their own ability to engage with composting behaviors. These behaviors may include source-separation or management of a home composting system without significant disruptions to their lifestyle or personal goals [8]. These include considerations of time, space, energy investments, knowledge level or experience with composting, as well as accessibility to resources and composting technology [5], [8], [23], [24]. Different demographic groups will tend to be influenced by different limiting factors to varying degrees depending on the economic, social, and cultural characteristics of that group. For example, younger people have been found to be more likely to perceive pro-environmental behavioral changes as disruptions to their lifestyle that conflict with personal goals and aspirations than older people [19], [25]. This has in part been attributed to a perceived time barrier that is common with younger people who engage in busy lifestyles. These individuals tend to believe that they do not have the time to adopt pro-environmental behaviors such as composting, which is a significant barrier to participation in residential composting [8], [25].

However, a study evaluating barriers to citizen engagement in residential curbside composting programs determined that while the perception that composting behaviors are time-consuming, direct pressures such as average work hours do not significantly impact participation [25]. Other determinants of engagement with residential composting behaviors include home ownership and family size [8], [25]. Both private home ownership and larger family size are correlated with increased composting behavior which can be attributed to a number of situational and practical factors [8], [25]. For instance, an individual renting an apartment might struggle more with adopting responsible food waste management practices that work with limited space and less control over setup than a private home owner that likely has more inside and outside space and doesn't have to adhere to rental agreements that might limit the types of composting system options [8].

However, of all of these considerations, those relating to convenience have been found to universally be the most effective at increasing participation in composting programs [23], [24]. A study performed in Sweden in 2014 evaluating the role that convenience plays on household food waste separation participation, revealed that installing sorting equipment directly into houses to improve convenience of food waste separation increased the volume of home-separated food waste by almost 50% [23]. This result was also investigated in a Canadian Study that was specifically evaluating the rates of participation in composting in high-density residences at varying levels of convenience by changing the physical distance the individual will have to go to participate [24]. With a 70% increase in composting behavior under highly convenient conditions, the study confirmed the relationship between convenience and engagement in pro-environmental behaviors with an emphasis on physical proximity [24].

Another significant factor that can influence an individuals' perceived behavioral control is the individual perception that food waste separation for composting is unhygienic, smelly, and will attract bugs or other pests [8]. This can also include the feelings of disgust and concern associated with the thought of handling expired foods during separation. These perceptions of food waste as 'gross' or 'messy' are more likely to be held by individuals with limited knowledge of or experience with composting and are barriers to perceived behavioral control. Conversely, individuals who are already engaging in other pro-environmental 'gateway' behaviors such as recycling or who are a part of a social group that share pro-environmental attitudes are more likely to have a greater perceived behavioral control and will be more open to adopting composting behaviors [8].

2.2.3 Subjective Norms and Social Pressures Surrounding Composting Behavior

Individual subjective norms and social pressures are considered to be equally important as individual perceived behavioral control when evaluating an individuals' intention to engage with composting behaviors. Subjective norms are determined by an individual's confidence that a behavior will be accepted by their social group or approved by an individual that they respect [8]. When an individual's immediate social group supports or actively engages in pro-environmental behaviors such as composting, that individual may feel social pressure to also perform the behaviors so as to not be perceived as an outlier in the group or face social rejection. Conversely, an individual is less likely to engage in these behaviors if they believe that they would be negatively perceived by their immediate social group [8], [19]. Perceived social pressures have been found to especially affect younger people who are more likely to have concerns over the ways that adoption of these behaviors could impact their social status than elderly people [19]. There is also a high correlation between family approval or having family members who are already engaging in food waste separation behaviors and a person's decision to also participate in these behaviors [8].

The Swedish study of household level source-separation behaviors demonstrated the effects of 'social normalization' on separation behaviors [23]. This study found that by installing separation equipment directly into all of the homes of their study group to increase convenience, they had inadvertently created a social norm in which food separation was the approved behavior in the study group. When members of that group saw all of their peers engaging with separation behaviors, they were influenced to also engage in separation behaviors so as to fit in with the larger group demonstrating the role that subjective norms play in individual behavior [23].

2.3 Aim of the Project

The aim of this project was to design a smart composting system that is able to produce viable compost. This composter will differ from traditional composters in a variety of ways- mainly in that it will be "smart," meaning it will use sensors and actuators to make necessary corrections in order to optimize the quality of the compost. Marketed towards busy young adults aged 18-35 who live in apartments, this composter aims to address and overcome the various barriers preventing young adults from participating in composting.

One of the main factors that keeps some from composting is what is called the "ick factor," typically referring to the odor emitted by improperly managed compost, or visually observing the food degradation process. Educating users on proper composting practices will help to minimize this, since compost under the right conditions should not produce an odor [26]. This composter design will aim to overcome the ick factor by ensuring that the compost maintains optimal levels of temperature, humidity, aeration, and correct ratios of carbon to nitrogen throughout the process. The sensors programmed in the smart composter will communicate with the system, telling it when to make certain corrective actions, and inform users of other actions they could take to improve the quality of their compost. Additionally, this composter will feature one chamber solely dedicated to the composting process. Once the compost is finished, it will empty into a collection drawer. The user will not be exposed to the food degradation process, further addressing the ick factor. Providing users with the tools to produce quality compost that doesn't smell or attract pests and minimizes the ick factor may empower those who lack the education or resources to participate.

This composter will also address the “time barrier” that serves as another factor preventing some from composting [25]. Typical composting can be seen as a time consuming and arduous process, and may take up to five weeks to reach the final product [26]. The composter will utilize sensors to control a heating system, rotation, and airflow throughout the chamber. Optimizing these values in the composter aimed for an approximate composting time of one week. Along with increasing the efficiency of the composting process, this composter will ideally require much less effort than traditional composting. The sensors will be programmed to respond to various levels of temperature, humidity, and aeration. The responses from the sensors will carry out most corrective actions that, in traditional composting, would have to be done manually by the user. This approach will help to overcome the time barrier to composting.

Another barrier that may hinder composting efforts is lack of living, countertop, or yard space. Younger generations are more likely to be renting an apartment rather than owning a home. Those that rent are more likely to be single, live in central cities lacking yard space, and have lower incomes than those that own homes [27]. These demographics serve as potential barriers to composting that this smart composter will address. Due to its small size and efficient and interactive process, this composter will cater to busy young adults living in apartments who want to make a positive impact on the environment. Additionally, the cost of waste collection will be reduced as food waste is diverted from trash bins to the composter [12]. The smart composter will also feature a display to inform users of the direct impact they are making, in terms of the amount of waste their composter has diverted from landfills or the percent by which their Carbon footprint has been reduced. This is a useful feature because research has shown that individuals who feel as though they are making a difference and who are more connected to the composting process are more likely to participate in composting [25].

In addition to feeling a connection to the composting process, feeling a connection to a wider community of individuals who compost may increase the desire to participate. This is due in part to the fact that people who are related to or are friends with those who compost already are more likely to be inspired to begin composting [8]. Connecting users of this composter through a social app to share tips, amount of compost produced, and troubleshoot any issues will likely inspire more individuals not only to start composting, but to stick to the process for long periods of time.

This composter will be marketed towards young adults who have busy lifestyles. These younger generations are actually less likely to participate in community composting efforts or use a curbside composting cart [25]. While they may be less likely to compost, younger adults are widely known for their desire to make a difference in the world. Research conducted by the Pew Research Center has shown that Gen Z and Millennials are likely to have increased activity in addressing and taking action against climate change than older generations [28]. These facts imply that there exists a barrier between young adults and composting; whether this barrier be the cost, time, space, or effort required to participate. Addressing and overcoming this barrier will inspire more young adults to begin composting, thus having a significant impact on the environment.

Chapter 3: Initial Design Process and Ideation

A full-scale engineering design process was conducted to create a working prototype of this smart composter. Based on market research and the desired functional expectations for this product, a number of specific criteria were selected to define the design requirements that must be met and the features that must be optimized to meet the project goals and objectives. Based on those criteria, a variety of composting system designs were developed using ideation strategies including mind mapping, circle sketching, individual brainstorming, and more. Six designs were then chosen and compared using two design matrices to determine the final system design.

3.1 Design Objectives, Requirements, and Specifications

The goal of this project is to design a smart composting system that has the capability to create viable compost. In doing so, the aim is to address and overcome the various barriers preventing young adults from participating in composting.

To accomplish this goal, the following objectives were created:

- Create a mechanical system that has all the necessary tools to make useable compost
- Ensure compost will be viable by creating an ideal composting environment that can be monitored and maintained in terms of aeration, temperature, moisture, and C:N ratio
- Improve the user’s composing experience by minimizing user input and ick factor

To achieve these objectives, design requirements and specifications were developed based on both customer and functional perspectives.

Design requirements relevant from a customer perspective:

- Safe to use
- Easy to use
- Reduced smell / ick factor
- Adaptability for various volumes
- Low energy use
- Durability
- Low Noise Level
- Low Cost
- Aesthetically Pleasing

Design specifications relevant from a functional perspective:

- Efficient aeration
- Effective heating
- Ease of manufacturing

- Removal of moisture / humidity
- Homogenous mixing
- Cost to manufacture
- Ease of food deformation
- Ease of food input
- Simplicity of design
- Ease of extraction
- Internal shape
- User interface
- Addition of moisture / humidity

Based on the design requirements associated with this type of device, a pairwise comparison as seen in Table 1 below was utilized to rank the importance of each requirement from 0-1 when compared to one another. The total points for each were then added up to determine which requirements were the most important to focus on for the design from a customer point of view.

Table 1: Pairwise Comparison Based on Design Requirements from a Customer Perspective

	Safety	Ease of Use	Cost	Adaptability	Durability	Energy Use	Noise Level	Smell / Ick Factor	Aesthetics	Total
Safety		1	1	1	1	1	1	1	1	8
Ease of Use	0		1	1	1	1	1	1	1	7
Cost	0	0		0	0	0	0	0	0.5	0.5
Adaptability	0	0	1		1	0.5	1	0	1	4.5
Durability	0	0	1	0		0.5	1	0	1	3.5
Noise Level	0	0	1	0.5	0.5		1	0	1	4
Smell / Ick Factor	0	0	1	0	0	0		0	1	2
Aesthetics	0	0	1	1	1	1	1		1	6
Cost	0	0	0.5	0	0	0	0	0		0.5

Based on this comparison, the design requirements were ranked according to their respective point totals as seen in Table 2 below.

Table 2: Ranking of Design Requirements Based on Pairwise Comparison from a Customer Perspective		
Ranking	**Requirement**	**Point Total**
1	Safety	8
2	Ease of Use	7
3	Smell / Ick Factor	6
4	Adaptability	4.5
5	Energy Use	4
6	Durability	3.5
7	Noise Level	2
8T	Cost	0.5
8T	Aesthetics	0.5

*Note: T indicates a tie for the ranking.

Safety was determined to be more important than any other requirement and therefore scored 8 points. It is crucial that the composter design is safe for the user and will not injure them throughout the device setup, the composting process, or device cleanup.

Ease of use was ranked second with a score of 7 points, as it only came second to safety. The composter is considered easy to use if the user can intuitively understand how to operate the composter. It is important to the design that the composter only requires minimal effort for the user.

Because *smell/ick factor* is one of the main barriers preventing people from composting, it was ranked third with a score of 6. The chosen design should aim to reduce this as much as possible while maintaining safety and ease of use.

The composter's *adaptability* was ranked fourth with a score of 4.5. The composter is adaptable if it allows for various volumes and food types.

Energy use was ranked fifth with a score of 4, as it seems of equal importance in the comparison with adaptability and durability. It is very important to consider how much energy the composter requires, because if the composter is using too much energy it can actually mitigate the positive effects of composting in the first place.

Durability was ranked sixth with a score of 3.5. The composter needs to be durable enough that it will not break or fall apart when running.

The *noise level* of the composter was ranked seventh with a score of 2 because while it would be nice if it was quiet and barely noticeable, many households are used to the noise of appliances such as dishwashers or washing machines running. The noise level does not impact the function of the composter, it is simply customer preference.

Lastly, *aesthetics* and *cost* were ranked last, each with a score of 0.5. While a sleek looking composter that is low cost may be ideal for customers, it was not integral to the function nor is it a barrier to composting.

Once the design requirements were ranked by importance according to the customer, the design specifications could be ranked by importance according to function using a second pairwise comparison as seen in Table 3 below.

Table 3: Pairwise Comparison Based on Design Requirements from a Functional Perspective

	Efficient Aeration	Effective Heating	Cost to Manufacture	Ease of Food Input	Homogeneous Mixing	Simplicity	User Interface	Ease of Extraction	Moisture / Humidity (Adding)	Moisture / Humidity (Removing)	Ease of Food Deformation	Ease of Manufacturing	Internal Shape	Total
Efficient Aeration		1	1	1	1	1	1	1	1	0.5	1	1	1	8
Effective Heating	0		1	1	0.5	1	1	1	1	0.5	1	1	1	6.5
Cost to Manufacture	0	0		0.5	0.5	1	1	0.5	1	0	1	1	1	4.5
Ease of Food Input	0	0	0.5		0	0.5	1	1	1	0	0	0	1	4
Homogenous Mixing	0	0.5	0.5	1		0.5	1	1	1	0.5	1	0	1	5.5
Simplicity	0	0	0	0.5	0.5		1	1	1	0.5	0.5	0	1	4
User Interface	0	0	0	0	0	0		0	1	0	0	0	1	1
Ease of Extraction	0	0	0.5	0	0	0	1		1	0	0	0	1	2.5
Moisture / Humidity (Adding)	0	0	0	0	0	0	0	0		0	0	0	0	0
Moisture / Humidity (Removing)	0.5	0.5	1	1	0.5	0.5	0	1	1		1	0.5	1	6
Ease of Food Deformation	0	0	0	1	0	0.5	1	1	1	0		0.5	1	4.5
Ease of Manufacturing	0	0	0	1	1	1	1	1	1	0.5	0.5		1	6
Internal Shape	0	0	0	0	0	0	0	0	1	0	0	0		1

Based on this comparison, the design specifications were ranked according to their respective point totals as seen in Table 4 below.

Table 4: Ranking of Design Specifications Based on Pairwise Comparison from a Functional Perspective

Ranking	Requirement	Point Total
1	Efficient Aeration	8
2	Effective Heating	6.5
3T	Ease of Manufacturing	6
3T	Moisture / Humidity (Removing)	6
5	Homogenous Mixing	5.5
6T	Cost to Manufacture	4.5
6T	Ease of Food Deformation	4.5
8T	Ease of Food Input	4
8T	Simplicity	4
10	Ease of Extraction	2.5
11T	Internal Shape	1
11T	User Interface	1
13	Moisture / Humidity (Adding)	0

*Note: T indicates a tie for the ranking.

Efficient aeration was ranked the most important requirement from a design and functional standpoint for this composter design and therefore received 8 points. Proper aeration is crucial to creating viable compost, as it makes sure oxygen is introduced into the system, which is needed by the microorganisms.

Effective heating was ranked second with a score of 6.5 points. The composting process itself does generate some heat on its own which is why this requirement was not tied for first, however, maintaining optimal temperature levels is still very important to the process.

From a design perspective, *ease of manufacturing* is very important to consider and therefore scored 6 points, tying for third. If this product made it to mass production, it would be ideal for its manufacturing process to be as simple as possible so that manufacturing lead times and costs are low.

Because it is more likely that the compost will be wet and not dry, *removal of moisture / humidity* is necessary to ensure that the compost process continues efficiently and oxygen can continue to flow through the food particles. This requirement therefore received 6 points, tying for third.

Homogenous mixing ensures even composting conditions throughout the chamber, making sure that one area is not experiencing faster or lower quality composting than another. It received a score of 5.5, ranking at fifth place. While it does make sure the compost matures at the same time, composting could still occur without it as it does in natural outdoor composting.

Similar to ease, the *cost to manufacture* the product should ideally be as low as possible to increase profit margins if this product were to reach mass production. The prototype manufacturing also needed to stay within the given budget of this project. This aspect was ranked sixth with a score of 4.5.

Ease of food deformation makes the composter more hands-off for the user and is also useful because having smaller pieces of food scraps makes the composting process more efficient. It received a score of 4.5 and was ranked sixth because it aligns with consumer and functional requirements.

Ease of food input is necessary to consider as it does align with the objective of making the composter as hands off as possible. However, it is more important for customer ease of use than actual function of the composter and was therefore ranked eighth with a score of 4.

Simplicity of design ties into the ease and cost of manufacturing. More complex designs result in parts, fabrication, and assembly that are also more complicated. This increases the cost as well. However, while simplicity is beneficial, the design still needs to achieve functional and performance expectations which is why it is ranked eighth with a score of 4.

Similar to ease of food input, the *ease of extraction* makes the process more hands off for the user and means that less time and effort is required. Again, while this is more important for customer ease of use than actual function of the composter, this factor received a score of 2.5 and was ranked tenth.

The *internal shape* of the comosting chamber is important to consider because some geometries can provide enhanced mixing abilities. However, because this is not the sole factor impacting those mixing capabilities, it was ranked low and tied for eleventh with a score of 1.

The *user interface* of the composter should provide an educational and/or community aspect to composting by incorporating information and statistics about the process and the user's direct impact on the environment. This is important because it can make composting a more pleasant experience and get people excited about composting. However, because this is not tied specifically to the functions related to the composting process, it was ranked eleventh with a score of 1.

The *addition of moisture / humidity* was ranked the lowest at 0 points, as it is unlikely that moisture would need to be added to the compost. The compost itself is typically on the wetter side than the dryer side, so including this function is not as necessary.

In addition to these project based criteria, additional constraints included:

- Completion within the academic time frame of four terms
- Department provided project budget of $1250

These objectives, requirements, and constraints were held paramount while developing 48 different composting systems through many ideation techniques.

3.2 Brainstorming and Ideation

The design process continued with ideation, where a variety of brainstorming tools were utilized to create general designs, including a mind map, subsystem element sketches, and circle sketching. The mind map, which can be seen in Figure 5 below was divided into seven categories that correlated to the main functions of the composting system: food input, mechanical grinding, aeration system, moisture/humidity system, heating system, extraction of compost, and user interface. The team expanded upon each component by brainstorming ways to achieve each function. For example, in the aeration category, the team came up with “suction / pull air out,” “positive / push air through,” and” mechanical turning” as means to aerate the system.

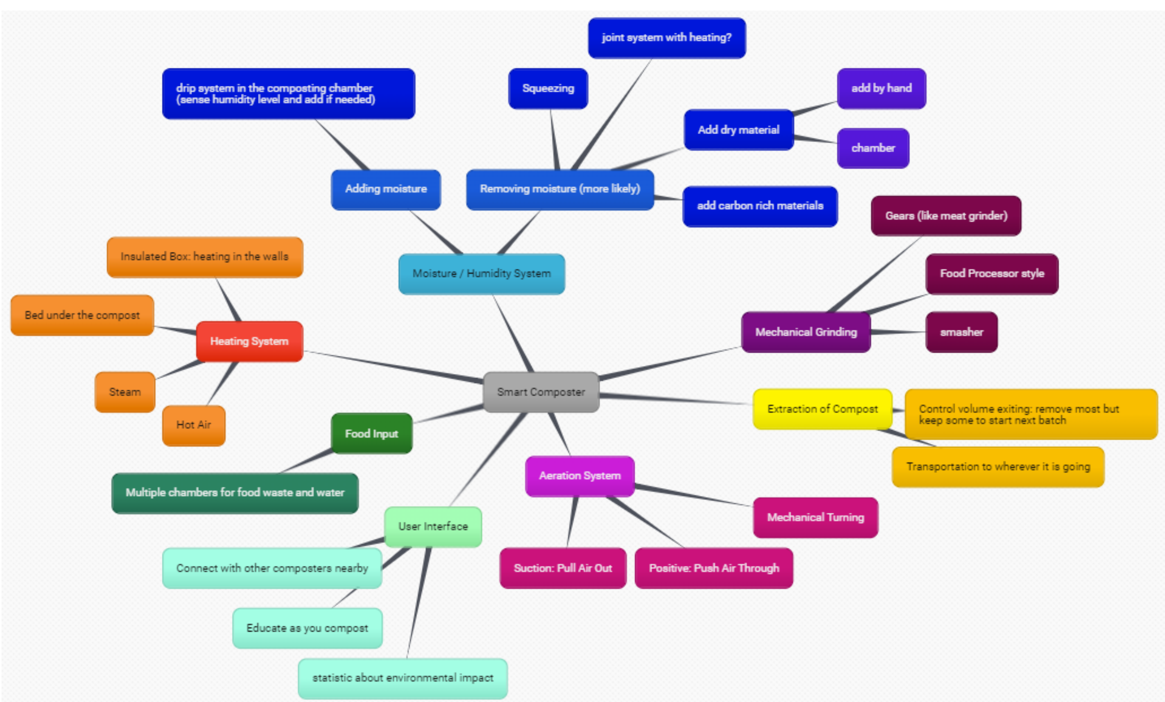
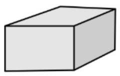
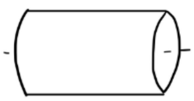
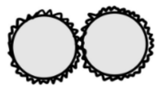
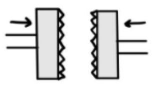
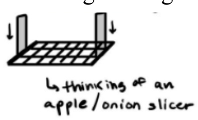
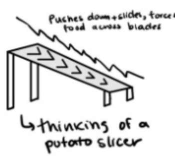
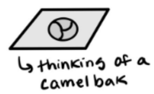
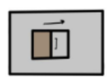
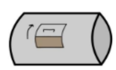
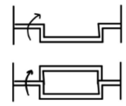
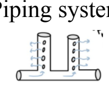
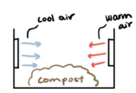
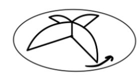
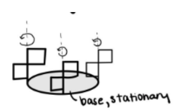
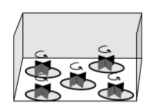
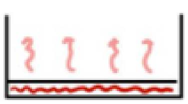
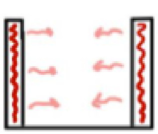
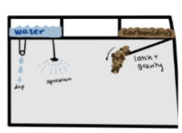
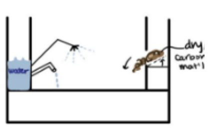
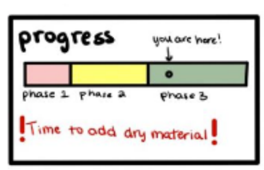
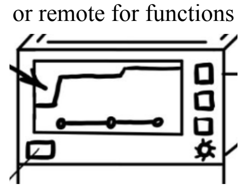
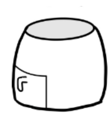
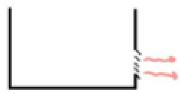
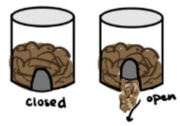
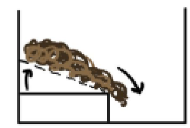


Figure 5: Mind map for composter design ideation

Based on the ideas generated from the mind map, the team created sketches, seen in Table 5, to go into more detail on various elements for each functional category. Such components included general shape of the composter, mechanism to cut/grind food, food insertion opening, methods of aeration, methods of heating and cooling, reservoirs for carbon-rich material, user interface, and compost output method.

