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April 8th, 2024

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Dear Professor,

This report entitled MTE 482 Capstone Final Design Report was written by group 17 of MTE 482 Winter 2024 class. This report is submitted to detail the project background along with the final design and implementation.

The goal of the project is to gain experience with the engineering design process by applying the process to identifying a problem, determining the specifications, and creating a solution that satisfies the specifications. This report will cover the problem background, final design details, testing and performance, and project management. It covers the process taken by the group on designing, implementing, and testing the final design as well as justification for the design choices.

This report was written entirely by the members of Group 17 of MTE 482. It has not received any previous academic credit at this or any other institution. Some information from this report references content written by the members of Group 17 for MTE 481. We would like to acknowledge the help of clinic engineer Paul Groh for his guidance in powering the system. Additionally, we would like to thank Professor Xianguo Li from the MME Department for his guidance during the initial design process last term during MTE 481.

Best,

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4B Mechatronics Engineering

UNIVERSITY OF Waterloo

Department of Mechanical and Mechatronics Engineering

MTE482 Capstone Final Report: Apple Crisp

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Executive Summary

The purpose of this report is to outline the comprehensive scope of the capstone project, covering final design solutions that address the identified problem, as well as the manufacturing and testing processes for the system. It details the step-by-step creation of a system from scratch and evaluates its performance for the intended purpose.

The design specifically targets the critical need to divert organic waste from landfills to mitigate climate change and reduce methane emissions, in line with the United Nations' 13th Sustainable Development Goal [1]. Particularly in regions like Waterloo and Toronto, organic waste diversion rates in multi-residential buildings are significantly lower compared to single-unit dwellings. Apple Crisp's final design addresses this issue by incorporating criteria and constraints identified through a needs analysis.

The needs analysis leads to the formulation of clear goals, specifying the design's objectives and constraints for problem resolution. These objectives include achieving a 50% volume reduction for food scraps, processing food waste within one week, ensuring the system can stop all mechanical motions within three seconds, and designing the device within a budget of $600. Safety measures are integral to the design, therefore, the system must incorporate emergency states, user input controls, and temperature sensors to ensure optimal operating conditions. The system must also maintain a temperature below 40 degrees Celsius.

Apple Crisp integrates two main mechanisms: heating and mixing. It raises and maintains the internal temperature at an optimal level for dehydration using positive temperature coefficient (PTC) chips, while simultaneously mixing inserted food waste at fixed intervals to evenly distribute heat. The mechanical and electronic construction of Apple Crisp occurred concurrently, with the mechanical team designing the outer casing, commissioning laser cuts to RPC, and assembling 3D printed components with machined elements. Meanwhile, the hardware/software team tested the electronics individually, in subsystems, and as a whole to integrate them with the mechanical components.

Testing results confirm that Apple Crisp successfully achieved the system's goals and constraints. During a 6.5-hour test cycle, a 75% volume reduction was achieved, demonstrating a processing time of within one day. Safety measures were implemented by locking the system with a servo during operation, providing start and stop buttons for user interaction (with the stop button serving as an emergency stop), and ensuring internal insulation to dissipate heat and maintain user contact points below 30°C. Additionally, the project remained within the $600 budget and met all financial objectives. The final build of Apple Crisp weighed 6.3kg, with dimensions of 0.356m in height, 0.305m in width, and 0.305m in depth, making it an accessible system that adheres to the detailed design objectives and constraints outlined in the report.

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1.0 Introduction

This paper identifies the technicalities of the design process along with the appropriate resources, measures and engineering judgement exercised to achieve the final design solution. In the introductory section, the motivation for the design is restated, along with the project scope, objectives, and constraints.

1.1 Background

While the rate of appropriate organics waste disposal across Canadian households has been increasing since the introduction of green-bin curbside collection programs, there is still a substantial percentage that fail to divert organics waste from landfills. A recent statistic stated that high-rises in Toronto divert 40% less organic and recyclable waste than the city's single-unit dwellings [2]. This issue has also been observed in the Region of Waterloo where multi-residential buildings with less than six units are not included in the city's green-bin curbside collection initiatives.