Table 5: Sketches of Elements for Each Functional Category

General Shape	Food Cutting Mechanism	Opening for Food Input	Aeration Methods
Rectangular / square box  Cylindrical   Air fryer 	Rotating “gears”  Squishing / crushing  Slicing / dicing  	Hinged lid  Screw on lid  Slider  	Rotating wands  Piping system  Air flow over compost  Rotating fins   
Heating and Cooling	**Reservoirs**	**User Interface**	**Compost Extraction**
Heated bed  Heated walls  Ventilation	Above compost  On sides  Cereal dispenser	Big touch screen / iPad  Smaller display with buttons or remote for functions 	Slide out tray / drawer  Air fryer style basket  

	 Coffee ground dispenser 		Dumps into separate chamber 

These sketches served as a way to explore options and visualize the ways in which each functional requirement could be achieved. These options were considered with respect to the ranked design requirements.

Circle sketches were also drawn by the team to build off of each other's ideas and come up with a base idea for the main mechanisms. During the circle sketching process, each team member began with their own virtual "paper" and had 2 minutes to sketch an idea. After time was up, the "papers" rotated between team members so that each person was presented with another team member's sketch. Team members then had 2 more minutes to add to the sketch they were given. This cycle was repeated until all team members had contributed to each others' original sketch. One example of a circle sketch generated can be seen in Figure 6 below. While this brainstorming method is fast paced, it allows for creative ideas to be generated, since each person had such a short amount of time to add to each sketch. Because the circle sketching was not done on physical paper, some group members sketched while others added text explanations of further opportunities.

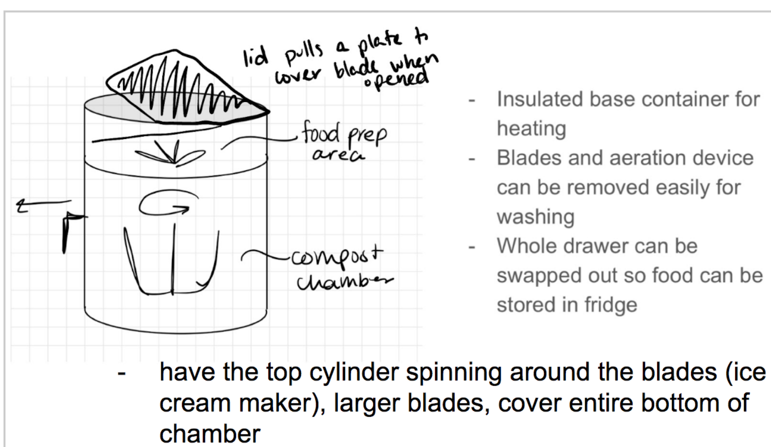


Figure 6: Example sketch generated during team circle sketching session

Applying key elements of the engineering design process, such as creating the mind map and circle sketches, as well as all members generating additional individual ideas, allowed the team to get a better idea of what concepts should be implemented in the composter design to achieve the functional design requirements.

3.3 Initial Design Concepts

After mapping out all the criteria needed for a functioning composter and starting some initial sketches, several design concepts were generated. These ideas included integration methods for different parts of general functionality, as well as aesthetics and usability. No designs were considered "bad" ideas at this point in the design process. Six sample designs of the 48 generated during ideation were identified as final design contenders. These specific designs were chosen because each highlights different feature options that the team explored and wanted to compare. During ideation, the team was faced with several major design questions and decisions in regards to the composter system.

1. Should the composter be single or multi-chamber?
2. Should the composter include reservoirs with browns and/or water?
3. Should the composter be oriented vertically, horizontally, or at an angle?
4. Should the composter utilize wands, an orbital arm, or gravity to mix the compost?
5. Should grinding and/or chopping of the food waste occur within the composter or as part of a separate apparatus?

Each of the six designs discussed below relate to at least one of these questions.

3.3.1 Design 1: Multi-Chamber with Reservoirs

Design 1 uses rotating cylinders with spikes on them to grind up the food waste once the lid is removed and it enters the composter. Once this process is complete, the food waste moves into the horizontal compost chamber and is mixed using a three pronged wand. The chamber is heated and insulated, with small piping at the bottom for aeration that introduces oxygen into the system. Additional water and browns reservoirs are located on the sides of the composter (similar to a Keurig coffee maker), ready to add if moisture content or carbon to nitrogen ratio is off. Once the compost cycle is complete, a trap door opens and the compost falls into the drawer below for extraction. A mockup of the general system can be seen in Figure 7 below.

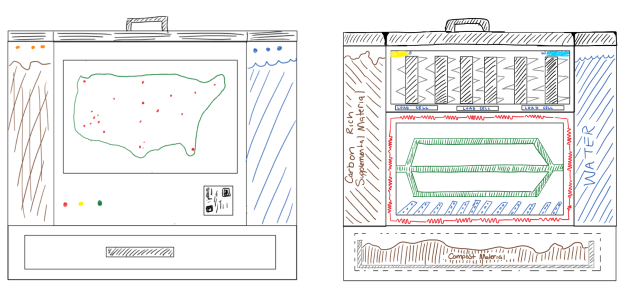


Figure 7: Sketch of the multi-chamber with reservoirs system design

This design is hands off and intended to be very easy for the user to operate. Because the grinding / chopping mechanism is part of this composter, food deformation is easy and takes no extra effort from the user. Incorporating reservoirs into this design is also ideal so the user does not have to add any water or browns manually. The wands provide efficient aeration and the chamber is heated and insulated so effective heating can take place. The user interface also is appealing, as it allows the user to see where other people are composting around the country. This design aligns with the majority of the established design specifications for the composter, but does lack in areas such as simplicity and ease of manufacturing.

3.3.2 Design 2: Single Chamber with Browns Reservoir

Design 2, shown in Figure 8, also features mechanical grinding as part of the device, with two gear-like horizontal cylinders grinding the food scraps as they pass through the trap doors and fall into the chamber. A dry carbon reserve, or browns reservoir, is included to account for any adjustments that need to be made to maintain the carbon to nitrogen ratio. This reservoir rests on a load cell that is able to determine the amount of browns added and automatically add the correct amount needed to stabilize the C/N ratio. The composting occurs in one main chamber and extraction of compost occurs via turning the composter on its side to dump the soil out.

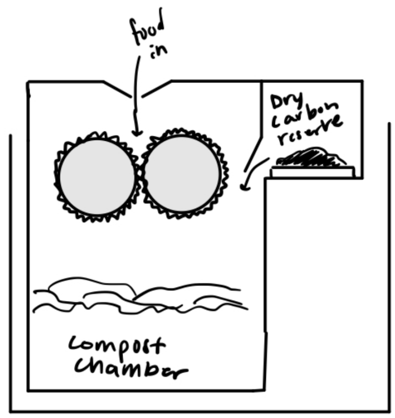


Figure 8: Sketch of the single chamber design with an added browns reservoir

This design lacks the effective heating and efficient aeration specifications that are very important to the composting process. Safety is also a slight issue, as the mechanical grinding gear mechanism is very close to the top of the composter and someone could easily put their hand in too far when inputting their food waste. Additionally, there is no active aeration occurring via mixing or turning of compost. Extraction of the mature compost also does not appear to be easy. However, this design does have a browns reservoir and can therefore help remove moisture and add carbon rich material as needed. It is also very adaptable to different volumes.

3.3.3 Design 3: Single Chamber with Rotary Air Lock

The main goal of this design is to use a rotary air lock to keep the compost chamber as sealed as possible during the process and therefore reduce ick factor. Pre-chopped food is placed in the lock when it is in the open position and the food falls through into the compost chamber. The rotary lock is then turned to the locked position, sealing the chamber. This design also features an orbital mixing arm similar to a Kitchen Aid mixer that is designed to mix and aerate the system. When the compost cycle is complete, the floor of the chamber slides out and the mature compost falls into the extraction chamber. A full system sketch and close-up of the rotary lock design can be seen in Figure 9 below.

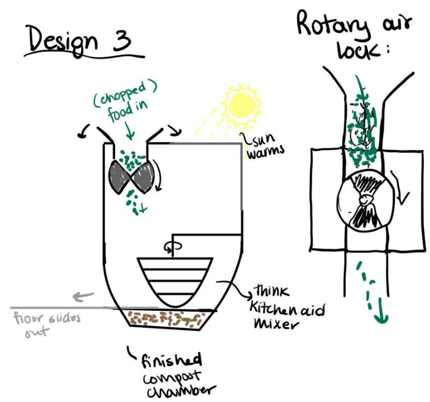


Figure 9: Rotary airlock design sketch

This design aligns very well with the design requirement of reducing ick factor. The rotary lock design ensures a sealed environment that the user does not have to look at, smell, or interact with. The mixing arm aspect also shows an emphasis on efficient aeration and homogenous mixing. However, this design does lack a heating and food deformation system. This means that there is still some effort required by the user. This design hits the established design requirements well, but lacks in the design specifications area.

3.3.4 Design 4: Angular Rotating Barrel

This design, shown in Figure 10 and inspired by a concrete mixer, involves a motorized barrel that is oriented at an angle. The lid unscrews, allowing the user to input food into the top. The barrel rotates, mixing the food scraps inside and composting occurs, and when the process is complete, there is a slidable opening on the barrel that allows the compost to fall out into a bin. This design also features an insulation sleeve with heating, as well as a separate compartment for electronics.

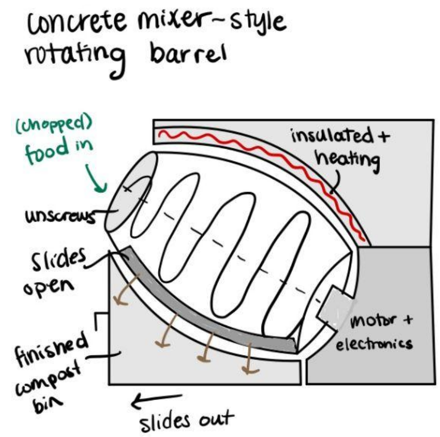


Figure 10: Sketch of angular rotating barrel design

This design achieves homogeneous mixing and efficient aeration by using the angle of the barrel to its advantage. It features built in heating as well, though the sliding door feature could have an impact on the effectiveness of it. It is also adaptable in the sense that it can fit a range of food waste volumes.

3.3.5 Design 5: Horizontal Rotating Barrel with Food Pod

Design 5, seen in Figure 11 below, was designed as a single chamber "plus" design. It features a horizontal rotating barrel as the compost chamber, with a food pod addition that works as both a chopping/grinding and storage container.

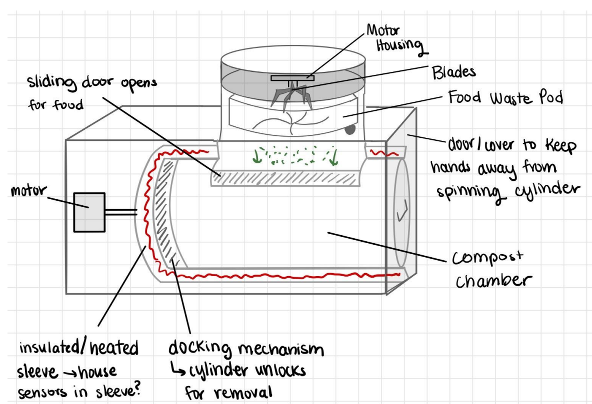


Figure 11: Full system sketch of horizontal rotating barrel with food pod

To use the food pod, the user would open the outer lid, add in their food waste, close the outer lid, and then pull a tab to dispense the waste into the main pod chamber. The pod could then be stored in the fridge until full or the user is ready to compost. When mounted on the composter and activated, the blades inside the food pod would rotate, chopping and grinding the food within. Annotated sketches showing the various aspects of the food pod are displayed in Figure 12 below.

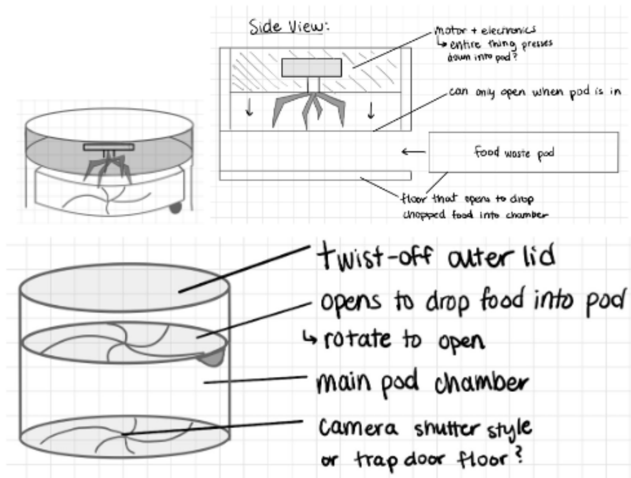


Figure 12: Food pod sketches and design details

To start the cycle, the floor of the pod would be opened by the user to drop the food waste into the chamber. The chamber itself is heated and insulated and has a sliding door that is lined up with the bottom of the food pod using a docking station to make the transition clean. Once in the compost chamber, the barrel will rotate, mixing and aerating the food inside. Fins are also located inside in the barrel to aid with scooping pieces so that none are getting stuck. This feature can be seen in Figure 13 below which shows the cross-section of the barrel.

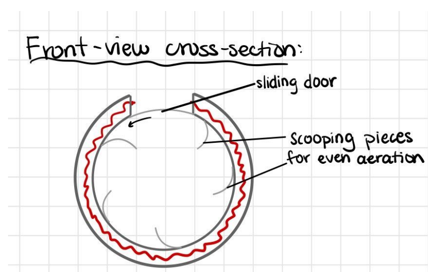


Figure 13: Cross-section sketch of the barrel to show sliding door and fins

The compost chamber itself can also be removed via a handle on the right side that allows the user to pull it out once undocked. They can then remove the compost directly into a location of their choice. This design utilizes gravity to its advantage to effectively aerate the compost as the barrel rotates. The fins also contribute to help achieve even aeration and homogenous mixing. The addition of the food pod to the design also makes food input and deformation simple for the user.

3.3.6 Design 6: Conical Screw Mixer

This design, inspired by industrial conical screw mixers, features an orbital arm with an auger attached that mixes the compost. This auger follows the angle of a cone and is intended to grind up the food against the side of the chamber as well as slightly chop it while mixing. Food waste is stored in a pod and then released into the conical compost chamber that is heated and insulated. It is there that the orbital arm rotates and mixes the compost. An additional browns reservoir is included to dispense carbon rich material as needed to maintain the compost's carbon to nitrogen ratio. When the compost cycle is complete, the compost falls into the drawer below via a sliding panel with a handle. A sketch of this design can be seen in Figure 14 below.

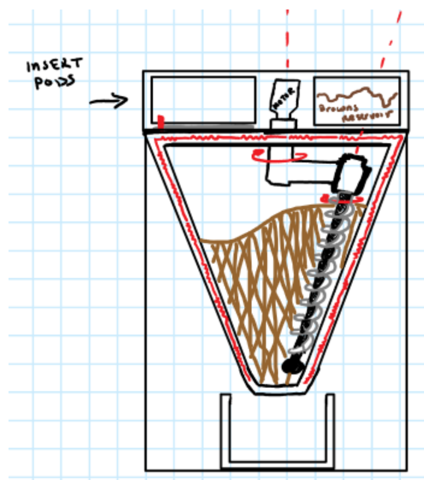


Figure 14: Conical screw mixer design sketch

This design focuses on efficient aeration, homogenous mixing, effective heating, and ease of input, deformation, and extraction. The internal shape is also unique. These characteristics make for an ideal composting environment according to the design specifications. However, it is still important to note that this design is more complex and therefore likely more difficult and costly to manufacture.

These initial design ideas helped the team come up with a list of design criteria to consider in further rounds of design iterations. Creating pairwise charts to rank that set of design criteria as well as the various components of the composter led the team in a direction to narrow down to a few final designs.

3.4 Design Comparisons

From the initial 48 design concepts generated during ideation, six were chosen as final design contenders and compared using two Pugh design matrices based on the design requirements discussed previously. Per the ranking from the pairwise comparisons comparing the design requirements and design specifications to one another, each element was assigned a point value. For the design matrices, the top design aspect from the pairwise was weighted the most and given the highest number of points, while the bottom design aspect was weighted the least and given the lowest number of points. The Pugh design matrix calculates total point values for each design by taking the value assigned in the design column, multiplying it by the design specification point value, and then summing the column. These totals are then compared between designs to determine which design is ideal for the application based on the design requirements.

Table 6: Design Matrix Comparing Final Design Contenders Based on Customer Perspective Requirements

Design Option — Design Requirement	Design Spec Point Value	Baseline: Lomi Home Composter	Design 1: Multi-Chamber with Reservoirs	Design 2: Single Chamber with Browns Reservoir	Design 3: Single Chamber with Rotary Air Lock	Design 4: Angular Rotating Barrel	Design 5: Horizontal Rotating Barrel with Food Pod	Design 6: Conical Screw Mixer
Safety	8	0	-1	-1	1	0	-1	0
Ease of Use	7	0	1	1	0	0	0	1
Smell / Ick Factor	6	0	0.5	0.5	1	0	1	1
Adaptability	5	0	1	1	0	1	1	1
Energy Use	4	0	0	0	0	0	0	0
Durability	3	0	0	0	0	0	0	0
Noise Level	2	0	0	0	0	0	0	0
Aesthetics	1	0	0	0	0	0	1	0
Cost	1	0	1	0	0	0	1	0
Total:	-	0	8	7	14	5	5	18

Table 7: Design Matrix Comparing Final Design Contenders Based on Functional Perspective Requirements								
Design Option — Design Specification |	**Design Spec Point Value**	**Baseline: Lomi Home Composter**	**Design 1: Multi-Chamber with Reservoirs**	**Design 2: Single Chamber with Browns Reservoir**	**Design 3: Single Chamber with Rotary Air Lock**	**Design 4: Angular Rotating Barrel**	**Design 5: Horizontal Rotating Barrel with Food Pod**	**Design 6: Conical Screw Mixer**
Efficient Aeration	13	0	1	0	1	1	1	1
Effective Heating	11	0	1	-1	-1	1	1	1
Ease of Manufacturing	11	0	-1	0	-1	0	-1	-1
Moisture / Humidity (Removing)	10	0	1	1	0	0	0	1
Homogenous Mixing	8	0	1	0	1	1	1	1
Cost to Manufacture	8	0	-1	0	-1	0	-1	-1
Ease of Food Deformation	6	0	1	1	0	0	1	1
Ease of Food Input	6	0	1	1	-1	-1	1	1
Simplicity	5	0	-1	0	0	0	-1	0
Ease of Extraction	3	0	1	-1	1	0	1	1
Internal Shape	3	0	0	0	1	1	1	1
User Interface	2	0	1	-1	-1	-1	0	-1
Moisture / Humidity (Adding)	1	0	1	0	0	0	0	0
Total:	-	0	39	5	-8	27	28	41

Two matrices were created in order to evaluate more specific design aspects of the composter. While the first matrix, Table 6, considers the design requirements based on the customer's point of view, the second one, Table 7, focuses on design specifications from a functional perspective. Based on the results from the design matrices above, it was determined that the Conical Screw Mixer Design was able to achieve the most design requirements and specifications and was therefore chosen to serve as the basis for the composter design.

Chapter 4: Final System Design

The final design consists of four main subsystems: the food pod, the orbital arm, the composting chamber, and the extraction mechanism. The compost begins in the food pod, where food scraps are chopped into smaller pieces and stored until the user is ready to run the cycle. At that point, the pod is placed on top of the assembly and the bottom panel is slid out, allowing the food to fall into the compost chamber below. Within the compost chamber, the compost material is mixed and aerated by the orbital arm. As with design 6 mentioned in the previous chapter, this final assembly is inspired by the function of industrial conical screw mixers. This consists of a conical mixing basin (the compost chamber), and an angled screw arm. The screw attachment rotates on its own axis, bringing material from the bottom of the basin to the top, while the arm rotates in an orbital manner, ensuring that material on all sides of the basin are reached [29]. While in the compost chamber, the compost material also experiences heating via devices adhered to the chamber, and fan-powered aeration routed inside with tubing. Finally, once the compost cycle is complete, a crank is turned to lower the gasket plate from the bottom of the chamber, which is then pulled out to allow the compost to fall into the extraction drawer at the bottom. Figure 15 shows the CAD model of the final assembly, labeled by subsection.

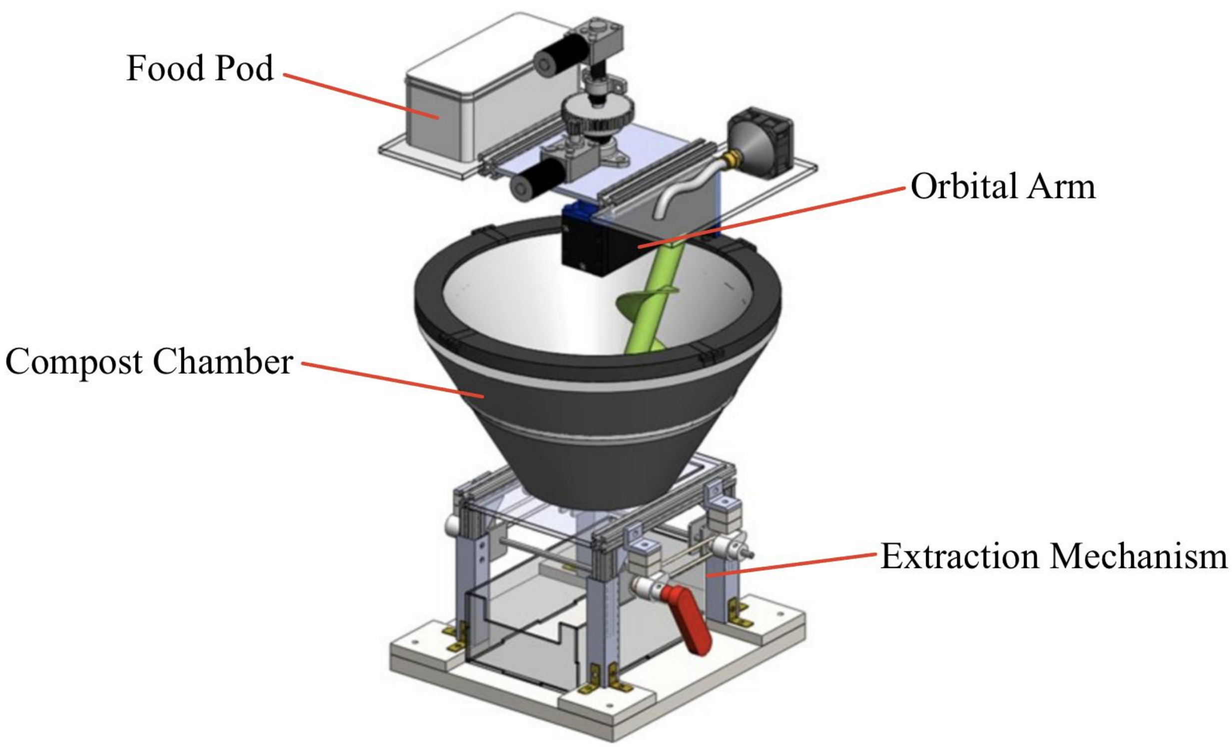


Figure 15: CAD model of the final smart composter assembly

4.1 The Food Pod

4.1.1 Detailed Design Description

The food pod was designed to act as a chopper and storage container for the user's food scraps in between composting cycles, allowing the user to fill the pod and begin a composting cycle at their convenience. This is a valuable feature for the composter's design, considering the target demographic for this product– 18-35 year old individuals, especially those living in apartments who may not have the outdoor space for composting. Since all the team members fit this demographic, their own food waste habits were examined over the course of one week to determine if there was a need for such a device. All five team members observed that they produced extremely little compostable food waste each day. This simple observation indicated a need to have a device to store food waste in between composting, to gather up enough scraps to begin a composting cycle. Such storage containers exist on the market, however none that the team saw online were designed to be stored in a refrigerator [30]. Not only is this a unique idea, but this would aid in slowing the degradation process of the scraps, so there wouldn't be any decomposing food waste on user's counters. This would greatly decrease the ick factor commonly associated with composting.

4.1.2 Selection of Final Design

One of the team's key design goals was for the composter's design to require as little user input as possible. One way the team sought to achieve this was through incorporating food deformation into the composter's design. This would eliminate the need for users to manually pre-chop up their food scraps with a knife into smaller compost-friendly pieces. Since the augers that were tested were determined to have little to no chopping effect, the team chose to incorporate both the chopping feature and the food storage container into one design– the food pod.

Vegetable choppers were chosen for the pod design due to their availability, affordability, and versatility. Since so many different designs for these choppers existed on the market, the team chose to purchase and modify one rather than custom make one. Two different vegetable choppers were considered for use as the food pod– by OXO and Maipor, pictured below (Figure 16 and Figure 17).

Figure 16: The OXO vegetable chopper

Figure 17: The Maipor vegetable chopper

To select the chopper to be used in the final design, the team conducted tests with food scraps obtained from the WPI dining hall. Foods of different sizes, toughness, and textures were chopped on the pod, and the chopping ability along with other notes was recorded. The testing procedure and results are pictured below (Table 8 and Table 9). It was determined that the OXO chopper was able to chop tougher foods better than the Maipor one, which was adequate in chopping food. This was an important factor considered, however the geometry of the OXO chopper was not ideal for its required use. It had a curved bottom with a cutout on the back side for dumping chopped food that would have required a custom plug to be made to seal it for the purposes of this project. To avoid this extra unnecessary design and manufacturing time, the team selected the Maipor chopper for creating the food pod.

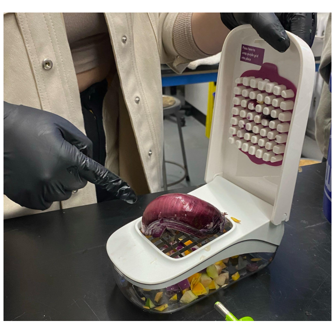
Table 8: Testing Procedure for Vegetable Chopper Selection		
Step 1	**Step 2**	**Step 3**
Place food on clean chopper blades	Slowly close the chopper over the food to chop it	Open lid, observe, and record results
		

Table 9: Test Results of Vegetable Chopper Selection		
	Chopping Ability	**Notes / Observations**
OXO	Able to chop pineapple core, pineapple rind, and watermelon rind	- Chopper lid was prone to slamming shut, creating loud noise and potential safety hazard if fingers were to get caught
Maipor	Able to chop watermelon rind, banana peel, onion, and tomato slices	- Watermelon rind required much more force to chop than the OXO - Chopper lid was prone to bending under high force - Chopper lid did not snap fit onto the base which caused some wiggling during use

4.1.3 Manufacturing and Assembly

Once the team had selected the vegetable chopper, it was modified to fit the needs of the project as seen in Figure 18. The bottom of the chopper was cut out via a manual mill in Washburn Shops. A 3D printed bottom was designed and attached to the container by custom 3D printed brackets. The pod was specifically designed to allow for sliding of the base in the brackets, such that the food scraps stored inside may fall out when the base is pulled out. When the pod has been filled and the user is ready to compost, it can be set in its place on the acrylic layer supported by the top framing layer. The user can then slide the bottom out, dropping the scraps into the compost chamber below.

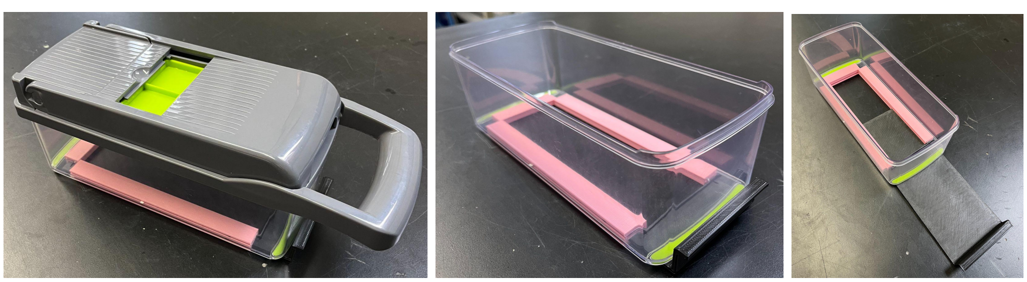


Figure 18: Images of the final food pod design, with the chopper lid on (left), bottom in closed position (middle), and the bottom in open position (right)

4.1.4 Final Design Validation

To verify the functionality of the food pod design, the team conducted testing in a similar manner to that of the vegetable choppers. Food was chopped using the chopper until it was completely filled. The pod appeared to hold in moisture from the food well without leaking. It was then placed over a container and the bottom was slid out. The food scraps experienced difficulty falling into the container with gravity alone, and required the external force of team member's hands to push the food out of the pod.

4.2 The Orbital Mixing Arm

After the pre-deformed food waste has been introduced into the main composting chamber of the system, the mixing arm will be used to aerate the compost and to maintain a homogenous mixture of materials through the duration of the composting process. By periodically rotating and stirring the compost it ensures uniform characteristics such as temperature, moisture content, oxygen, and pH level throughout the mixture during operation. This will promote more efficient composting and a higher quality compost product.This chapter discusses the design process for some of the main features of the Orbital Mixing Arm.

4.2.1 Detailed Design Description

The mixing arm design for this prototype was modeled after the mixing apparatus used in industrial conical screw mixers and therefore features many of the same main components. The mixing arm motion is characterized by the simultaneous rotation of the 'screw' attachment and the rotation of the orbital arm housing about the central axis of the chamber. The screw attachment is held at the same angle as the conical composting chamber and lifts the composting materials from the bottom of the chamber to the top as it rotates. The orbital arm housing simultaneously directs the screw attachment around the perimeter of the composting chamber as it rotates to ensure that there are no 'dead' pockets in the chamber where composting materials are not being mixed by the arm. The arm mixing arm is mounted securely to the cover of the main chamber which also houses the arm transmission system that drives the simultaneous rotation of both components. This design can be seen below in Figure 19.

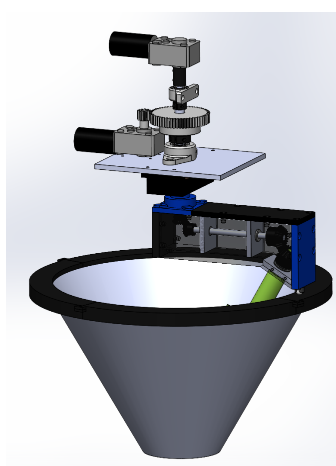


Figure 19: Model of orbital mixing arm

4.2.2 Design Assumptions

To begin the design process for the mixing arm drive system, the conditions under which the screw attachment would be working were considered. Since the food waste passes through the pod before entering the main composting chamber, the mixing arm only needs to lift and mix pre-deformed materials. Therefore, it can be assumed that this will limit the risk of the arm getting stalled or stopped if large chunks of food get caught between the screw and the walls of the chamber. However, other than that, the specific loading conditions that the screw attachment will experience are largely unpredictable and will likely be inconsistent from cycle to cycle depending on the density, volume, moisture content or other properties of materials being composted.

As such, it was necessary to make some assumptions about the environmental and loading conditions present during the composting process. To get insight into some of the conditions that the arm could experience during operation, the team considered other appliances that have similar modes of operation or functional requirements. The team decided that an average kitchenaid stand mixer would be an appropriate model system for this investigation. A stand mixer is designed to mix both wet and dry food ingredients with a wide variety of properties into a homogenous mixture. The main goal of the mixing arm for this prototype is essentially the same. It must be designed to produce and maintain a homogenous mixture of both wet and dry food waste scraps of varying properties. Additionally, since the composter design was intended to be a countertop appliance, it will have similar dimensional and geometrical characteristics to a stand mixer. Therefore, the team made the following assumptions:

Assumption 1: The mixing system for this prototype will experience comparable loading conditions to an average baking stand mixer. Therefore, the drive system for the mixing arm must be capable of producing an approximate output torque of 5 Nm for both the orbiting arm and the screw attachment.

Assumption 2: The mixing system for the composter prototype will require similar rotational speeds to the lower speed settings of a stand mixer since the mixing arm will not be deforming the composting materials and the mixing will be performed over a much longer period of time. Therefore the drive system for the mixing arm must be capable of producing an approximate speed of 100 rpm for the screw attachment and a lower approximate speed of <10 rpm for the orbiting arm.

4.2.3 Mixing Arm Design Process

The conclusions drawn in the previous section served as a starting point to inform many of the design decisions that went into the final Mixing Arm Design. This section highlights the iterative process used to design the main features of the mixing arm including the screw attachment, the main drive system, the rotary power transmission mechanism, the housing geometry, and the support structures.

4.2.3.1 Mixing Screw Design

One of the first major design decisions that were made was the selection of the screw mixing arm attachment. The helical geometry was selected for this apparatus due to its proven mixing abilities in particle mixing on an industrial scale. As the threads of the screw are rotated, they exert an upward force on the composting materials in the chamber. This lifts the materials from the bottom of the chamber to the surface where oxygen is being supplied.

The team initially considered designing and manufacturing a custom screw attachment. However, the machine shop on campus did not have the necessary tooling to do so, and it proved expensive to have it custom manufactured by an outside vendor. Thus, it was decided that it would be preferable to purchase an existing auger online which had the necessary geometry. Four augers, each with differing shaft lengths, outer diameters, screw pitch, and materials, were purchased. These consisted of three planting augers of varying sizes, and one wood auger. It was then necessary to evaluate their mixing performance in terms of ease of rotation and approximate time to produce a uniform mixture. Upon receipt of the smallest planting auger, the team decided it was too small to use. The other three were first subjected to mixing testing (Figure 20), but following poor performance by the wood auger, only the green and black augers were then assessed for grinding (Figure 21). The procedure and results (Tables 10 and 11) for these two tests are listed below, and the complete associated notes can be accessed in Appendix

Figure 20: Mixing test of green auger attachment

Mixing Test Procedure:

1. Add two different colors of stained particles (rice/sand /soil) into the cone, with each color having the same volume.

2. Fix an auger attachment to the drill.
3. Turn the drill on at a constant speed and begin orbital motion around the cone. Simultaneously start a stopwatch.
4. Observe the contents of the cone until a cohesive mixture of colors is observed.
5. Stop the stopwatch, record the time, and take note of particle behavior through the experiment (observe results at bottom and top of cone)
6. Repeat steps 2-5 with each of the other auger attachments.

Table 10: Auger Mixing Test Results			
Auger Type	**Trial 1: Time to Combine**	**Trial 2: Time to Combine**	**Observations + Notes**
Green (3”)	~15 sec	10sec	Mixed quite quickly and smoothly
Black (4”)	~15 sec	12sec	Very comparable to green, maybe have felt smoother (a tiny bit easier to move through rice)
Wood (1”)	30+ sec	-	Bit fell off, takes much more force to move around, did not mix well

Figure 21: Grinding test of black auger attachment

For grinding testing, the team utilized two gallons of food waste provided by Morgan Dining Hall. This waste consisted of egg shells, onion scraps, cantaloupe rinds, bell pepper insides, and banana peels.

Grinding Test Procedure:

1. Mark a fill line on the cone.

2. Fix an auger attachment to the drill, and insert the auger so that the tip touches the bottom of the cone.
3. Fill the cone with food waste up to the line.
4. Turn the drill on at a constant speed and begin orbital motion around the cone. Simultaneously start a 3 minute timer.
5. Grind continuously until the timer concludes, taking note of particle behavior through the experiment (observe results at bottom and top of cone).
6. Empty the cone, then repeat steps 2-5 with each of the other auger attachments.

Table 11: Auger Grinding Test Results

Auger Type	**Results**
Green (3")	- Most foods broke down relatively well except for the cantaloupe rinds
Black (4")	- Broke down onions, eggs, banana peels, and pepper core - Onion skin/eye, pepper stem, and cantaloupe rinds did not break down
Wood (1")	- Did not test following poor mixing results

Following these two tests, it was determined based on the results in Tables 10 and 11 that the green auger would be most ideal for this application due to its superior mixing ability. However, the poor cutting performance on rougher materials displayed by all augers led to the decision for the food to be chopped prior to its entrance into the composting chamber. Thus, the idea of a vegetable chopper was integrated into the food pod design.

4.2.3.2 Mechanism Design for Rotary Power Transmission to Auger Attachment

After an auger was selected, the next major consideration was designing a mechanism that would transmit rotational motion from the motor housing to the auger attachment at the end of the orbital arm housing. Some of the key considerations that impacted this design included the orientation and required motion of the auger attachment to produce optimal mixing. To maximize the auger's compost lifting capacity and prevent any 'dead' pockets where materials in the chamber are not being reached, the auger must be positioned as it rotates such that the auger shaft is parallel to the wall of the chamber and its the edges of its screw thread is flush with the wall of the chamber as it rotates.

Several mechanisms that are commonly used in applications where rotary power transmission is required were considered for the arm design including universal joints, constant velocity joints, bevel gears, and belt transmission. The first of these was the universal joint which consists of a cross shaped coupler pinned to the two shafts. This joint was considered due to its capacity to transmit torque and rotational motion between two relatively long shafts that are misaligned such as in car transmission systems [31]. However, universal joints are not preferable in applications where acute shaft angles are required and are not capable of rotational transmission at constant angular velocities [31]. A constant velocity (CV) joint was also considered as a potential replacement for the universal joint. However, while CV joints can transmit rotational power at a constant rotational velocity, these joints are still not preferable for the applications that require acute shaft angles and are more expensive [32].

After the universal and CV joints were eliminated, the team considered both bevel gears and belt transmission. A formal comparison of both options was performed through a design matrix in which each mechanism was evaluated against the desired characteristics of the mechanism. This is shown in Table 12 below. For each desired characteristic, both the gear drive design and the belt drive design were evaluated and the more suitable design for that criteria was assigned a 1 with the other being assigned a 0. The totals for each option were calculated to determine the preferable design. From this comparison it was concluded that while the belt drive design is preferable in some capacities such as lower cost, low sound production, and decreasing the concentration of weight at the end of the orbital arm, the gear drive design was the better option for this application. A gear drive system would be preferable for longevity, would have lower maintenance requirements, would have a higher transmission efficiency, and would require less space for operation.

Table 12: Design Matrix for Power Transmission Mechanism Selection

Desired Characteristic	Gear Drive	Belt Drive
Minimized Sound Produced During Operation	0	1
Lower maintenance requirements	1	0
Minimize Space Requirements	1	0
Minimized Weight Concentration at Tip of Arm	0	1
Maximize Durability and longevity	1	0
Minimize Vibrations during Transmission	0	1
Minimize Cost	0	1
Maximize Efficiency/ Higher Transmission Ratio	1	0
Minimize Losses due to Friction	1	0
Maximize simplicity of Design and Assembly	1	0
TOTAL	**6**	**4**

After deciding to use the gear drive system, a conceptual design of the transmission system was created. This design, pictured in Figure 22, featured two sets of bevel gears that transfer power from the motor to the auger attachment. One set of these gears would transmit power between a vertical shaft connected to the motor housing to a horizontal shaft inside the arm housing at 90 degrees. The second set of bevel gears would transmit rotational motion between that horizontal shaft and the auger attachment at the same angle as the wall of the chamber as described above. To ensure proper shaft alignment, bearings were incorporated into the design in the housing of the orbital arm.

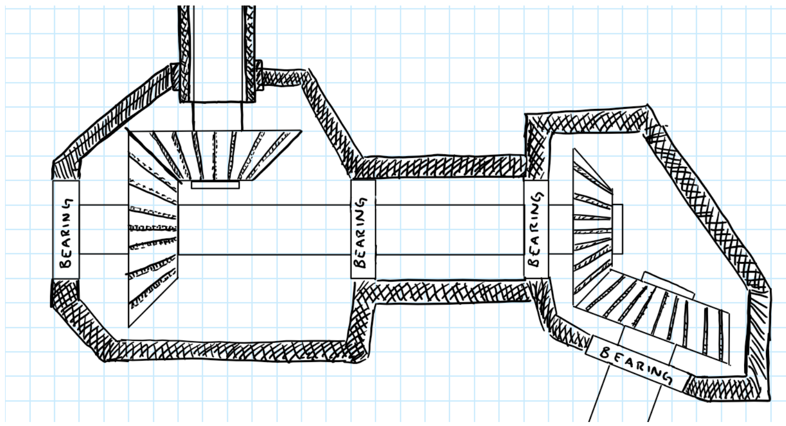


Figure 22: Initial conceptual design of the bevel gear rotary power transmission system

While 90 degree bevel gears were relatively simple to find, angled bevel gears were very difficult to obtain. Only a single option existed for angled bevel gears that were appropriate for the project budget. This was a set of bevels designed for a 60 degree shaft angle, with 20 teeth, and an 8 mm shaft size. These gears limited the options for shaft selection to an 8 mm shaft. The length of the horizontal shaft was determined by the top radius of the conical chamber and the vertical shaft length was limited by the distance from the top plane of the chamber to the motor housing which was dependent on other systems.

The final bevel gear train transmission design is pictured in Figure 23.

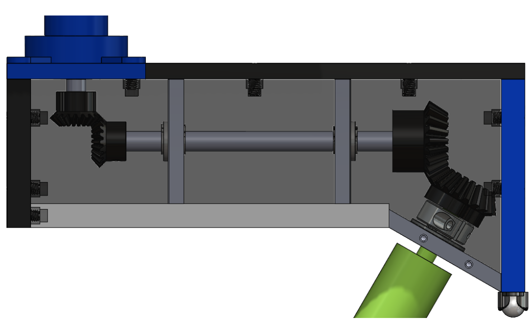


Figure 23: Final iteration of rotary power transmission design for auger attachment

4.2.4 Main Drive System Design

As described previously, the simultaneous rotation of the auger and orbital arm must be driven by a specialized transmission system located above the mixing chamber. The design of this transmission system had to be carefully considered so that the assumed loading conditions and desired rotational speeds described in section 2 of this chapter would be satisfied. More specifically, the transmission system must be designed to simultaneously produce an output torque of approximately 5 Nm with an output speed of approximately 100 RPM for the auger attachment and an output torque of approximately 5 Nm with an output speed of <10 RPM for the orbital arm housing. To produce the desired output motion characteristics, the design had to transmit rotational power from a motor to both the outer housing of the arm and the internal gear train for the auger attachment. Because the internal bevel gear train was designed to be contained within the orbital arm housing, the team decided to make the shaft transmitting power to the arm housing hollow. This hollow shaft was positioned such that the solid vertical drive shaft for the bevel gear train would fit inside it concentrically.