A significant percentage of these populations reside in these multi-residential buildings without organics collection. Over 30% of Waterloo's population live in apartments and many of these buildings do not offer any organic waste collection, whether by city initiatives or private companies. Similarly, 44% of Toronto's occupied dwellings are made up of apartments – buildings with poor rates of organics waste diversion.

Diverting organics waste from landfills is crucial in combating the reduction of greenhouse gas emissions (GHG) as per Sustainable Development Goal (SDG) 13 outlined by the United Nations [1]. Landfills are unsuitable for proper decomposition of organic food matter as the waste is forced to decompose anaerobically in the absence of oxygen. Though anaerobic decomposition is not inherently harmful, the uncontrolled environment leads to increased GHG emissions in carbon dioxide, nitrous oxide, and methane in comparison to traditional decomposition methods.

A decomposed why-why diagram seen below in Figure 1 summarizes the relevance of the issue.

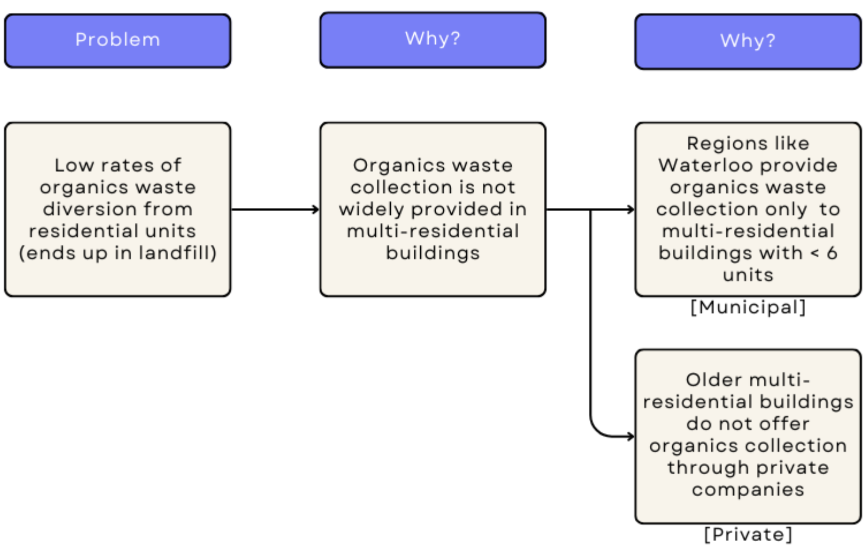


Figure 1: Why-why diagram

The general needs statement is formulated as follows:

Multi-residential buildings have low rates of organics waste diversion because they lack accessibility to collection initiatives. A method of diverting food waste in these residences is required.

1.1.1 Needs Assessment

Identified stakeholders consist of multi-residential building residents, building owners, governing powers on municipal and provincial levels, and organics waste collection facilities.

Residents

The solution targets multi-residential building residents as the primary user of the system. It should appeal to the residents as something that can be easily integrated into their disposal routines. Options would vary from being a large-scale building solution or a system that can individually collect and process organics.

Building Owners

A solution's scale of integration is important to consider in the design as the installation of a building-wide system is quite costly to implement. It would be unlikely for building owners to agree with. Meanwhile, a smaller and more inconspicuous solution that is adopted by individual units would require little to no effort from the owners.

Governing Powers

Ontario's Ministry of Environment, Conservation, and Parks (MECP) issued a statement in 2018 requesting buildings with six or more units in municipalities of at least 5000 residents to target a rate of 50% diversion in food and organic wastes by the year 2025, almost doubling the recorded rate of 27% in Toronto.

Organics Waste Collection Facilities

Since these multi-residential buildings lack organics collection, the designed solution attempts to process food waste into sterile and dry material. As such, the food waste can be stored for an extended period of time and appropriately disposed of at these facilities at a later point in time. This collection process could either be implemented by the building owner, or the city's collection initiatives. Alternatively, the processed food waste could also be dropped off at an organics collection facility at the convenience of the user.