For this configuration, two initial conceptual designs were created for the transmission system that used worm gears as a means of directly transmitting rotational motion and torque from the motor(s) to the two drive shafts. Worm gears were initially selected due to their relatively small space requirements and high gear ratios which would increase the torque while decreasing the speed of rotation from the motor. In the first design, pictured in Figure 24, the team attempted to use a single motor for power transmission to both the hollow orbital arm drive shaft and the solid auger attachment drive shaft in an attempt to minimize the space requirements for the transmission housing. However, the limited selection of available worm gear sets that were compatible with the shafts did not provide a wide enough difference in gear ratios to produce the required output speeds of 100 RPM and <10 RPM for their respective components.

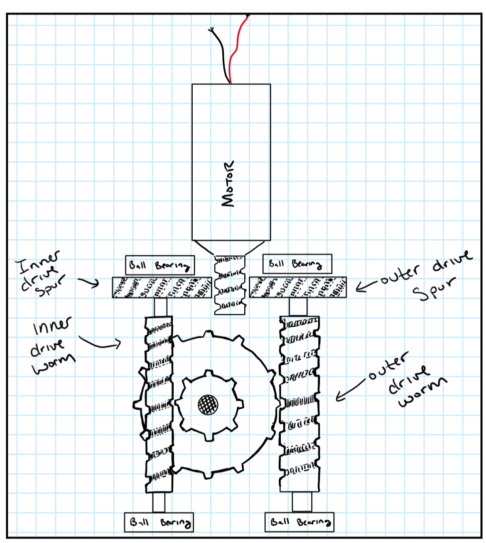


Figure 24: Top down view of initial conceptual design of single motor drive system

The design was then adapted to include two separate motors for each drive shaft. The second conceptual design, pictured in Figure 25, would make it easier to produce the required difference in output rotational speeds. However, even with this adaptation, the worm gear sets available were not suitable for the desired output motion. For both the 8 mm vertical shaft and vertical hollow shaft, the only available worm gear sets had a gear ratio of 10. To produce the desired auger output speed of 100 RPM, the motor would have to be rotating at a speed of 1000 RPM.

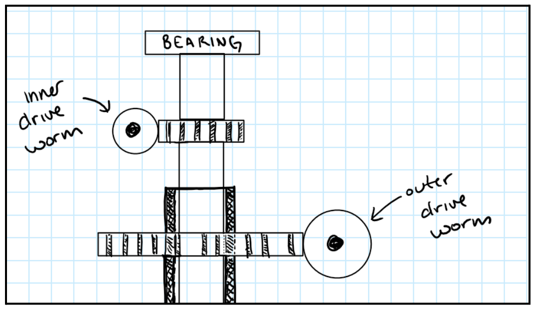


Figure 25: Sketch of second conceptual design of double motor drive

The team decided that it would be simpler and more cost effective to simply couple a 130 RPM motor directly to the solid vertical drive shaft. Since the bevel gear train has a gear ratio of 1, the output speed of the auger attachment would also be 130 RPM. This motor was also rated for an output torque of 25 kg-cm, or about 2.5 Nm. For the orbital arm transmission, the worm gears were replaced with a set of spur gears with a gear ratio of 5. This gear train was connected to a 27 RPM motor which would produce an output speed of about 5.4 RPM for the Orbital Arm housing. This motor was rated for an output torque of 5.88 Nm which, after passing through the spur gear train, would produce an output torque of about 29.4 Nm to drive the orbital arm motion. The final transmission system design is pictured in Figure 26.

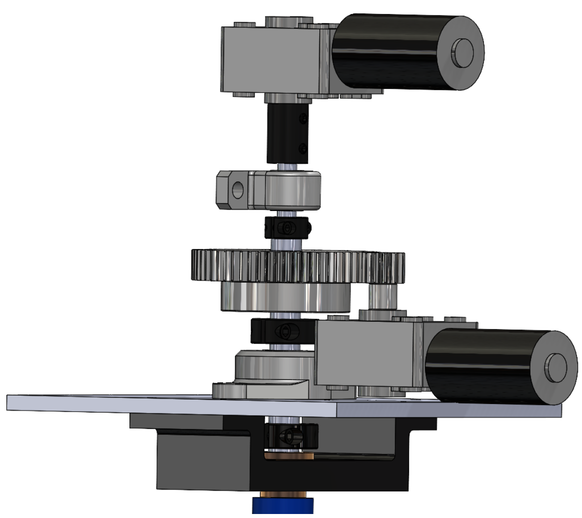


Figure 26: Isometric view of orbital arm transmission system

4.2.5 Arm Housing Design

The orbital arm housing contains the bevel gear train that transmits rotational power from the motor housing to the auger attachment. An optimal design for the housing would be structurally sound, have a small volume and would be lightweight. The design of the orbital arm housing geometry and main features was dependent on a number of design decisions previously described for the transmission and relative orientation of different parts in the mixing system.

Based on its general functional requirements, initial ideation of the arm housing design resulted in a very general design that showed off the main features. This design, shown in Figure 22, shows the main components of the arm including a casing around the bevel gear train that is rigidly connected to the vertical hollow drive shaft. The housing design necessitated the incorporation of support structures for the horizontal bushing alignment bearings as well as an angled bearing support plate to align the auger shaft at a 60 degree angle.

As the team continued to plan this feature, design for manufacturability became an important consideration for the arm housing. Aluminum was initially selected as a potential material to build the arm out of due to the fact that it has desirable material properties, is lightweight, and relatively inexpensive compared to other similar materials. To ensure that the design would be manufacturable and simple to assemble, the team initially planned to break the housing up into a series of Aluminum panels that would be secured together with bolts. This design, pictured in Figure 27, would feature three compartments separated by two built in vertical bearing supports. However the stock material that would be required to manufacture the housing for this design was too expensive. The team finally decided to 3D print the housing.

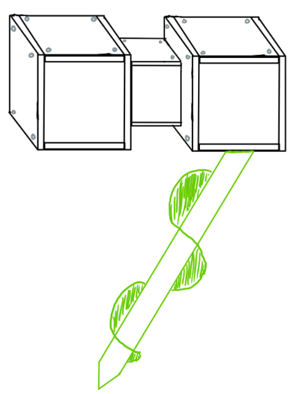


Figure 27: Conceptual design of arm housing broken into panels for manufacturability

The team finally decided to 3D print the orbital arm housing. Since 3D printed plastic was lighter than aluminum and additive manufacturing allows for more complex geometries, the geometry could be simplified. The main body of the housing consisted of side walls extruded from a flat base to create a ‘U’ cross sectional geometry. Slots were added to the walls to secure two small panels that would hold the bushing bearings that align the horizontal shaft in the bevel gear train. Cover panels were also printed for the two ends of the housing and the top surface. These were secured with machine screws and heat set inserts.

A consistent issue throughout the orbital arm housing design process was the rigid connection between the hollow drive shaft that transmits rotational power from the motor to the housing and the housing itself. For the aluminum panel design, the solution was to design a flanged part with a hollow center for the vertical shaft to fit through. For this design, a gear could be mounted to the narrow top of the part for transmission and the flanged part bould be bolted into the top surface of the arm housing. This design is pictured in Figure 28.

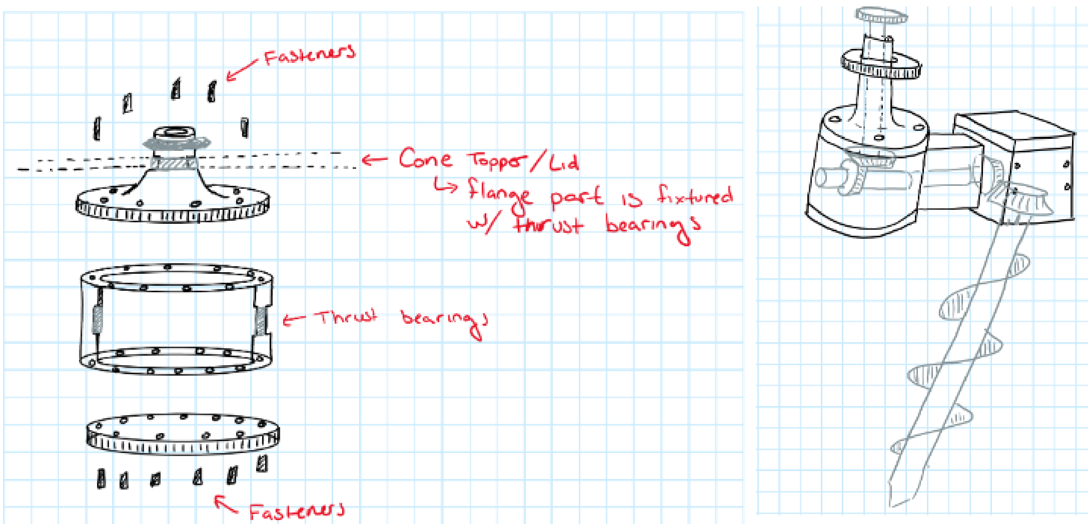


Figure 28: Initial conceptual design for flange connection

When the design was adapted to a 3D printed part, the bottom geometry of the part was modified to a square cross section (Figure 29). The new challenge became attaching the hollow drive shaft to the 3D printed part. The solution was to set screw a small metal bearing housing onto the bottom of the hollow shaft and then bolt the bearing housing into the 3D printed flange part with heat set inserts and machine screws (Figure 30).

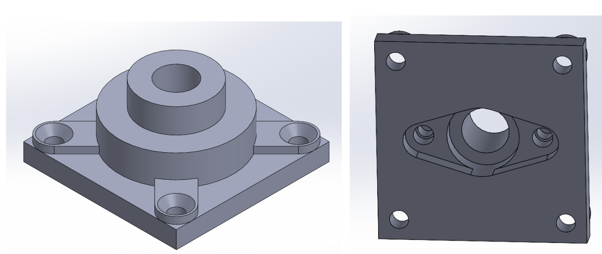


Figure 29: Modified 3D printed flange part

Figure 30: Exploded and assembled view of flange/hollow shaft connection

4.2.6 Support Track Design

By analyzing the geometry of the arm for areas of potential failure, it was concluded that extra supports must be added to accommodate the weight of the auger. The mass of the auger was measured to be 671g using a small scale. If the full weight of the auger (6.8251 N) was assumed to be acting straight down due to gravity at the point of attachment on the orbital arm, this would produce a relatively large moment in the arm of 0.922 Nm.

$$M = W_{Auger} * length\ of\ arm\ housing$$

$$M = (0.671kg * 9.81\frac{m}{s^2}) * (0.14m)$$

$$M = 0.922\ Nm$$

As such, to reduce the risk of potential misalignment of transmission components due to sagging, the team decided to create a support structure that would counteract the downward weight force.

The initial consideration for this added support was to implement a turntable, or “lazy susan,” bearing around the perimeter of the cone to facilitate the orbital movement. Examples of these bearings are shown in Figure 31 below.

Figure 31: Examples of turntable or “lazy susan” bearings [33], [34]

However, it was found to be much less expensive and just as effective to add roller bearings to the end wall next to the auger, and construct a track along the edge of the cone for them to roll along (Figure 32). It was 3D printed into four pieces, in order to fit on the print bed, which were then attached to one another with screws and bolts at connection points. The track is connected to the cone via L brackets. Due to the angle of the cone, the base of the track was built at an angle to allow for attachment to the brackets, as shown in Figure 32. Subsequently, holes were drilled into the cone for the bracket screws to pass through. Since the track was 3D printed, heat set inserts were used to pass the screws through the bracket into the track.

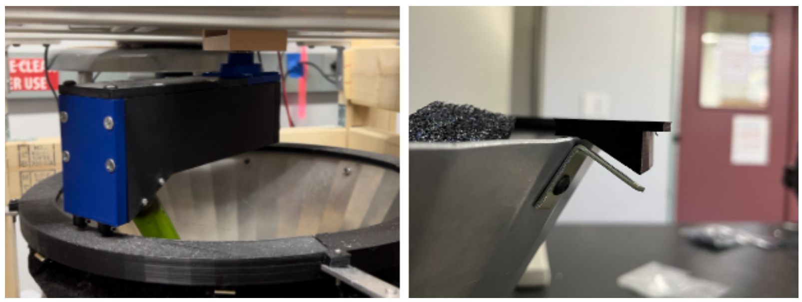


Figure 32: Images of support track, showing support of ball bearings (left) and angled connection to L bracket (right)

4.2.7 Manufacturing and Assembly

The final design of the mixing arm, pictured in Figure 33, incorporates all of the individual design elements described in the previous section of this chapter. The drive system transmits rotational motion on the concentric vertical and hollow drive shafts. The hollow shaft is fixed to the outer housing of the orbital arm via a 3D printed flange connector. The solid vertical drive shaft transmits rotational motion through a train of bevel gears contained within the orbital arm housing to the auger attachment which is supported by a hexagonal thrust bearing. To increase the support on the end of the orbital arm housing.

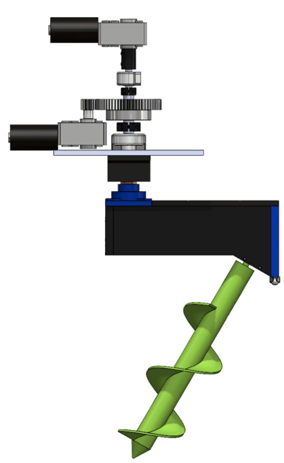


Figure 33: Mixing arm final design

4.2.7.1 Manufacturing of Parts

While many of the parts used in the arm subassembly were purchased from various manufacturers, several key components of the arm had to be custom manufactured. Different parts required varying manufacturing processes depending on the intended material used and function within the overall arm assembly. A list of all parts custom manufactured or modified by the team is listed in Appendix D. Throughout the arm part manufacturing process, the team worked closely with a machinist in Washburn shops who oversaw or performed the more complex manufacturing processes for this prototype. While many of the parts that were purchased only required minor modifications such as cutting drive shafts or set screwing the gears, some parts such as the main support plate, auger, and the vertical and angled bearing support plates required more custom modifications.

The main support plate was manufactured from a ¼" thick sheet of aluminum stock material. To serve its purpose in the overall mixing arm assembly, the stock material needed to be modified such that there were mounting holes for the bracket, 27 RPM motor, and the mounted ½" bearing. The most important design feature for the plate was the center-to center distance from the ½" central hole to the shaft for the 27 RPM motor, as this spacing would ensure proper meshing of the spur gears and alignment of shafts. With that in mind, the team created a detailed sketch of the support plate dimensions and then manufactured it using the CNC mill in Washburn Shops (see Appendix D).

The angled and vertical support bearings were manufactured similarly. The parts were modeled in Solidworks with the main features being the holes in which the bearings would be inserted. These holes were designed to allow for a press fit between the bearings and the support plates. Drawings of the 3D models, shown in Appendix D , were utilized to machine the plates out of Aluminum stock material.

The final major part modification that the team had performed for the mixing arm subassembly was welding a ⅜" hexagonal shaft protrusion to the end of the auger. This modification was necessary to ensure that the auger would be compatible with the rest of the parts in the mixing arm assembly. To perform these modifications, the existing hexagonal shaft was first removed with a hacksaw. Then the new hexagonal shaft was welded onto the main body of the steel auger.

Due to constraints on budget, time, and access to certain manufacturing processes, some of the parts that were initially intended to be manufactured from metals or other higher quality materials had to be replaced with 3D printed material for the purposes of this functional prototype. The 3D printed parts include the arm housing, flange connection piece, and supporting bracket.

As with the rest of the model, all 3D printed parts were originally designed on SolidWorks, then sliced and printed at either the 3D printing lab in the Innovation Studio or the Advanced Rapid Prototyping Lab in Higgins Laboratories. The Rapid Prototyping Lab was preferable because it is a controlled environment with machines that are given more frequent maintenance, and are only operated by an experienced professional, therefore they tend to produce more reliable and higher quality parts.

Of the available printers at the Rapid Prototyping Lab, the Dimension SST 1200es was the best fit for this project. It uses ABS, which is relatively inexpensive to print from, and produces parts with relatively high strength, stability, and heat deflection temperatures [35]. Additionally, it utilizes secondary, dissolvable support material, which gives better structural integrity to some of the parts with more complex geometries within the assembly. The original plan was for all parts to be printed this way. However, due to time constraints the longer end wall and the flange connection had to be printed in the Innovation Studio.

Although the same printer was not available in the Innovation Studio, it was decided to continue printing with ABS for consistency. The only printers in this lab which support ABS are the Ultimaker 3 Extended printers, so these machines were used. The parts were oriented with the most holes along the z axis as possible. This allows them to print with the best quality, due to the layer-by-layer construction occurring on the x-y plane. Additionally, the slicer settings were adjusted to have increased infill and reduced layer height, which increases the strength and adhesion of the part layers. It should be noted that the Ultimaker machines do not use dissolvable support material like the Dimension machine, so a bit more post-processing by hand was required to fit the screws and heat set inserts. All 3D printed parts of the arm housing are shown below in Figure 34, and a full list of parts, materials, and printers is shown in Appendix F.

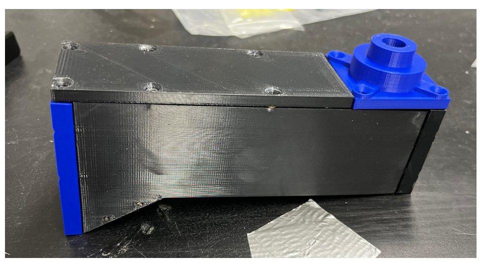


Figure 34: 3D printed arm housing

The bracket was originally made from scrap metal, however towards the end of the term, issues with its machinability rendered it unusable for this prototype. Due to the limited time available to redesign this part, it was decided to print using the Taz 6 printer in the Innovation Studio. Figure 35 shows the final printed bracket.

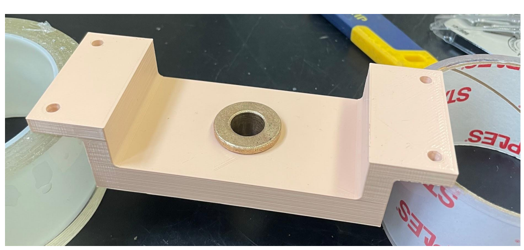


Figure 35: 3D printed bracket

In order to allow these parts to be attached to one another with screws, it was necessary to incorporate heat-set inserts. These are threaded metal rings with ribbed edges which, when melted, adhere to 3D printed material. Parts were designed with holes at the desired connection points, leaving room for the insert as well as the tail of the screw. Once the parts were printed, a soldering iron was used to gently press the heat set insert, heating it up and placing it into the predefined hole. The before and after of this process can be seen in Figure 36.

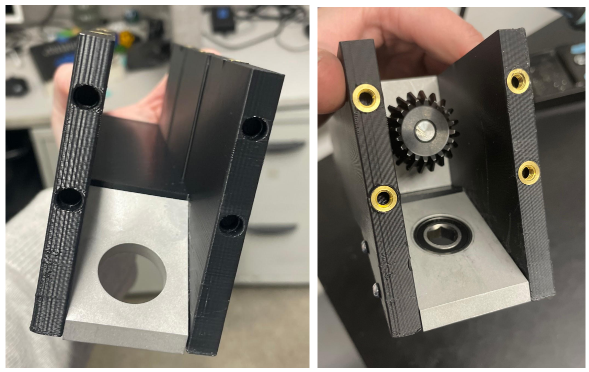


Figure 36: 3D printed part before (left) and after (right) insertion of heat set inserts

4.2.7.2 Full Mixing Arm Assembly

After all of the parts for the mixing subsystem had been manufactured, purchased, or otherwise procured, the mixing arm was assembled for testing. To create the arm, the overall assembly was split into the subassemblies detailed in Appendix G which were assembled separately and then combined. The first subassembly shown in Figure 37 is the main arm housing assembly. This assembly consists of the 3D printed main arm housing, the housing cover panel and short end panel which are screwed into the main housing. This subassembly also includes the angled bearing support plate with the hexagonal shaft bearing through which the auger will fit eventually. All other subassemblies are fixed onto this main arm housing subassembly to construct the final arm assembly.

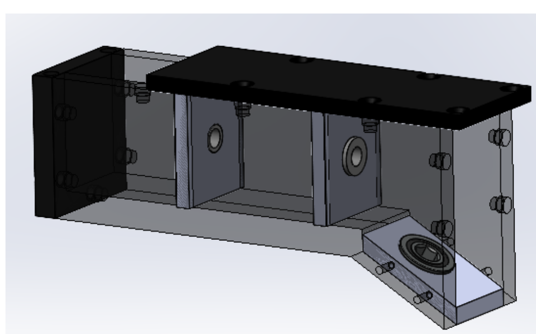


Figure 37: Arm housing assembly

The second subassembly, shown in Figure 38, is the auger assembly which consists of three parts. These are the auger, one of the 60 degree bevel gears, and a nylon spacer that serves to hold the gear at the correct height to mesh with the other 60 degree bevel gear. The nylon spacer was put on the hexagonal shaft of the auger first and then followed by the 60 degree bevel gear which was set screwed onto the hexagonal shaft. To connect the auger subassembly to the arm housing assembly, the hexagonal auger shaft was slid through the angled bearing plate hexagonal bearing before adding the nylon spacer and gear.

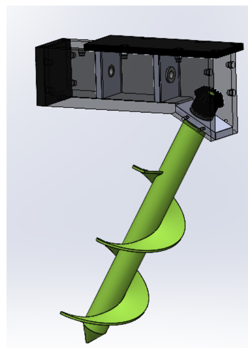


Figure 38: Auger subassembly added to full assembly

The third subassembly was the Plate Assembly, shown in Figure 39, which was built around a ¼" aluminum sheet that served both as a platform on which the motors and gear systems could be mounted and as a means of incorporating the completed arm assembly onto the main composter assembly via two parallel extrusions. This plate supports the majority of the weight of the arm and also supports the orbital rotation drive system including the hollow shaft, the 27 rpm motor, the lower bracket and bearing, and the 3D printed flange part. To connect the plate subassembly to the main assembly, screw the 3D printed flange into the main housing using 10-32 machine screws.