1.2 Problem Statement

From the needs assessment and analysis of stakeholders, the design is specified to address the problem on the scale of individual units of multi-residential buildings. This is the conclusion made after considering the obstacles in designing a wider-scale integrated solution for an entire building. The problem statement is revised as such:

Design an indoor system to address the low rates of organic waste diversion in multi-residential buildings.

Next, the design features are outlined in the following subsections to address the design goals, specifications, and objectives to define what a successful solution should achieve.

1.2.1 Design Goals

There are three main goals in designing a system to address the problem statement outlined above:

- Goal 1: System processes scraps into a storable product
- Goal 2: Accessible – the system is user-friendly, easy to implement
- Goal 3: Safe and sanitary – the system is suitable for indoor use

To provide users with an alternative to organics collection, Goal 1 aims to process food waste into a storable product. This means targeting weight and volume reduction by removing moisture to remain shelf stable. Goal 2 ensures the system is an appealing solution that is easy to install, operate, and adopt for target users. Finally, Goal 3 considers the prevention of hazards by designing around possible pinch points, maintaining safe operating temperatures, and monitoring the air quality for any volatile organic compounds.

1.2.2 Design Specifications: Objectives and Constraints

A successful design will be evaluated on the following objectives and constraints. These design specifications are determined by consideration of the design goals in the previous section.

Objectives

- The system should achieve a minimum volume reduction of 50% for processed food scraps
- The system should process food scraps in less than 1 day from input to output
- The system should respond to user inputs (including e-stop) and be able to halt all processes within 3 seconds
- The budgeted amount spent on the fabrication and build of the system should be within a $650 budget, however each team member is willing to contribute equally for a total of $1000 if necessary. This $650 budget was revised from the initial $600 in January 2024.
- The emissions from the system should not exceed 500 parts per billion (ppb) Total Volatile Organic Compound (TVOC) levels in a 2m radius from the system.

TVOC levels are a measure of safe indoor air quality, and typical indoor measurements are approximately 350ppb but should not exceed 500ppb to be considered safe [3].

Constraints

- Moving mechanisms must be fully contained during the processing cycle to prevent pinch points
- The weight of the system must not exceed 20kg for ease of installation
- The system’s dimensions must not exceed 1 m in height, 0.5 m in width, and 0.5 m in depth for suitable household use
- The external temperature of the system must not exceed 60°C to ensure user safety
- The contact points of the system that require user interaction must not exceed 40°C
- The system’s conception and creation must be feasible within the seven-month timeframe of the capstone project timeline

The constraint for limiting external temperature of the system references the Standard Guide for Heated System Surface Conditions that Produce Contact Burn Injuries, ASTM C1055 [4]. It states that irreversible burn damage will occur when touching a surface at 140°F (60°C) any longer than five seconds. The system is to ensure external surfaces will not exceed this temperature.

NASA produced a standard for touch temperature limits taking into consideration the tolerance and onset of pain [5]. Their findings determined that 45°C to be the limit for classifying material temperatures as safe to touch. To ensure safe operation, 40°C is the designated maximum temperature for any expected contact points requiring user interaction.

2.0 Final Design

The final design of the system includes design details, modifications from previous design, as well as construction and manufacturing. Testing the system and details on its performance are also discussed.

2.1 Final Design Details

This section delves into the details of the mechanical, hardware, and software aspects of the Apple Crisp system. Mechanical components include the outer enclosure, lid, and body, each designed with specific functionalities. Hardware details encompass sensor selection and placement, along with the heating subsystem, while software aspects revolve around the programmed state machine for system operation, ensuring efficient functionality throughout the dehydration cycle.

2.1.1 Mechanical

Figure 2 illustrates an exploded view of the Apple Crisp body, showcasing the vertical arrangement of all components, as well as the complete assembly of the entire system.

Figure 2: Apple Crisp overall structure

The system comprises three primary components: the lid, body, and outer case. The outer enclosure is sized at 12 inches by 12 inches by 14 inches (0.305 meters by 0.305 meters by 0.356 meters). The lid and body of the system are joined together with hinges.

As detailed in the MTE 481 report, the lid features a design with inward curvature, strategically implemented for ventilation regulation. Within this design, the lid accounts for the addition of mounts to house a carbon filter for odor reduction and accommodating sensors. Additionally, a silicon ring is securely fastened using metal wire between the lid and the contact point of the inner pot. Furthermore, a dedicated slot is provided for the locking servo motor, ensuring secure locking and safety during system operation.

The system body's primary structural framework has two levels, separated by a wooden shelf. At the upper level, an inner pot is situated to house food scraps, equipped with a mixer blade driven by a DC motor. The blade is intended to stir the contents, thereby facilitating optimal heat distribution. Directly beneath the inner pot, two positive temperature coefficient chips (PTCs) are positioned for heat generation, atop a thermally insulating ceramic board. Encompassing these components is an outer pot, thermally insulated with melamine foam, and serves to mitigate heat transfer to the outer casing, where user contact occurs.

The vertical integration of these elements is secured with M6 bolts and nuts. The lower level accommodates mounts for various hardware components, such as the Arduino board, bus bars, relay, and power units.

2.1.2 Hardware

Three sensors are utilized to monitor the environment of the system: air quality, humidity, and temperature. These sensors were selected and justified in the final design report from MTE481. The air quality sensor, Adafruit SPG30, returns a reading in parts per billion for the Total Volatile Organic Compound (TVOC) in the surrounding air. This sensor is placed on the outside of the lid, near the hole in order to read the TVOC of the generated steam to ensure that the output is safe. The humidity sensor, Adafruit HTU21D-F, returns a reading for the relative humidity in the environment. Relative humidity measures water vapor based on the temperature of the air. It is expressed as the amount of water vapor in the air as a percentage of the total amount that could be held at its current temperature [6]. This sensor is placed on the inside of the lid to monitor the humidity during the dehydration process to estimate the state of the food scraps placed inside (i.e. the level of "dryness" of the food scraps). Finally, the temperature sensor, Adafruit MCP9808, returns a reading of the temperature of the environment in °C. From discussion with Professor Xianguo Li, the ideal internal temperature of the system should be approximately 60-70°C. This range maximizes the rate of water evaporation while avoiding "cooking" the food scraps if the temperature is too high.

The heating subsystem is also included in the hardware portion of the system. Positive temperature coefficient (PTC) chips are used to heat the system. These chips are connected to two bus bars (positive and negative terminal) which are connected to a 12V 4A power supply.

2.1.3 Software

The program written for the systems is based on the state machine seen in **Error! Reference source not found.**.