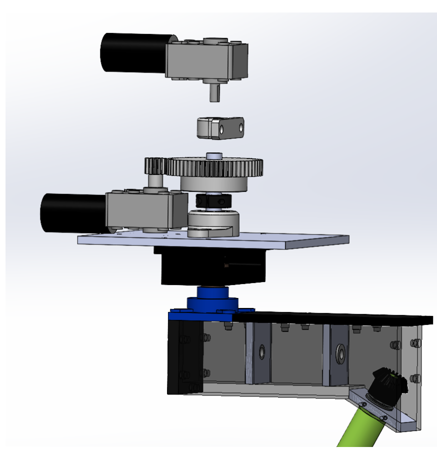


Figure 39: Plate subassembly added to full assembly

The fourth subassembly was the long end panel assembly, shown in Figure 40, which consists of the two roller ball bearings which are screwed into the 3D printed long housing end-panel. These bearings will allow the end of the arm housing to rest on and roll along the support track as it is rotating without impeding its motion. To connect this subassembly to the main arm assembly simply screw this panel onto the main housing with the 10-32 machine screws.

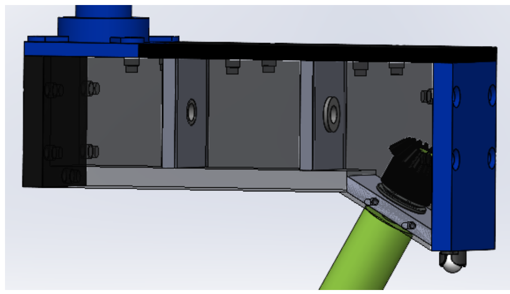


Figure 40: Long end panel subassembly

The fifth subassembly, shown in Figure 41, was the horizontal shaft assembly. This sub assembly consisted of the horizontal 8 mm diameter solid shaft with one of the 90 degree bevel gears set-screwed into one end and one of the 60 degree bevel gears set-screwed into its opposite end. To keep the shaft in the correct positioning and the gears meshed with their partner gears, the horizontal shaft bushing bearings were pressed into the vertical bearing supports. The 8 mm diameter shaft was passed through these two bearings in the plates and held in place on either side with two 8 mm shaft collars which prevented translation of the shaft relative to these plates. To incorporate this sub-assembly into the main arm assembly, push the vertical bearing support panels into the vertical slots in the main housing (before adding the cover panel). The 60 degree bevel gears should mesh and allow for smooth rotation. Adjust shaft collar locations if necessary.

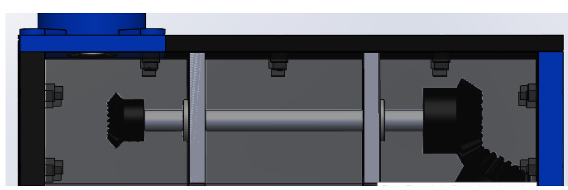


Figure 41: Horizontal shaft subassembly

The sixth subassembly, shown in Figure 42, is the vertical shaft subassembly. This sub-assembly consists of the 8 mm diameter vertical solid shaft. Fixed to the bottom tip of this solid shaft is the second 90 degree bevel gear. At the top of the vertical shaft is an 8 mm motor shaft coupler which fixes the vertical shaft to the 130 RPM motor. To connect the vertical shaft subassembly to the main arm subassembly, feed the solid shaft with the bevel gear on its bottom tip through the hollow shaft in the plate sub assembly (before fixing it to the main housing) such that both 90 degree bevel gears mesh. Secure the 8 mm shaft collar above the spur gear such that the 90 degree gears remain meshed and no vertical translation is possible.

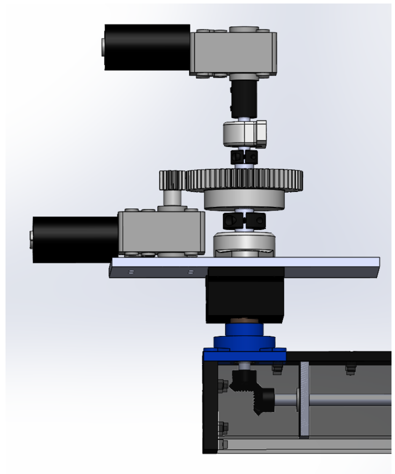


Figure 42: Vertical shaft subassembly

The seventh and final subassembly, shown in Figure 43, is the roller track subassembly. This consists of the four 3D printed roller track pieces which are screwed together and fixed to the top of the main mixing chamber such that the edge of the long end panel of the arm housing can rest on it as the arm rotates.

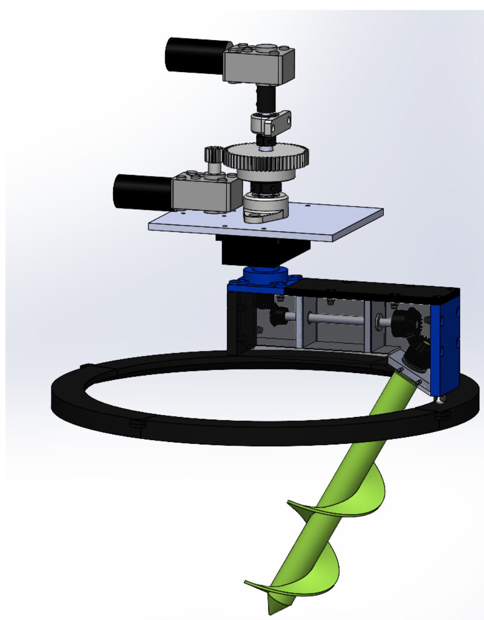


Figure 43: Roller track subassembly

After each of the above steps were performed, the Mixing arm was fully assembled as shown in Figure 44 and was ready for testing.

Figure 44: Fully assembled orbital mixing arm

4.2.8 Orbital Mixing Arm Design Validation

After the arm was fully assembled, the team performed a simple test procedure to verify the functionality of the mixing system. The first tests were performed before the mixing system was integrated into the full composter design. In these tests, the two motors driving the mixing arm transmission were tested individually using the code in Appendix I. To perform this test, the plate that holds the transmission system was clamped down onto the lab bench such that the auger and arm housing just cleared the bottom of the table. Using this configuration shown in the physical arm assembly photo in Figure 44 (right), the 130 RPM motor connected to the vertical 8 mm shaft was turned on to verify that the rotation would successfully be transmitted through the arm. The 130 RPM motor was then turned off and the 27 RPM motor was turned on to verify that the rotation would successfully be transmitted to create the orbital motion of the arm housing about the central axis of the arm.

After both of these initial tests were deemed successful, the orbital mixing arm was integrated into the full composter assembly for additional testing of the transmission system. These secondary tests were intended to verify that the motors could be run simultaneously to produce the desired output motion for both the auger attachment and the orbital arm housing. In the first trial for these tests the transmission system successfully produced the desired orbital arm housing motion but the auger was not rotating consistently. The team hypothesized that this issue could be attributed to additional friction due to the fact that the auger was rotating in a different direction than the orbital arm housing. In the second trial, the leads into the motor controller were switched for the 130 RPM motor to change the direction of rotation. The motors were run and this time resulted in successful output motion that was smooth for both the auger and the orbital arm. The setup for this experiment is pictured in Figure 45.

Figure 45: Setup for secondary testing of the mixing system transmission

4.3 The Aeration System

The purpose of the aeration fan is solely to introduce oxygen into the compost chamber, thus allowing for aeration to occur. While it plays a crucial role in the aeration process, its intended function was not to actively aerate the compost. Thus, the team selected a simple fan designed for cooling computers, with a relatively low output of 16 cubic feet per minute. The team also selected activated carbon filters for the aeration fan, due to their ability to effectively filter out unpleasant odors [36]. The team chose to use 12mm plastic tubing since it was a readily available resource. Pipe fittings and a fan cover were also purchased to complete the assembly. A custom flange adaptor was 3D printed to connect the pipe fittings to the fan. The fan, powered by two DC lead wires, which were connected to a 9V battery and manual ON/OFF switch. A detailed model of this fan set up is shown in Figure 46.

The aeration assembly sits in place on an acrylic sheet supported in the top layer of framing as seen in Figure 47. The orientation of the fan points “out”, such that it will pull air through the system and filter out all odors produced during composting.

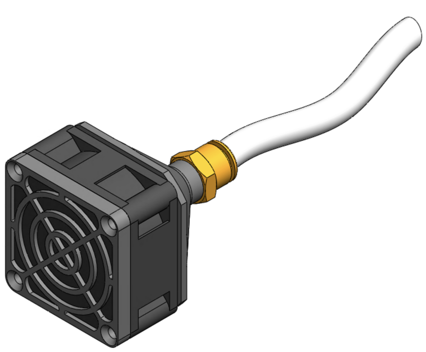


Figure 46: CAD model of the aeration assembly

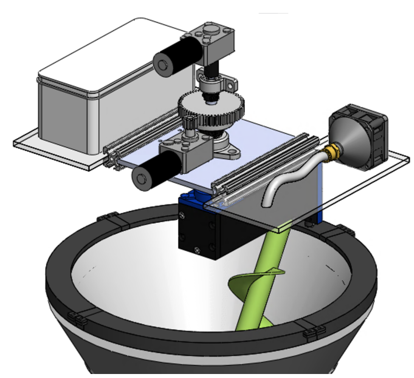


Figure 47: Zoomed in image of the aeration assembly sitting on the acrylic sheet above the compost chamber

4.4 The Compost Chamber

The compost chamber is the main location where the composting cycle occurs (Figure 51). The cone shape allows for effective aeration when paired with the auger orbital arm and with the help of an aerating fan which introduces oxygen into the system; (see Chapter 7 for more details on the aeration system). This combination ensures there is no dead space during mixing, as the auger bit is set at the same angle as the cone walls as shown in Figure 48.

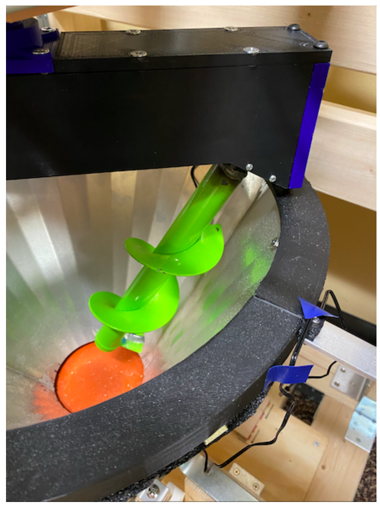


Figure 48: Image showing cone geometry matching the angle of the auger bit

The body of the chamber was custom manufactured out of aluminum, measuring at 7 inches in diameter at the top and 10.3 inches tall. In order to facilitate a warm enough environment for effective composting, polyimide heating film stickers powered by a 12-volt power source through UMLIFE electronic temperature controller switches are strategically placed to wrap around the bottom third of the cone where the majority of the composting will occur (Figure 49).

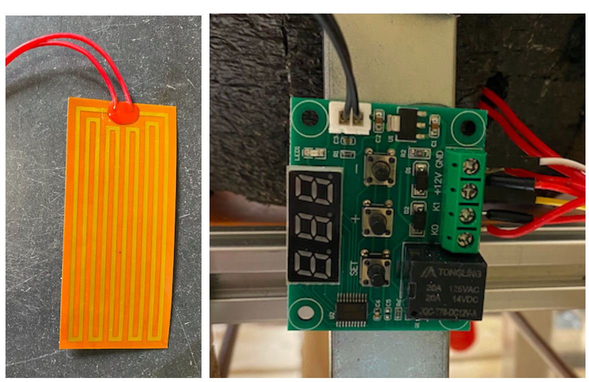


Figure 49: Polyimide heating film sticker (left) and UMLIFE electronic temperature controller switch (right)

The temperature controllers allowed the team to create a cooldown temperature so when the heaters heat the cone to a specific temperature, the heaters will cool down or stop heating, preventing them from overheating the compost chamber. These adhesive heaters, along with polyethylene foam insulation wrapped around the entirety of the cone, provides a controlled environment for composting (Figure 50). A DHT11 temperature and humidity sensor connected to an Arduino is able to provide the user with information about the chamber conditions (Figure 55); in the future, the readings from the sensor could be set up in a feedback loop with the heating stickers to better regulate the heating conditions based on which part of the composting cycle is occurring.

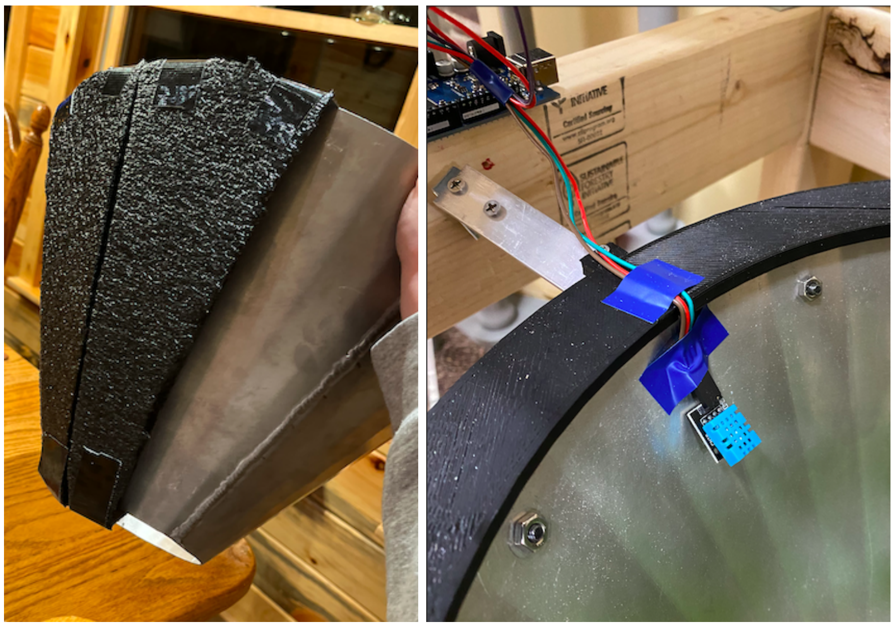


Figure 50: Polyethylene foam insulation (left) and DHT11 temperature and humidity sensor (right)

Figure 51: Final compost chamber subassembly

4.4.1 Selection of Final Design

The size and geometry of the compost chamber (referred to as the cone) was selected to match the angle of the auger on the orbital arm and to hold approximately a week's worth of food scraps for a one to two person household.

4.4.1.1 Material Selection: Heat Testing on Galvanized Steel Cone

Material selection was done through thermal analysis. Heat testing on the originally purchased galvanized steel cone was performed with food scraps and it was completed per the following procedure:

1. Two heating stickers connected to temperature controllers set to heat to 60 C were taped opposite of each other vertically to the bottom outside of the cone.
2. The cone was filled halfway with a fairly homogeneous mixture of food scraps including egg shells, watermelon rind, pineapple core/rind, and cantaloupe rind/core.
3. A temperature probe was added to the center of the cone, stuck in about halfway down the depth of the food scraps.
4. The heaters were turned on, and every minute for eight minutes, the temperature of the center of the food scraps was recorded.

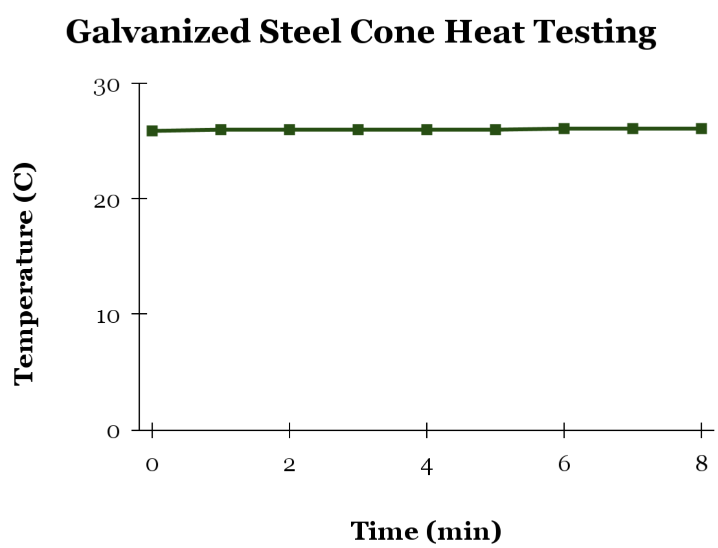


Figure 52: Results from heating testing of the galvanized steel cone

From the results of this first heat test shown in Figure 52, it became clear that the heating stickers on the galvanized cone were not conducting enough heat to heat up food scraps. As testing was being performed on this cone, decisions around the geometry of the orbital arm were being made. As the geometry of the orbital arm was to be designed around the gears that were selected, this initial cone was not going to match the geometry of the arm as nicely as the original design called for. This prompted the team to explore other material options to both ensure that the conical mixer inspired design would behave as intended, while also improving the thermal conductivity of the chamber. Aluminum, a material that is used frequently in manufacturing and thermal applications, was chosen to be analyzed in comparison to galvanized steel.

4.4.1.2 Material Selection: Heat Testing and Analysis Comparing Galvanized Steel to Aluminum

Heat testing to directly compare the thermal conductivity of aluminum to the galvanized steel cone was performed per the following procedure:

1. Using a sheet of 1/16th inch thick piece of aluminum slightly larger than a heating sticker, the heating sticker was taped to one side while the temperature probe from the temperature controller (programmed to heat to 60 C) was taped directly opposite to it on the other side of the sheet.
2. The heater was turned on, and every minute for ten minutes, the temperature of the aluminum plate was recorded.
3. Steps 1 and 2 were repeated with the heating sticker taped to the outside of the galvanized steel cone and the temperature probe taped directly opposite of it on the inside of the cone.

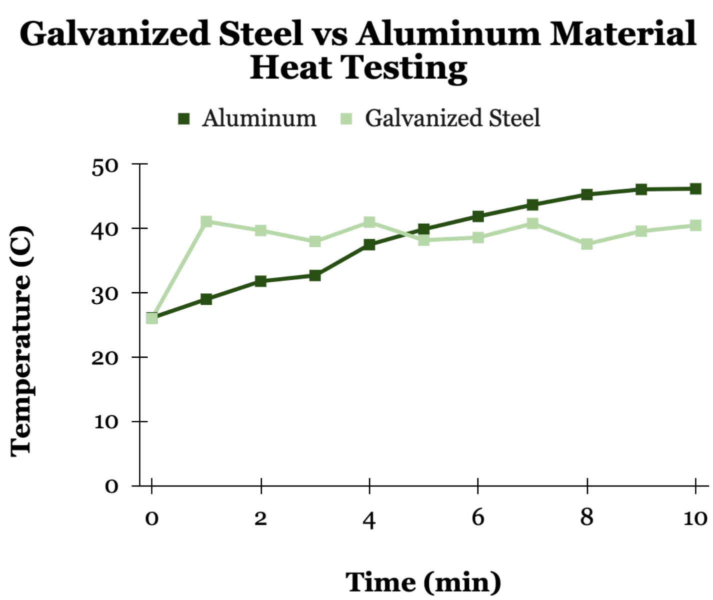


Figure 53: Results from heating testing comparing galvanized steel to aluminum material

The heat test results, seen above in Figure 53, showed that aluminum was able to heat much more effectively than galvanized steel. The galvanized steel heated quickly initially, but it was not able to continuously rise in temperature like the aluminum, indicating that there was more heat loss in the galvanized steel than in the aluminum. Aluminum was able to retain heat even without the aid of insulation; the aluminum material rose to a higher temperature than the galvanized steel cone in the same amount of time. These observations were confirmed through thermal calculations comparing the rate of heat transfer of galvanized steel to aluminum, the results of which are shown in Table 13 (calculations can be found in Appendix C).

Table 13: Heat Transfer Rate of Galvanized Steel vs Aluminum at Various Thicknesses

Material Thickness [in]	Galvanized Steel Heat Transfer Rate (Q-dot) [W]	Aluminum Heat Transfer Rate (Q-dot) [W]
0.0625	5781.4	12274.4
0.080	4516.7	9589.4
0.090	4014.9	8523.9

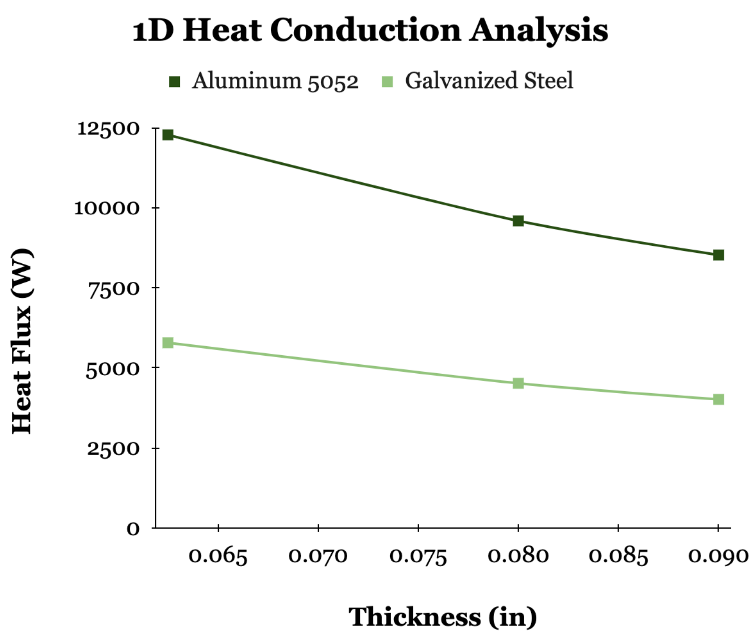


Figure 54: Thermal analysis of galvanized steel vs aluminum material

In this analysis, various material thicknesses were also compared as shown in Figure 54; the thinnest measurement (1/16 inches) analyzed was the thinnest the material could be before the structural integrity of the cone could be compromised during manufacturing. It was determined that 1/16 inch aluminum was the best material to manufacture the cone from. Due to the thermal benefits of aluminum and ability to match the geometry of the orbital arm, the team chose to have a custom cone manufactured at Quality Fab Inc, pictured in Figure 55.