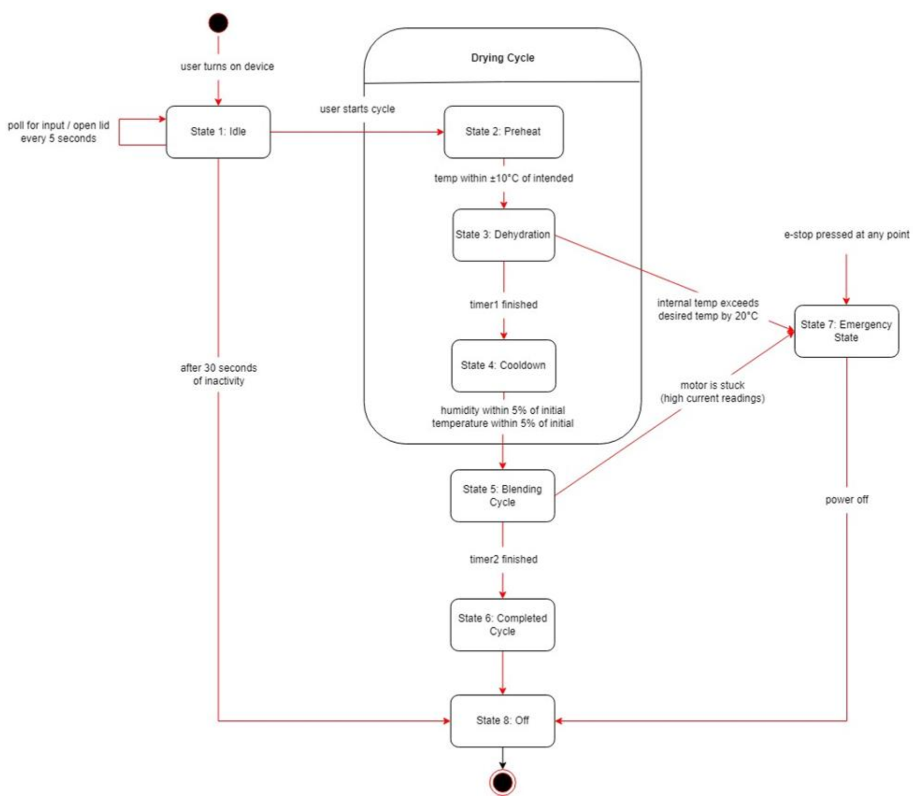


Figure 3: State machine diagram [7]

When the device is powered on by the user, it will first begin in the idle state, awaiting user input of food waste in the inner compartment. After the user has placed their food waste into the device, the start button will be pushed to indicate that the user is ready to begin the cycle. In the preheat state, the relay switches on, enabling the connection between the PTC chips to the power supply to begin heating the system. Once the temperature sensor reads an internal temperature of 45°C, the program exits the preheat state and moves onto the dehydration state. This is the longest state of the system lasting a total of 8 hours. Here, the mixing servo motor turns on for 10 seconds and rests for 20 seconds, making the mix cycle 30 seconds long. Simultaneously, elapsed time, air quality, humidity, and temperature readings from the sensors are printed onto the LCD screen so that the user can constantly monitor the environment. Finally, once 8 hours of dehydration have passed, the system then enters the cooling state. This state is finished once the internal temperature of the system is below 30°C, meaning it is safe for the user to reach into the system. After cooling, the cycle is complete. Refer to Appendix C for the written software.

The system includes several safety measures built into the program. At the start of the preheat state, a locking servo motor on the lid activates. This prevents the user from being able to reach their hand into hot and moving parts. It is only until the cooling state is complete (internal temperature <30°C) when the locking servo unlocks the system. Another safety feature is the emergency state, which can be entered in two different ways. The first method is when the temperature sensor reads an internal temperature of >90°C. The second method of entering the emergency state is from user input via buttons. In the emergency state, the mixing motor turns off, the relay connecting the PTCs to the power supply turns off, and a message is printed on the LCD to inform the user.

2.2 Modifications from Original Design

Several changes of the initial design are made for the final design. These changes are based on deeper considerations of the system's functionality and system complexity.

2.2.1 Overall Build

The decision to transition from the original plan of constructing the outer case with thermoplastic to plywood was guided by various considerations. While thermoplastic materials offer design flexibility, they often lack the requisite strength and durability compared to plywood. Given the system's functional demands, such as accommodating pots and enduring frequent handling, plywood was a more viable choice due to its superior structural integrity and resistance to wear and tear. Additionally, the ease of fabrication afforded by laser cutting plywood allows for precise construction and facilitates rapid prototyping, potentially reducing production time and costs compared to molding thermoplastic or utilizing pre-made bins available in the market. Incorporating the idea of laser cutting wood adds modularity to the design, enabling easier adjustments during testing if needed. The design simplicity of the outer case was achieved using AutoCAD to create basic boxes with finger joints, as shown in Figure 4. Following laser cutting, the plywood pieces were joined using adhesive. In order to enclose all components securely while allowing for convenient access during testing procedures, two side doors were precision-cut into one side of the system. These doors are affixed to the system using hinges, enabling easy opening and closure as necessary.

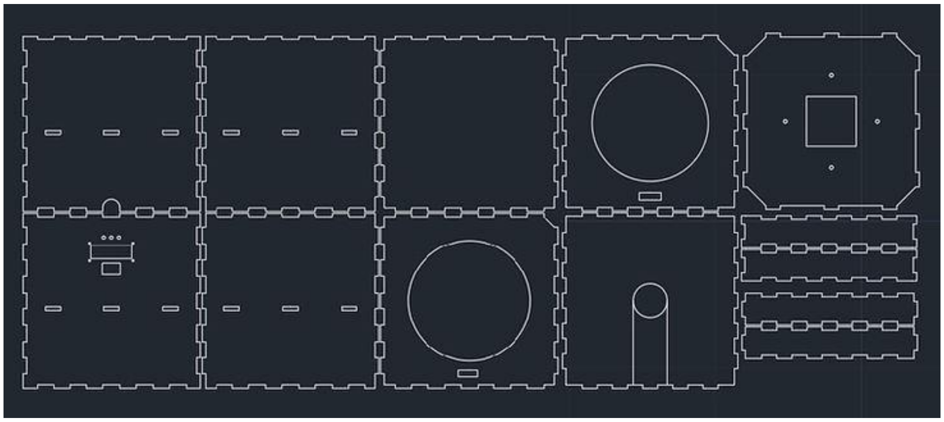


Figure 4: AutoCAD drawing for the outer case

2.2.2 Blending Method

The original design proposed in MTE481 included a mechanism that breaks down dehydrated food waste to achieve a higher reduction in volume. A blender was chosen to cut the food waste inserted, however, there were no available options for a 5V DC motor to have a high enough torque while having a fast rotational speed as a blender. Thus, the final design of Apple Crisp shifted from blending to mixing the food waste with a high torque, which allows a better distribution of heat and effectively accelerates the dehydration process. A 26kg servo motor was selected to allow a high torque for successful mixing of food.

2.2.3 Heating Method

Initially, nichrome wire was chosen as the heating method of the device. This type of material has high electrical resistivity, making it useful as a heating element. Appliances such as toasters and hair dryers utilize nichrome wire to generate heat [7]. However, nichrome wire on its own is not electrically insulated meaning an insulation method would need to be designed. In the past, ceramic molds have been made to both hold the wire in place and to electrically insulate it to prevent shorting any circuity. This would add complexity to the system and would require more time. An alternative heating method would be to use PTC chips. The electrical resistance increases as the temperature rises, enabling the device to self-regulate its heat output [8]. As these chips are ceramic, they are already electrically insulated. Not only do these chips provide a simpler method of heating, but it is also safer and more efficient due to its self-regulating behavior. As a result, PTC chips are chosen as the new heating method.

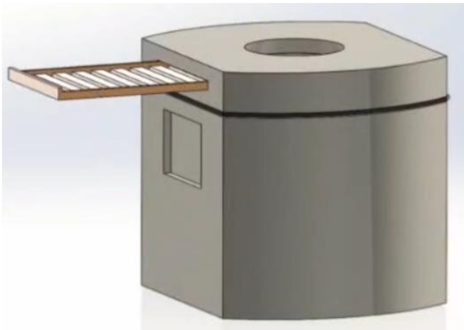
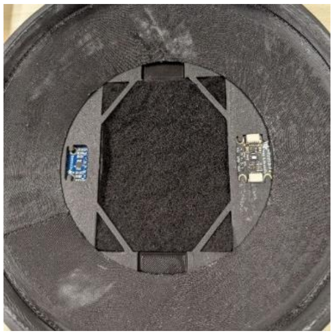
2.2.4 Power Supply

In the original design, the RD-125A power supply was chosen due to its small form factor, dual output (separating the microcontroller power and heating power for safety), and ability to meet the system's power requirement of 95W. Due to the selected heating method of using PTC chips, a problem of initial current draw spiking would need to be addressed. This adds complexity to the system's design and the possibility of making the system unsafe if not done correctly. After consulting with Paul Groh on the power supplies available in MESS (Keysight U8002A), it was decided that these power supplies would be a better choice. Unlike the RD-125A, the U8002A has a built in current and voltage limits for better protection. With these power supplies, the initial spiking current would be limited and would not cause damage to the system. The disadvantage of the U8002A is its large form factor making it unable to fit within the system. However, the current protection is extremely beneficial and thus, the U8002A is chosen to be the new power supply of the system.