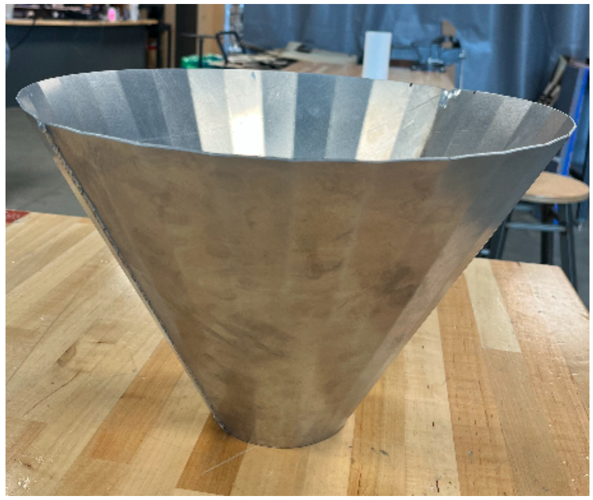


Figure 55: Custom manufactured aluminum cone from Quality Fab Inc.

4.4.2 Design Validation: Heat Distribution Testing on Aluminum Cone

After receiving the manufactured cone, heat distribution testing was conducted. The team was interested in seeing not only if material in the cone could heat up as predicted, but also if heat could be evenly distributed with the assistance of the orbital arm to facilitate even composting throughout the entire chamber. This testing was completed per the following procedure:

1. The cone was filled with a 3" layer of rice and heated with temperature controllers (adhered to the outside of the bottom third of the cone) set to heat until 60 C for 20 minutes.
    a. Pieces of 2-by-4s lay across the top opening of the cone to act as a "lid" and contain the heat throughout testing.
2. The temperature probes that form a cooldown feedback loop with the digital temperature controllers were placed about an inch away from the middle of the cone. This cooldown cycle was programmed to heat up to 60 C before cooling down to 59 C.
3. After allowing the cone to heat up, the team probed the rice with a thermistor in 5 different spots, one inch apart from each other, to measure the temperature at different locations across the cone.
4. Finally, the rice was mixed with the auger for 1 minute and the temperatures were re-measured.

As predicted, when temperature measurements were taken after step 3, the locations closest to the walls of the cone (where the heaters are located) had the highest temperature while the center of the cone had the lowest temperature as plotted in Figure 56. The results from the temperature measurements taken after step 4 showed that the heat was much more evenly distributed after mixing. This indicated that the auger orbital arm has the potential to contribute to even heat distribution and thus homogeneous composting throughout the entire chamber. It also showed that the aluminum material in combination with insulating foam creates a warm environment conducive to effective composting.

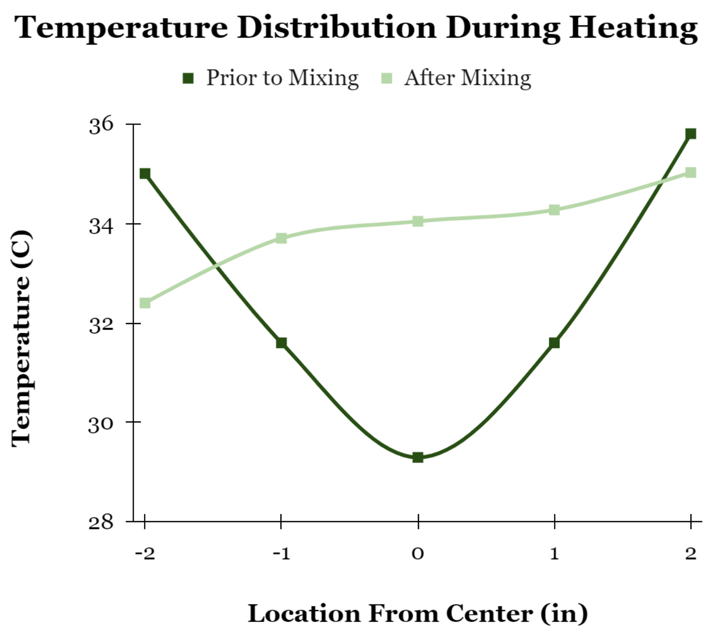


Figure 56: Results from temperature distribution testing in aluminum cone

4.5 The Extraction Mechanism

The extraction mechanism serves as the method to remove the mature compost from the compost chamber when the cycle is complete. This is currently done using a manual system. Once the compost is in the drawer, the user can remove the drawer as well and dispose of their compost wherever they please.

4.5.1 Detailed Design Description

Once the compost cycle is complete, the mature compost can be removed from the compost chamber via a crank and cam system. The user turns the crank partway, rotating two shafts with cams from the high position to the lowered position. These shafts are connected through a pulley system to ensure the cams move in tandem. This rotation unseals the bottom of the cone from the gasket material on the slider, which was placed to ensure no leakage from the compost chamber. Lowering the cams allows the user space to pull the slider out, allowing the compost to fall into the acrylic drawer below. The CAD model and physical prototype of this subsystem can be seen in Figures 57 and 58 respectively.

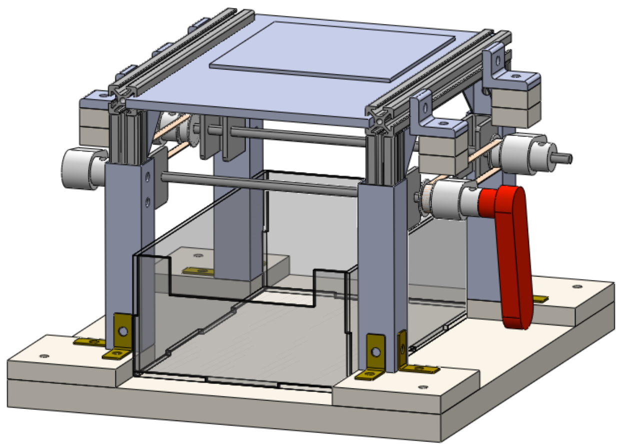
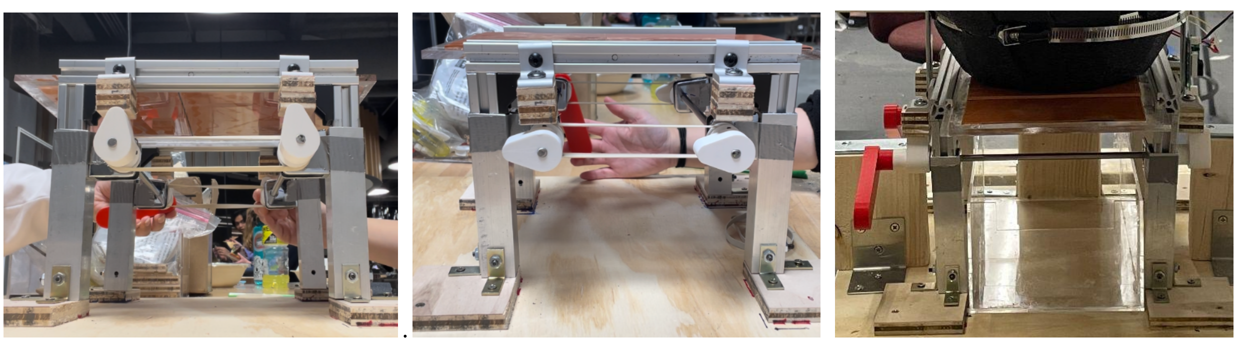


Figure 57: CAD of the extraction mechanism design



(a) (b) (c)

Figure 58: Prototype of the final extraction mechanism in (a) the high/sealed position, (b) the low/unsealed position, and (c) the position under the cone

4.5.2 Selection of Final Design

Initially, because the system design as a whole was inspired by industrial conical screw mixers, the design for the release mechanism followed that idea. As seen in Figure 59 below, in this design there is a hole in the bottom of the conical chamber that can be opened and closed using a sliding bar and panel.

(a) (b)

Figure 59: Release mechanism for an industrial conical screw mixer in the (a) closed position and (b) opened position

A cardboard prototype was created following this design to gain insight into how the parts would fit together and if this would work for a composting application. During this initial prototyping, there were concerns about the size of the hole being too small for compost removal and that some compost would get stuck in the chamber. It was then decided that the design would transition away from having only a portion of the bottom of the cone cut out, and towards having the entire bottom removable by sliding out a platform, later referred to as the slider.

However, the bottom of the cone still had to be sealable, so the next design step was figuring out how to seal the bottom of the cone during the process, but have it able to unseal so the slider could be removed when it was time for extraction. First, it was determined that there would need to be some sort of gasket material sealing the bottom of the cone so that there would be no leakage out the bottom from the compost during mixing. However, by adding the gasket, it would be much harder for the user to pull out the slider. A cam system seemed to be the best solution, as they could move the slider covering the bottom of the cone up and down a controlled amount. The slider only needed to be lowered enough to unseal the gasket so that there was less resistance as the user tried to pull it out, so these cams could be designed relatively small. Again an initial cardboard prototype was created as seen in Figure 60 below to understand how the motion would work and if this type of cam system would work for this application.

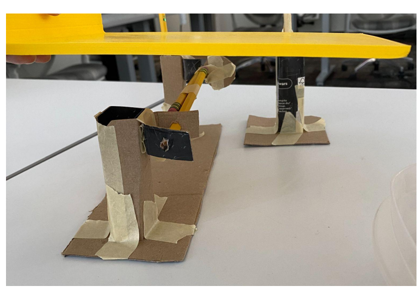


Figure 60: Partial cardboard prototype of the cam system

After experimenting with the cardboard model, it was decided that the cam system was feasible. There would be four cams in total, two for each side of the slider with keyed shafts running through them.These shafts would rotate, lifting and lowering the cams and the slider. Once this new design was thought out, a more detailed design was developed and fabricated.

4.5.3 Manufacturing and Assembly

This system was then manufactured using a combination of 3D printed, laser cut, and existing parts that were adjusted to fit the needs of the design. The cams, crank, and pulley wheels were 3D printed on the Ultimaker 03 printer with a D profile hole so that they would be keyed to the shafts and move as they move. Rubber bands were used to connect the pulley wheels to each other perpendicular to the shafts. Because the slider and the drawer had all flat sides, they were laser cut out of acrylic material. The sides of the drawer were designed to be a puzzle piece fit and were also glued together for extra security. Gasket material was glued to the slider to prevent leaks. The entire extraction system was built on a wood base. Metal hollow square tubing was secured to it and T-slotted extrusion was connected to form a wide U shape that would fit inside the tubing and could be lifted up and down. Metal brackets were also secured to the hollow tubing to hold the rotary shafts. An exploded view of the CAD for the extraction mechanism assembly can be seen in Figure 61 below.

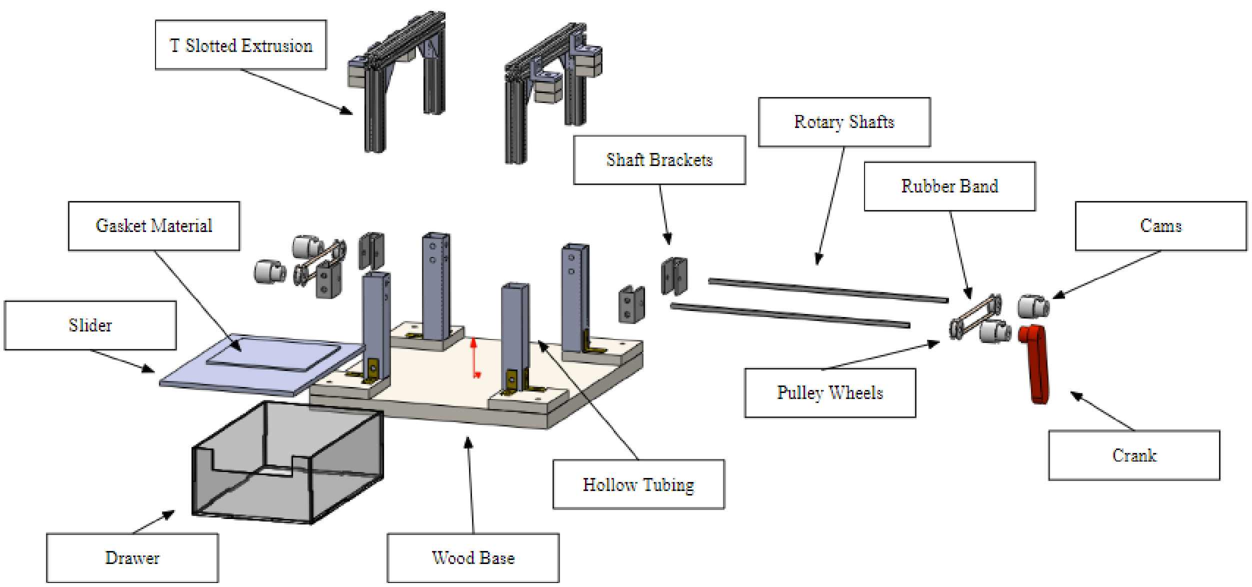
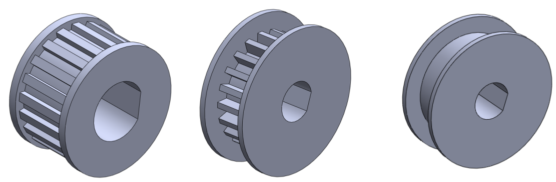


Figure 61: Exploded view of CAD model for extraction mechanism assembly

4.5.4 Unit Testing and Final Adjustments

Once the extraction mechanism was assembled, multiple unit tests were run to make sure it was functioning properly. On the first run through, it was observed that the shafts were not working in tandem even with the pulley system in place. The rubber bands appeared to be slipping off the pulley wheels and the single crank system was not able to overcome the forces of both cams hitting the wood to go into high position. In order to overcome this, the pulley wheel design was adjusted twice, first to have higher lips so the rubber band would stay on the wheel, and second to remove the printed texture and add sandpaper instead to ensure no slippage during rotation. The three different designs for the pulley wheel can be seen below in Figure 62.



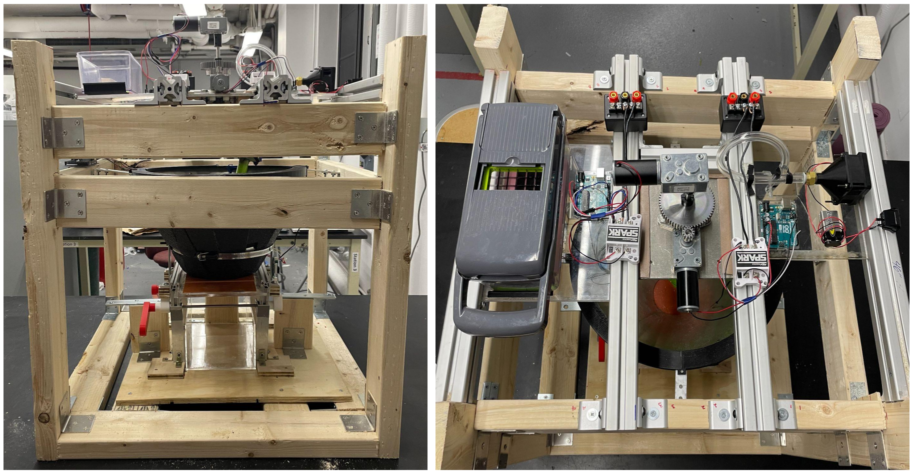
(a) (b) (c)

Figure 62: Design for the pulley wheels
(a) First iteration of pulley wheel design with printed texture
(b) Second iteration of pulley wheel design with a larger lip
(c) Final pulley wheel design with no printed texture so sandpaper could be added

Additional unit testing was conducted once the cone was in place to make sure the cams moved the slider up and down the correct distance to seal and unseal the compost chamber. Overall, the system integrated well and worked correctly.

4.6 Full System Integration

The vast majority of the framing for the composter was made from 2x4 wood studs, due to their ease of accessibility, affordability, and versatility. The framing consists of four vertical posts and multiple horizontal support layers. The bottom layer acts as a base for the composter, and two additional layers provide support for the overall structure as well as support for individual components of the composter. The extraction mechanism was secured to the base of the system, with the cone sitting atop it, creating a seal when the cams were in the high position. The conical compost chamber was secured to the base of the system with L brackets that were connected to wood posts. These L brackets were attached to an adjustable metal ring that slid into the foam insulation of the cone. Spokes were added at the top of the cone to provide additional support by connecting the track to the wood framing. The top layer of the framing utilized Aluminum extrusion to hold up two acrylic sheets where the aeration fan and the food pod were placed. This extrusion also was designed to support the weight of the orbital arm. To integrate the orbital mixing arm subassembly into the overall system, the Aluminum plate that the arm is mounted on was fitted between the two horizontal Aluminum extrusion bars at the top of the frame. This held the plate such that the two concentric vertical shafts in the mixing arm were aligned with the central axis of the composting chamber. The level of the plate relative to the top plane of the composting chamber was carefully measured so the roller bearings on the end panel of the orbital arm would be in contact with the track, ensuring extra support during motion. The entire system can be seen in Figure 63 below.



(a) (b)

Figure 63: (a) Front view and (b) top view of the final smart composter prototype

Chapter 5: Broader Impacts

While smart composting is a sustainable practice that is gaining interest and attention, there are a number of factors that must be considered in the responsible design of a smart composting system. The following chapter describes how our product has impacts on the environment, health and safety of users, society, the economy, and ethics.

5.1 Environmental Impact

Composting provides an environmentally friendly alternative to the traditional method of depositing organic waste in landfills. Landfills are considered a counterproductive waste management system and are harmful to the environment, as they contribute to global warming through high production of greenhouse gasses and occupy land that could otherwise be used for agricultural purposes [37]. Composting recycles this organic waste into useful products which is a much healthier option for the environment. Many cities have already adapted composting as a waste reduction method and are trying to make it as easy as possible for people. Multiple have even started collecting food waste with the trash and recycling each week. The food gets composted by the city and then is used to enhance the soil. According to a news article last year, implementing this in San Francisco has even helped divert 80% of the city's waste from landfills [38].

If done correctly, composting can not only reduce waste, but also enhance soil fertility and plant growth. Compost can not only improve the water-holding capacity of the soil, but has also been proven to be more effective in improving soil quality than many commercial inorganic fertilizers [37]. The temperature buildup during composting can also eliminate soil-borne pathogenic organisms in the waste such as fungi [37]. Though compost is generally considered an environmentally safe technology, if the compost is not mature, toxic substances can be produced that are harmful to ecosystems. If the process conditions and composition of the substrate are not ideal, "obligate anaerobic methanogens may lead to the evolution of methane during composting" [37]. Methane is a large contributor to global warming, so it would be important that the composter could help regulate process conditions to prevent its production. Leachate, another toxic substance, can also be generated by compost, which is problematic because they include "ammonia-nitrogen, heavy metals, chlorinated organic and inorganic salts" which can be very harmful [37]. Assessing the possible environmental impacts that compost leachates could have is therefore very important and can be done by looking into their nutrient composition and concentration [37].

In addition to toxic substances, a number of gasses are produced in immature compost that can be odorous, detrimental to the environment, and can cause pollution. Composting produces CO_2 and water vapor, as well as "CO, NH_3, CH_4, N_2O, H_2S, NO_x and volatile organic compounds (VOCs), that have varying impact on air quality" [37]. NH_3, H_2S, and VOCs are all odorous, and N20 and CH_4 "possess an atmosphere-warming potential 310 and 20 times greater than CO_2, respectively, whereas VOCs and NOx have a warming potential approximately 2000 times higher than CO_2" [37]. Odorous emissions usually are created when the biomass is delivered and preprocessed, as well as during the composting process itself, especially during turning [37]. As seen through the information above, making sure to produce mature compost can help prevent risks to the environment. Utilizing a smart composter will not only educate the user on the composting process, but also help ensure that the compost is viable.

5.2 Health and Safety

It is also important to consider the health and safety of users that are operating the smart composter. Using contaminated compost, especially in a food garden, could be very detrimental to the health of the consumer, so it is important that the smart composter produces viable compost and keeps the user aware of its composition. Including sensors to read and regulate the metal content and salinity for example would be beneficial and help ensure there were no potential safety hazards. Additionally, as discussed in the previous section, composting can produce a number of gasses. While these emissions might not directly result in health problems, they "could be associated with negative health effects which may thus lead to defensive reactions of people due to psychological effects" [37]. Using a smart composter over a more traditional method of composting would ensure that the gas emissions are monitored and can be regulated, keeping the user safe.

This composter also follows the codes and standards related to this work, which also demonstrates its safety of use. While intended for the workplace, some OSHA standards on appliances and safety can also apply to household appliances. OSHA regulations require visual inspection, electrical assessment, and appliance markings for all appliances. For visual inspection, cords must be accessible to inspect but managed to prevent them from being a hazard, be repaired or replaced when the outer jacket is damaged, and have a legible manufacturing label with warnings [39]. No wires can be exposed. As for electricity, "appliances must be supplied with the energy requirements specified by the manufacturer for operating safely in the location of operation" [39]. There should also be a suitable outlet that can be used to plug in the appliance not at risk of water intrusion. Finally, appliance markings must be present, including "a rating in either volts and amperes, or volts and watts. As necessary, any externally required motor overload protection or specific operating frequency must be specified" [39]. Information about disconnecting means and durability requirements must also be present. This means that our composter must not have any visual hazards, use a safe amount of energy for an apartment, and have the necessary markings.

5.3 Social and Global Impact

Developing a low cost, easy to use composter allows more people to feel like they are able to take the step to start composting. This composter creates an accessible means to get more people involved in learning about the benefits of composting as much or as little as they want. Even if the customer chooses not to engage very much with the educational aspect of the composter, the fact that they are actively composting at all can be very influential to the people around them. Engaging in any sort of household level actions, such as composting, to improve one's environmental impact can positively contribute to the growing global issues caused by climate change and global warming. Having a countertop composter may encourage discussion from roommates or guests who notice the novel item. It may spark conversations about the importance of composting, along with strategies to appropriately compost.

One of the main barriers to engaging in "green behaviors" is an individual's perception that their social group will not approve of these behaviors. Similarly one of the main indicators of engaging in these behaviors is if the individual's immediate social group is already engaging in other "green behaviors" [8]. The specific social mobile application that optionally connects with our smart composter focuses on building community between young people looking to learn more about composting, allowing them to actively engage socially in "green behaviors." People will be able to ask questions, share ideas, and generally build more knowledge about composting. Additionally, because our composter will focus on being self contained and apartment friendly, it may change the way that young people see composting. Instead of being a worm filled dirt pile that attracts flies, it will be a sleek countertop appliance that will efficiently make compost that can be used to reduce waste sent to landfills and provide nutrients to any apartment-dweller's plant collection.

5.4 Economic Factors

The cost of some smart composters similar to ours are currently on the market for hundreds of dollars, meaning they are not very cost-friendly for young adults. These composters likely cost so much due to their many composting settings, expensive looking exterior, and the large amount of marketing to slightly older consumers. This reinforces the perception that composting is a "luxury" activity reserved only for the very wealthy and "green freaks" or activists. Composting shouldn't be an expensive endeavor, and it can technically be done for virtually no money, but investing in our smart composter in particular ensures that users can learn the needed information about composting while also having the benefits of an efficient, beginner friendly solution. It also produces nutrient-rich compost that can be added to any household plants, adding value to the composter.

5.5 Ethical Considerations

Ethically, it is important for us to consider the way we are marketing the smart composter, ensuring that it is in fact creating good quality compost that can support plant life. The composter will not just be grinding up waste, but instead will be measuring the conditions of the compost chamber, allowing users to see the temperature and humidity levels throughout the entire process in case they need to make changes to the heating system or other aspects of the composting environment. It also has the potential to easily be converted to automatically making these adjustments throughout the cycle while still providing the data to users so they can be educated on how to create nutrient-rich compost. Our product will be key in giving confidence to young people to take steps to make a positive difference in their environment, so ethically speaking, that means we will only be providing scientifically accurate educational notes for the user to learn from.

It is also important to consider the impact composting has on the ethics of food waste. Food waste that ends up in a landfill or is incinerated adds to the production of methane, emission of pollutants, contributes to air pollution and climate change, and causes problems in public health [40]. Composting reduces the amount of waste that ends up in landfills and instead contributes to helping plants grow. However, sometimes it is easy to think that our sustainability efforts are helping when in fact they are contributing to the problems in other ways. We need to consider that our smart composter will use electricity, something that can negatively impact the environment. However, the hope with creating an educational aspect is that the customer can change to more sustainable composting methods confidently later on.

Per the Code of Ethics of Engineers, we should be "issu[ing] public statements only in an objective and truthful manner and shall avoid any conduct which brings discredit upon the profession" [41]. This means our composter should do what it is advertised to do, to show our competence as engineers. We must strive to consider the health and safety of those using the composter, again by working to produce good quality compost. Finally, we will continuously be aware of our environmental and sustainability impacts as we design and build a product that will ideally be an accessible tool for young people to contribute to sustainability efforts.

5.6 Conclusion

It is important to take these impacts into account to build a viable, affordable, and safe smart composter. This composting system needs to produce nutrient-rich compost and should incorporate some features that help the user know when the compost is ready for removal. This will help ensure that the compost is safe for the environment. The composter itself also needs to follow common codes and standards for appliances to ensure it is safe for users. As for social behavior, having a more technical and hands off approach rather than a traditional method of composting can help engage younger audiences and adding in a social aspect can also encourage younger people to participate in green behaviors. While the cost of smart composters is currently a barrier for many people, this composter is projected to be much more affordable. Ethically, there is an obligation when designing this system to make sure the product will match what is advertised, so it must fulfill the expectations described above: it will produce mature compost that is beneficial for the environment, be safe for all users, and an easy, hands off way to get into composting.

Chapter 6: Conclusion and Future Work

6.1 Conclusion

Over the course of the year, the team was able to conduct an extensive design and prototype process to create a smart composter. The goal of this project was to create a composter that is capable of producing viable compost, while having the ability to monitor and adjust various parameters associated with the composting process. After narrowing down 48 original design concepts, the team was able to successfully build a prototype that was an ideal environment for composting in terms of aeration and heating. It also produced the desired output motion in terms of both orbital and axial rotation.

It should be noted that the purpose of this project was not to replace manual composters, which clearly leave behind the least negative environmental footprint. Any machine which requires electricity will naturally have some negative environmental consequences. The goal, rather, is to encourage as many people as possible to compost - especially those who normally wouldn't. This project aims to improve the user experience of composting and to adapt it to any lifestyle (most specifically apartment life). Though this design consumes more power than traditional composting techniques, it would hopefully increase the population of people engaging with food waste separating behaviors, thus diverting a larger volume of waste from landfills. While this composter is in a very early stage of design with plenty of room for future work, it is an excellent first step in making composting more appealing and accessible to a new demographic, and has the potential for significant environmental impact.

6.2 Future Work

The scope of this project was greatly limited by several factors, most notably: time, budget, and resources. Therefore, were this project to continue, there are several key areas the team has identified as subjects of future work. These improvements span both the individual subcomponents as well as the system as a whole. The addition of an entirely new subsystem, the user interface, was also proposed.

The food pod, though an innovative aspect of this project, is still in an early stage of design. Since it exists as a modified version of a vegetable chopper, it is limited by this original geometry. This has resulted in a very small area on which to chop food, requiring extra initial chopping of larger items. In the future, it would be preferable to increase the size of the chopping area in order to decrease steps required by the user. Additionally, the included blades appeared to have a difficult time with tougher scraps, such as melon rinds. This could be addressed with sharper blades, or using stronger plastic to allow more force during chopping. Finally, it was discovered during testing that upon release, small pieces of food got stuck along the remaining edges at the bottom of the pod. Suggested solutions include adding a slope to better utilize gravity, integrating a vibration aspect, or simply expanding the removable plate to span the entire bottom of the pod. These changes would likely be more easily accommodated by designing a custom food pod, rather than modifying an existing product.

Though the team successfully achieved the desired motion of the orbital arm, there is room for improvement in its design. The limiting factors of budget, time, and resources had an effect on many areas of the project, but notably restricted the quality of the manufactured parts of the arm. As mentioned in the design section, the original plan was to machine the arm housing entirely out of metal, however these limitations required that several parts, such as the housing and the flange, be 3D printed. Suggested future work for the arm would be to manufacture it out of metal with better material and mechanical properties to increase longevity. Swapping to a smaller auger has also been proposed in order to reduce the size of the aluminum cone required for the compost chamber.

Aside from aiming to reduce the overall size, there are several areas of the compost chamber that could be built upon. An important piece of this project is making composting more appealing to a demographic that does not usually participate, and a large part of that is the aforementioned “ick-factor”. Thus, it would be ideal in the future to design a lid for the compost chamber which completely seals out smells, leaks, and visual access as best as possible. Also, additional sensors, such as temperature, moisture, and oxygen, should be incorporated and tied to feedback loops to monitor and adjust compost properties throughout the cycle. Another component to add would be an automated browns dispenser, which would release carbon-rich material into the chamber when its associated sensor reads that the C:N ratio is too low.

Similar to the food pod, the extraction mechanism still exists in a very early stage of its design. The major area of improvement for this subsystem would be to automate it, thus removing the need for the user to manually turn the crank. The cam system itself could also benefit from a design iteration, as it currently consists of 3d printed cams and rubber bands. Iterating and manufacturing these components from different materials would allow them to consistently function as intended.

One subsystem that was deemed fully outside the scope of this project was a consolidated user interface. Suggested future work in this area includes an educational aspect, where the user can view the progression of the compost. This could potentially display a progress bar which moves along as the food waste reaches each stage in the cycle, informing the user about each stage and its purpose. Furthermore, a social aspect was suggested, where the user could see how many people around them are composting. This could include a “friend” system or a competitive component.

Finally, there is much room for advancement on the system as a whole. For instance, one common complaint about existing smart composters on the market is the lack of verification that the machines actually produce viable compost, in terms of the qualities of good compost [42]. Running full cycle tests on the system while monitoring these properties with the sensors mentioned previously would allow for the viability of the compost produced to be verified. Additionally, there is much room for growth in terms of the size and aesthetic appeal of the project. As discussed earlier, the size of the cone was constrained by the size of the auger. Thus, switching to a smaller auger would greatly reduce the overall size of the machine. Future work should also include closing off the support structure with opaque material, improving visual appeal and removing the “ick-factor” brought by sights and smells.

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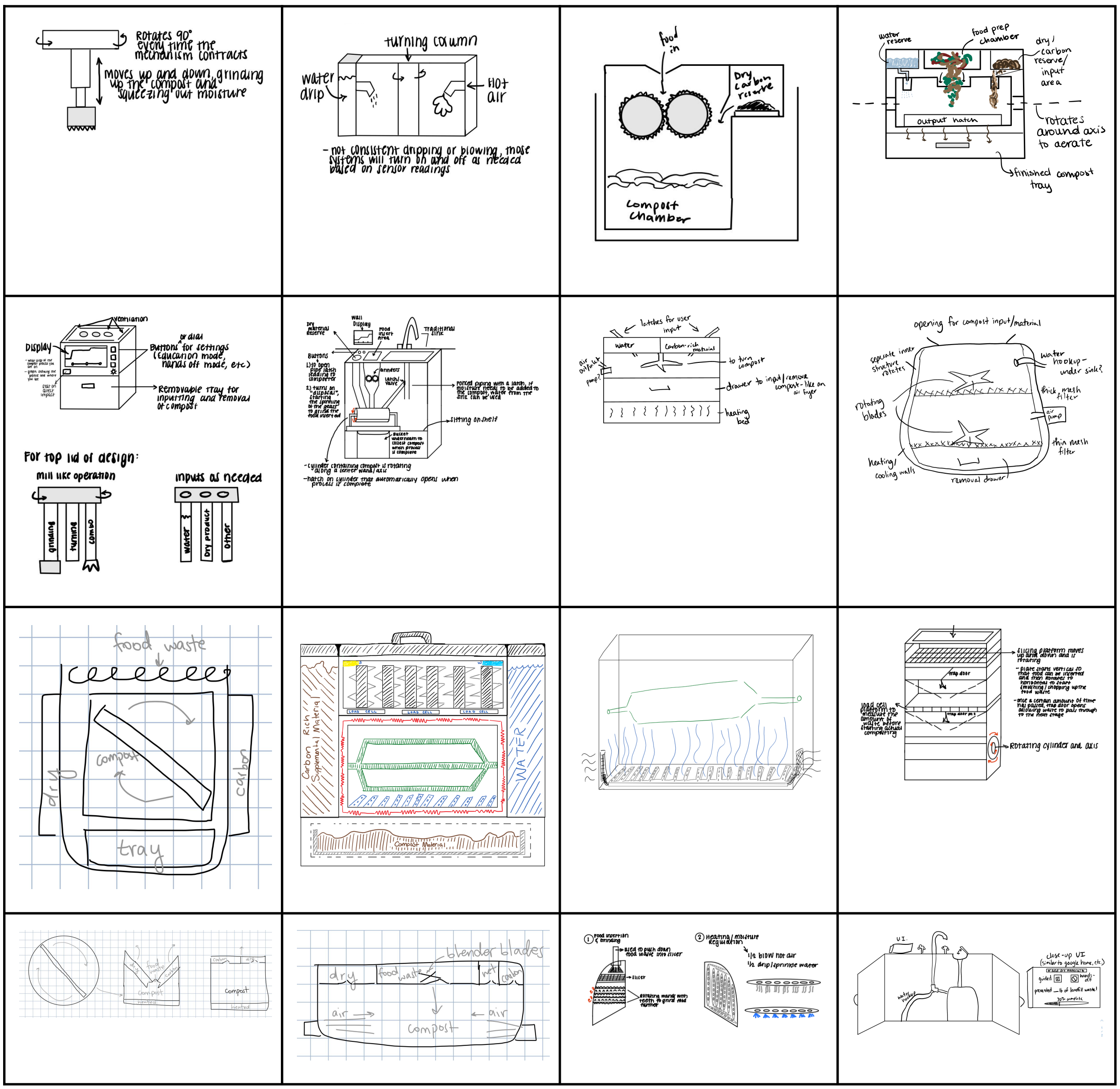
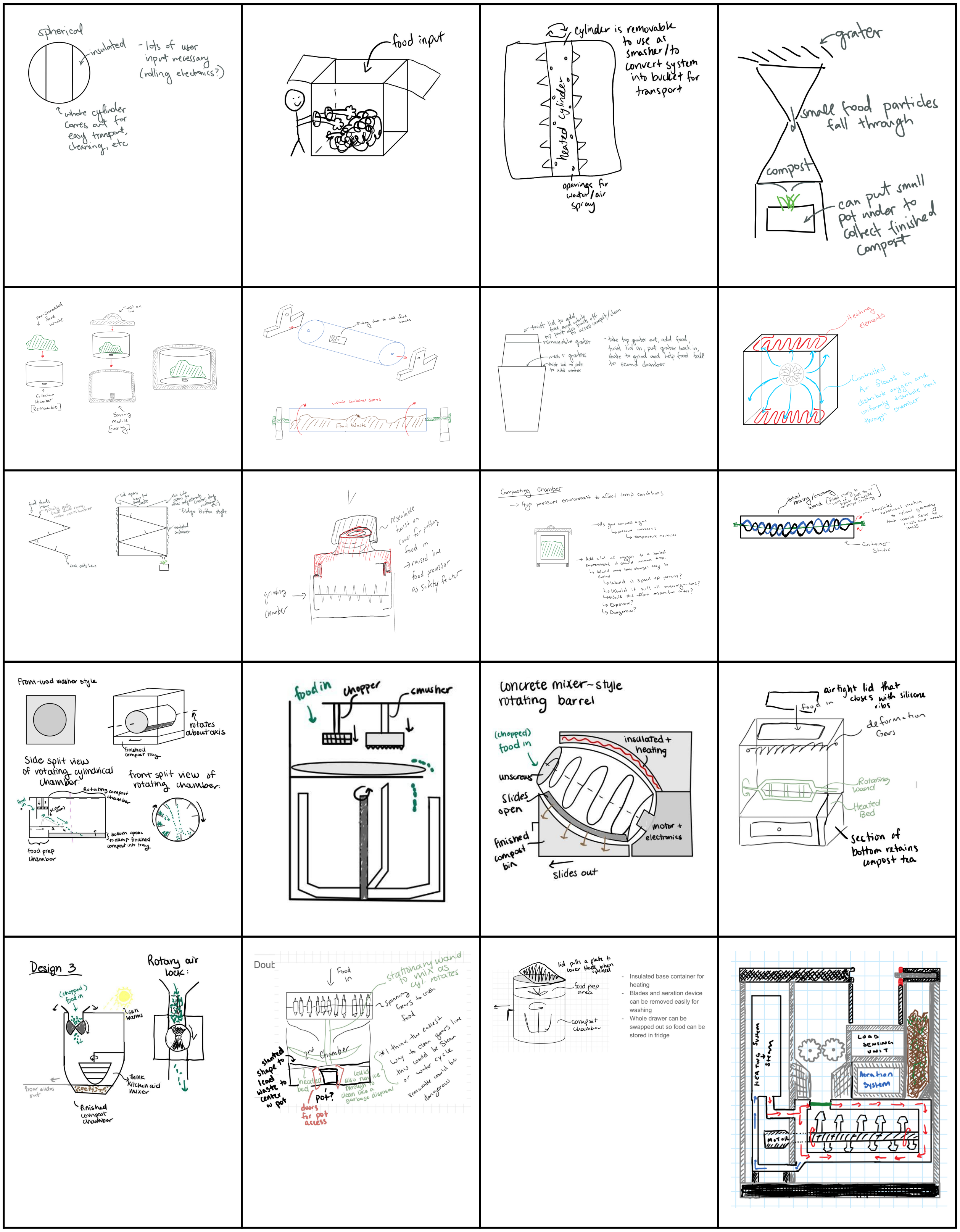
Appendix

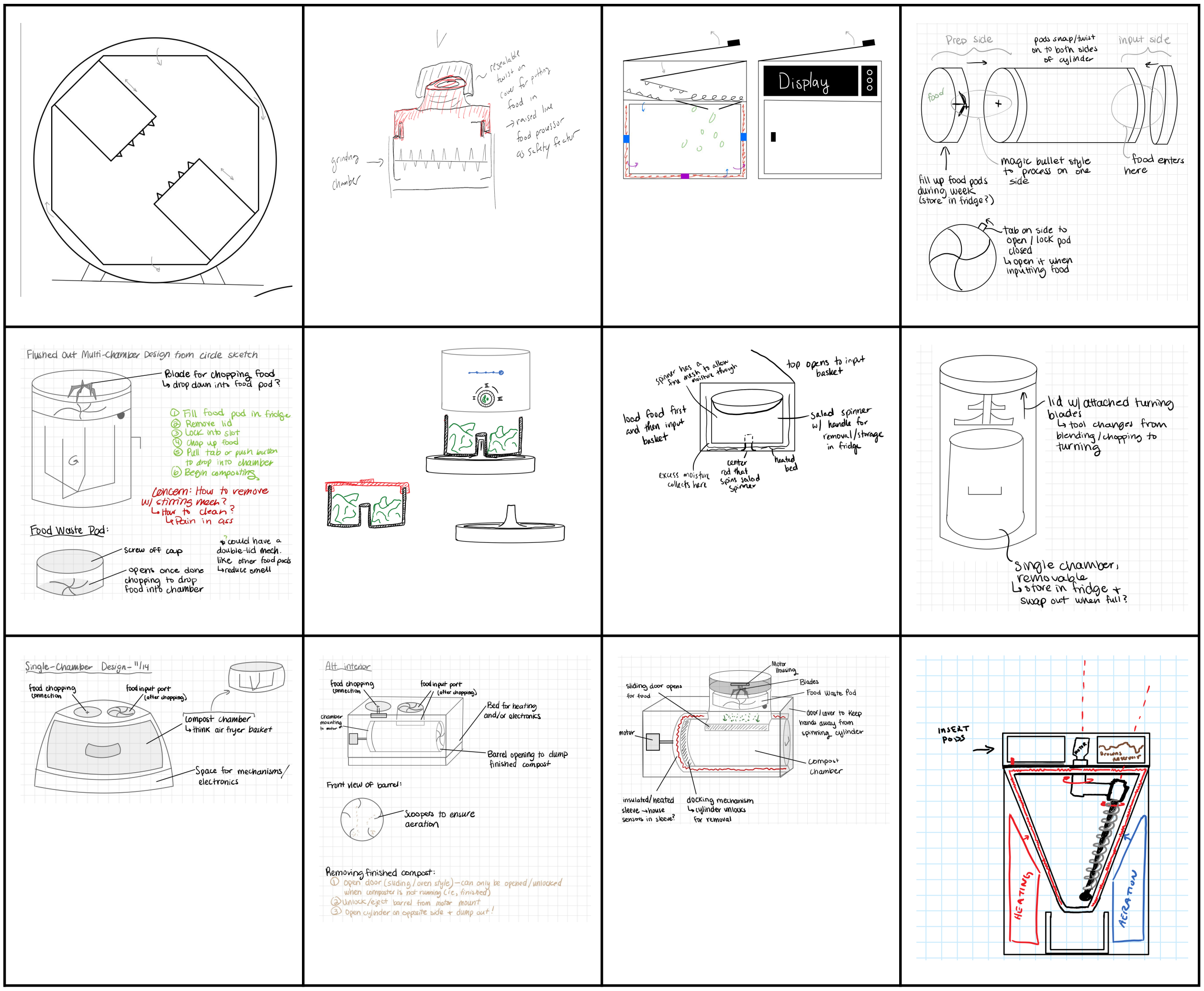
Appendix A: Initial Conceptual Designs

Below are sketches of all 48 initial design concepts the team came up with during the design ideation phase. They are ordered roughly in chronological order of when they were conceived, whether through brainstorming, circle sketches, directed prompts to facilitate ideas, or other means.





spherical
insulated
- lots of user input necessary (rolling electronics?)
whole cylinder comes out for easy transport, cleaning, etc
food input
cylinder is removable to use as smasher / to convert system into bucket for transport
heated cylinder
openings for water / air spray
grater
small food particles fall through
compost
can put small pot under to collect finished compost
Front-load washer style
rotates about axis
finished compost tray
Side split view of rotating cylindrical chamber:
front split view of rotating chamber.
food prep chamber
food in
chopper
smusher
concrete mixer-style rotating barrel
(chopped) food in
insulated + heating
unscrews
slides open
finished compost bin
motor + electronics
slides out
airtight lid that closes with silicone ribs
food in
deformation Gears
Rotating wand
Heated Bed
section of bottom retains compost tea
Design 3
Rotary air lock:
(chopped) food in
sun warms
think Kitchen aid mixer
finished compost chamber
Food in
stationary wand to mix as cyl. rotates
chamber
pot?
doors for pot access
Insulated base container for heating
Blades and aeration device can be removed easily for washing
Whole drawer can be swapped out so food can be stored in fridge
Heating System
Load Sensing Unit
Aeration System
Motor


resealable twist on cover for putting food in
→ raised line food processor as safety factor
grinding chamber
Display
Prep side
pods snap/twist on to both sides of cylinder
input side
food
fill up food pods during week (store in fridge?)
magic bullet style to process on one side
food enters here
tab on side to open / lock pod closed
↳ open it when inputting food
Flushed out Multi-Chamber Design from circle sketch
Blade for chopping food
↳ drop down into food pod?
① Fill food pod in fridge
② Remove lid
③ Lock into slot
④ Chop up food
⑤ Pull tab or push button to drop into chamber
⑥ Begin composting
Concern: How to remove w/ stirring mech?
↳ How to clean?
↳ Pain in ass
Food Waste Pod:
screw off cap
opens once done chopping to drop food into chamber
could have a double-lid mech. like other food pods
↳ reduce smell
spinner has a fine mesh to allow moisture through
top opens to input basket
load food first and then input basket
salad spinner w/ handle for removal/storage in fridge
excess moisture collects here
center rod that spins salad spinner
heated bed
lid w/ attached turning blades
↳ tool changes from blending/chopping to turning
single chamber, removable
↳ store in fridge + swap out when full?
Single-Chamber Design - 11/14
food chopping connection
food input port (after chopping)
compost chamber
↳ think air fryer basket
Space for mechanisms/ electronics
Alt. interior
food chopping connection
food input port (after chopping)
chamber mounting to motor
Bed for heating and/or electronics
Barrel opening to dump finished compost
Front view of barrel:
Scoopers to ensure aeration
Removing finished compost:
① open door (sliding / oven style) — can only be opened/unlocked when composter is not running (i.e., finished)
② Unlock/eject barrel from motor mount
③ Open cylinder on opposite side + dump out!
Motor Housing
Blades
Food Waste Pod
sliding door opens for food
door/cover to keep hands away from spinning cylinder
motor
compost chamber
insulated/heated sleeve → house sensors in sleeve?
docking mechanism
↳ cylinder unlocks for removal
INSERT PODS
MOTOR
Browns Reservoir
HEATING
AERATION

Appendix B: Complete Notes from Results of Auger Selection Testing

Auger Type	Trial 1: Time to Combine	Trial 2: Time to Combine	Observations + Notes
Green (3”)	~15 sec	10sec	Mixed quite quickly and smoothly
Black (4”)	~15 sec	12sec	Very comparable to green, maybe have felt smoother (a tiny bit easier to move through rice)
Wood (1”)	30+ sec	-	Bit fell off, takes much more force to move around, did not mix well

Auger Type	Food Mix	Results
Green (3”)	- Egg shells - Onion scraps - Cantaloupe rinds - Bell pepper insides - Banana peels	- Eggs broken down very well - Onion broke down well - Pepper and banana began to break down into some smaller pieces - Cantaloupe rind did not shred

Black (4”)	| |	- Did a good job of breaking up onion, eggs
		- Shredded banana peel string cheese style
		- Didnt break up well the onion skins, onion eye (mushed), or cantaloupe
		- Pepper core broke down a bit, stem did not
		- Smallest pieces at the bottom
		    - Some may have gotten stuck in the bottom piece
		- Larger pieces (cantaloupe and large onion pieces) were pushed upwards and almost out of the cone rather than shredding
		    - A lid forcing them back down may be helpful

Wood (1”)	N/A	- Did not test following poor mixing results

Appendix C: Cone Material Thermal Conductivity Analysis Calculations

Hand calculations for the heat transfer rate of various thicknesses of aluminum:

Conduction – movement of heat b/t two bodies that are in contact

Fourier's Law – 1D conduction

$$\dot{Q} = -kA\frac{\Delta T}{\Delta x}$$

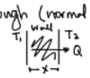
$\dot{Q}$: heat flux

k: thermal conductivity (of 5052 aluminum alloy) = 138 W/mK, typical at 77°F (from asm.Matweb.com)

A: area heat passes through (normal to direction of heat transfer) = 100 mm × 40 mm = 4000 mm² = 6.2 in² = 0.004 m²

ΔT: $T_1 - T_2$

Δx: thickness of wall



Δx = 1/16 in = 0.0625 in = 0.0015875 m

ΔT = 60 C − 24.7 C = 333.15 K − 297.85 K = 35.3 K

$$\dot{Q} = (138\ W/m\cdot K)(0.004\ m^2)\frac{(35.3\ K)}{(0.0015875\ m)}$$

$\dot{Q}$ = 12274.3937 W

Δx = 0.080 in = 0.002032 m

$$\dot{Q} = (138\ W/m\cdot K)(0.004\ m^2)\frac{(35.3\ K)}{(0.002032\ m)}$$

$\dot{Q}$ = 9589.370079 W

Δx = 0.090 in = 0.002286 m

$$\dot{Q} = (138\ W/m\cdot K)(0.004\ m^2)\frac{(35.3\ K)}{(0.002286\ m)}$$

$\dot{Q}$ = 8523.884514 W

Hand calculations for heat transfer rate of various thicknesses of galvanized steel:

$$Q = -kA\frac{\Delta T}{\Delta x}$$

Q: $heat\ flux\ = ?$

k: $thermal\ conductivity\ of\ galvanized\ steel\ =\ 65\ W/m\ K$

A: $area\ heat\ passes\ through\ =\ 100mm\ x\ 40mm\ =\ 4000\ mm^2\ =\ 0.004\ m^2$

$\Delta T\ = T_1 - T_2 = 60C\ -\ 24.7C\ =\ 333.15K\ -\ 297.85K\ =\ 35.3K$

Δx: $thickness\ of\ wall$

For $\Delta x\ =\ 0.0625\ in\ =\ 0.0015875\ m$

$$Q\ =\ (65\ W/m\ K)(0.004\ m^2)(\frac{35.3\ K}{0.0015875})\ =\ 5781.417\ W$$

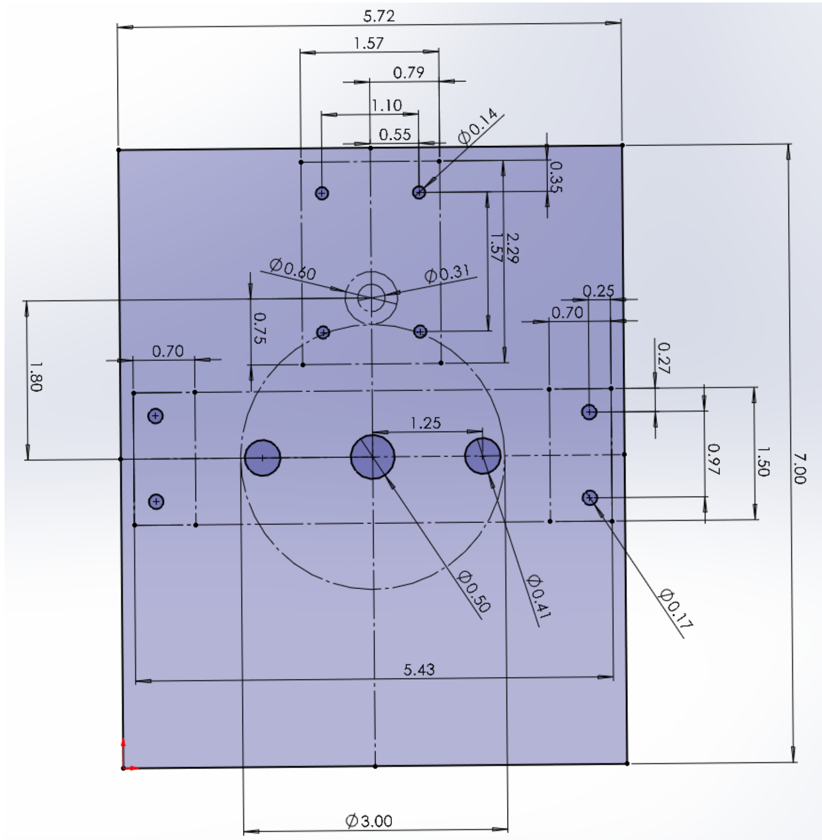
For $\Delta x\ =\ 0.080\ in\ =\ 0.002032\ m$

$$Q\ =\ (65\ W/m\ K)(0.004\ m^2)(\frac{35.3\ K}{0.002032})\ =\ 4516.732\ W$$

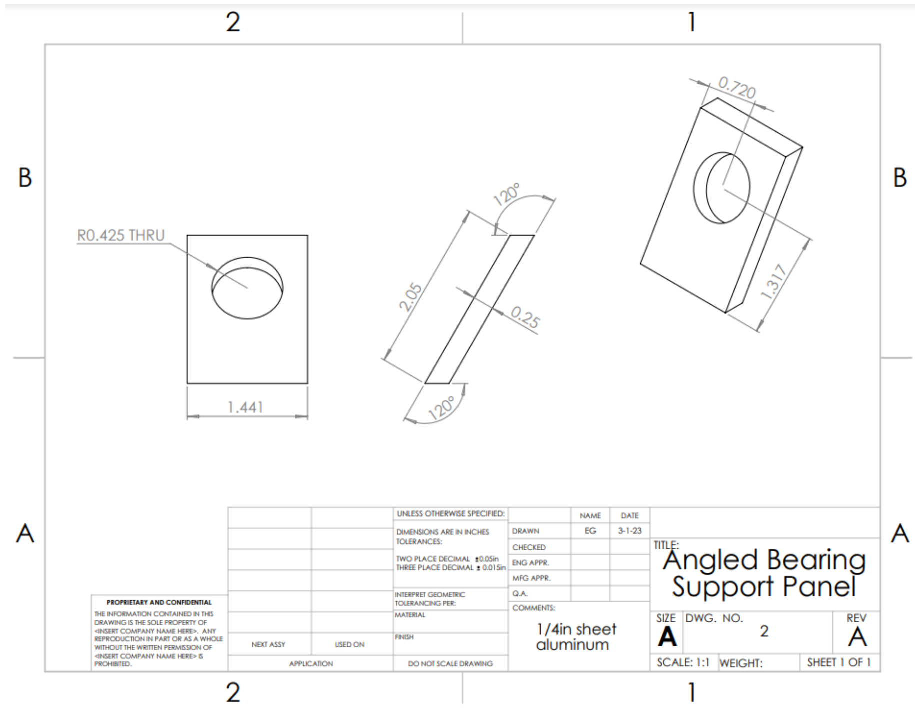
For $\Delta x\ =\ 0.090\ in\ =\ 0.002286\ m$

$$Q\ =\ (65\ W/m\ K)(0.004\ m^2)(\frac{35.3\ K}{0.002286})\ =\ 4014.873\ W$$

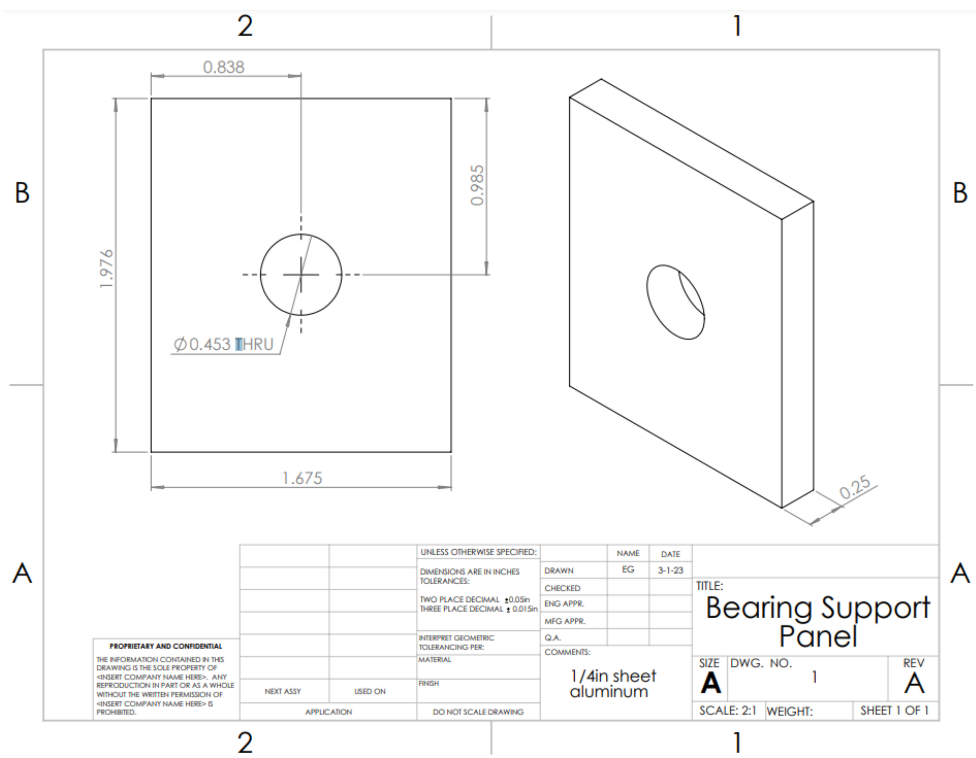
Appendix D: Technical Design Drawings of Orbital Arm Components



Reference Sketch of Main Plate CAD Model Used for Manufacturing the Part



Reference Sketches for Angled Bearing Support Used for Manufacturing the Angled Bearing Plate



Reference Sketches to Manufacture the Vertical Bearing Support Plates

Appendix E: Orbital Arm Part Modifications

Orbital Arm Part Modifications		
PART	**STOCK MATERIAL DESCRIPTION / INITIAL CONDITION**	**MODIFICATIONS**
Auger	Purchased from Amazon - 12” overall length with 3” screw diameter	● Welded a ⅜” hex shaft with 1.5” length to the end of the auger to replace the shaft that was too small
Hollow Drive Shaft	Purchased from mcMaster-Carr - 3ft long, Low-Carbon Steel Round Tube with ½” OD and 0.035” wall thickness	● Cut down to a length of approximately 135 mm ● ID opened on either end to 11 mm
Large and Small Spur Gears	Purchased from mcMaster-Carr	● Set screws added to both gears
Plate	Sheet of scrap metal - had a few existing holes already drilled but mostly intact	● Holes drilled for ½” mounted bearing and bearing bolts ● 0.13 (#6 screw) sized holes drilled to attach the lower bracket to the plate ● 4x 0.013 sized holes drilled
½” bearing housing w/ 2-bolt flange	Purchased from mcMaster-Carr - ½” inner diameter	● Set screws added to side face
8mm horizontal and vertical solid shafts	Purchased from mcMaster-Carr - 8mm OD - 400mm long stock material	● 8mm OD stock shaft was cut into two different shafts with the vertical shaft cut to a a length of 195 mm and the horizontal shaft being cut to a length of 135 mm
60 degree bevel gears and 90 degree bevel gears	Purchased from mcMaster-Carr - 8mm ID 60 deg - 20 teeth 90 deg - 20 teeth	● Set screws added to all 4 gears ● The center hole of just one of the 60 degree bevel gears was widened to fit on the ⅜” hexagonal auger shaft attachment
Vertical Bearing Supports Plates	Aluminum stock from Washburn Shops	● Plates cut down to correct dimensions ● Holes drilled in centers to allow press fitting of 12.00 mm OD horizontal shaft bushings
Angled Bearing Support Plate	Aluminum stock from Washburn Shops	● Plate cut down to correct dimensions ● Holes drilled in center to allow press fitting of 0.875” OD hexagonal shaft bearing

Appendix F: Orbital Arm 3D Printed Parts Materials and Printers Used

Part	Material	Printer Used
Housing - u shape	ABS	Dimension SST 1200es - WPI Rapid Prototyping Lab
Housing - lid	ABS	Dimension SST 1200es - WPI Rapid Prototyping Lab
Housing - short end wall	ABS	Dimension SST 1200es - WPI Rapid Prototyping Lab
Housing - long end wall	ABS	Ultimaker 3 extended - WPI Innovation Studio
Flange connection	ABS	Ultimaker 3 extended - WPI Innovation Studio
Bracket	PLA	Taz 6 - WPI Innovation Studio

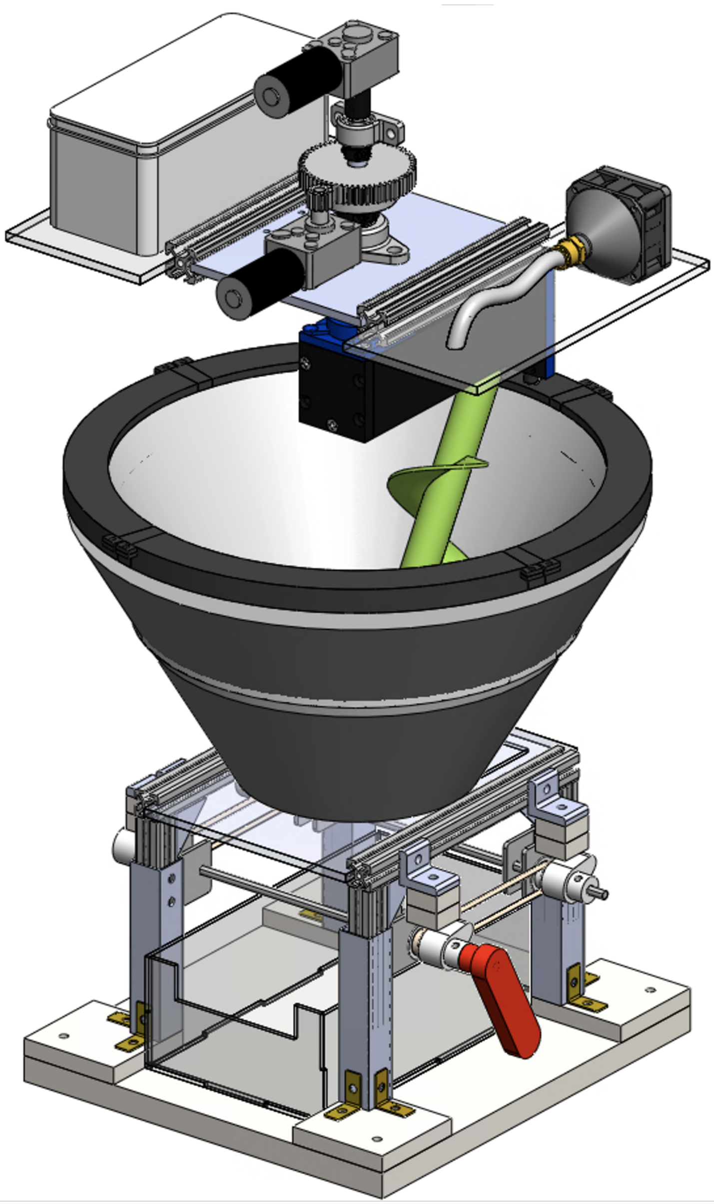
Appendix G: Orbital Arm Sub Assembly Parts List

Mixing Arm Subassemblies	
Sub-assembly #1 - Plate Assembly	**Parts Included**
	Large Spur Gear (60 teeth)
	Small Spur gear (12 teeth)
	27 RPM Motor
	#6-32 screws(x4)
	½” shaft Collars (x2)
	½” mounted bearing
	½” mounted bearing nuts and bolts
	3D printed bracket
	Bracket screws(x4)
	Lower ½” bearing
	8mm shaft alignment bearings (x2)
	3D printed flange
	½ bearing housing w/ 2 bolt flange
	#8-32 screws (x2)
	#8-32 heat set inserts (x2)
	Hollow shaft
Sub-Assembly #2 - Auger Assembly	**Parts Included**
	Auger
	1x 60 degree bevel
	Nylon spacer
Sub-Assembly #3 - Arm Housing Assembly	**Parts Included**
	3D printed Main Arm Housing

	Angled Bearing Support
	Hexagonal Shaft Bearing
	Angled bearing Fasteners (x4)
	3D printed Housing Cover Panel
	3D printed Short End Panel
	10-32 ½” machine screws
	10-32 heat set inserts
Sub-Assembly #4 - long end housing Panel	**Parts included**
	Long housing end panel
	10-32 heat set inserts
	Pololu Roller bearings(x2)
	Pololu Roller bearing Fasteners (#2-7/16) x4
	#2 Heat Set Inserts (x4)
Sub-Assembly #5 - Horizontal Shaft Assembly	**Parts Included**
	8 mm horizontal shaft
	1x 90 degree bevel gear
	1x 60 degree bevel gear
	2x 8mm shaft collar
	Vertical Bearing Supports (x2)
	Horizontal Shaft Bearings
Sub-Assembly #6 - Vertical Shaft Assembly	**Parts Included**
	8 mm vertical shaft
	1x 90 degree bevel gear
	1x 8 mm shaft collar
	8 mm motor shaft coupler

	130 rpm motor
Sub-Assembly #7 - Roller Track Assembly	**Parts Included**
	3D printed roller track (x4 pieces)
	#8-32 heat set inserts (x8)
	#8-32 screws (x8)
	1” L-Brackets (x8)
	#2 screws and nuts (x4)

Appendix H: Final CAD Model of Full Assembly



Appendix I: Arduino Code

```
int motor = 6;                          // Initialize pwm pin 6
int motorspeed = 0;                     // Initialize variable "motorspeed"


void setup() {                          // Setup loop - runs once

pinMode (motor, OUTPUT);                // Sets the motor pinmode as an output
Serial.begin (9600);                    // Initiate connection with serial monitor

}

void loop() {                           // Void loop - runs repeatedly

  for (int i = 50; i<230; i+=5)         // Set initial motor speed to 50, then increase
                                        //    in increments of 5 until it reaches 230
  {
    motorspeed = i;
    analogWrite (motor, motorspeed);
    Serial.println(motorspeed);         // Print current motor speed every second
    delay(1000);
  }
}
```

Arduino code for the orbital arm and auger rotation

```

void setup() {
  Serial.begin(9600);
  ads1115.setGain(GAIN_TWOTHIRDS);                        // Set gain to 2/3x
  ads1115.begin(0x48);

  StartTime = millis();                                   // Start a timer


  Serial.begin(9600);                                     // Initialize serial communication with computer:
                                                          // Initialize all the readings to 0:
}

void loop() {
 rawADCvalue = ads1115.readADC_Differential_0_1();        // Differential voltage measurement between A0 and A1 on the ADC
                                                          // In this case, input is  the voltage over the thermistor
 mV_voltage_across_therm = rawADCvalue * bit_res;         // Convert rawADC number to voltage in [mV]
 V_voltage_across_therm = mV_voltage_across_therm / 1e3;  // Express the voltage in microVolts

 V_voltage_over_ref_resistor = 5 - V_voltage_across_therm;     // Calculating voltage over reference resistor in Volts
 current = V_voltage_over_ref_resistor / ref_resistance;       // Calculating current over reference resistor in Amps
 therm_resistance = V_voltage_across_therm / current;          // Calculate resistance of thermistor in Ohms

 double therm_temp = (1/298.3) + (1/3950.0)*(log(therm_resistance/ref_resistance));
 therm_temp = 1/therm_temp - 273.15;                      // Calculating temperature read by the thermistor




  Serial.print("Volts Measured = ");                      // Checking that the volts measured across the thermistor are reasonable
  Serial.print(V_voltage_across_therm,2);

  Serial.print(",  Therm Resistance = ");                 // Checking that the resistance measured across the thermistor is reasonable
  Serial.print(therm_resistance,2);

  Serial.print("Temperature (deg C) = ");                 // Printing the calculated temperature read by the thermistor
  Serial.println(therm_temp,2);
  delay(500);

}
```

Arduino code for DHT11 temperature and humidity sensor, as seen in the ELEGOO UNO R3 Super Starter Kit tutorial book

Appendix J: Poster from Undergraduate Research Project Showcase