2.2.5 Lid Design

Table 1 below shows the original and new design for the carbon filter tray integrated in the lid of the system. The original design of the lid included a sliding grate as a tray to hold the carbon filter. However, a sliding tray was simulated in SolidWorks to have more heat loss through its openings. To minimize heat loss and increase the effectiveness of the heating system, the new design of the lid includes a mount that is slid into the slot of the funnel shaped inner lid. The mount holds the temperature and humidity sensor as well as secures the carbon filter. The original material was planned to be thermoplastic, however, to allow a more intricate design of the mount to be printed, ABS-like resin filament was used to 3D print the new design.

Table 1: Carbon filter tray design

Original Lid – Sliding Grate	New Lid – Prototype Mount	New Lid – Final Mount
		

2.3 Construction and Manufacturing

This section outlines the various manufacturing processes involved in fabricating and machining components for the system. It covers laser cutting for the outer casing, 3D printing of specialized components, drilling operations, design enhancements for mixer blades, and insulation techniques crucial for system functionality and safety.

2.3.1 Laser Cut Outer Case

As elaborated in Section 2.2.1, the complete outer casing of the system is constructed from plywood. Leveraging the facilities of the rapid prototyping center, the plywood undergoes laser cutting to attain precise dimensions and configurations. The assembled outer case is as shown below in Figure 5.

Figure 5: Apple Crisp assembled outer case

2.3.2 3D Printed Components

Many components that required specific design to fit Apple Crisp were 3D printed using PLA filament. Components that were 3D printed include: side panel door hook and slot, hinges, hinge restrictors, Arduino mount, 26kg servo motor mount, motor to blade socket shaft, SG90 micro servo mount, bus bar mounts, control relay mount, and air quality sensor cover. Figures of all the 3D printed components are included in Appendix B.

The sensor mount that secures the temperature, humidity sensors, and carbon filter is located inside the inner pot, which is exposed to a higher temperature and steam. After prototyping the mount in PLA filament and checking the fit inside the slot of the inner funnel part of the lid, ABS-like resin filament was used to 3D print the final design of the mount. Unlike standard resin material, which can be toxic when exposed to moisture, ABS-like resin is able to withstand moisture if it is not exposed to alcohol. The PLA prototype and final 3D printed mount can be found in Table 1 presented in section 2.2.5. Figure 6 shows how the mount is assembled in the inner funnel of the lid. The red part that holds the sensors slide in the slot first, then the blue side mounts are slid into the slot to secure the mount.

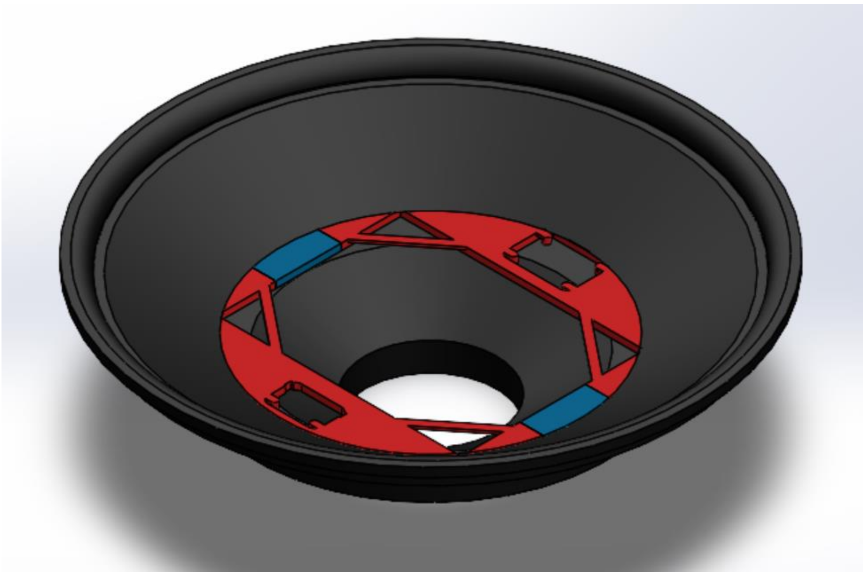


Figure 6: Carbon filter and sensor mount

2.3.3 Machining Holes

As described in section 2.1.1, M6 nuts and bolts serve to secure all components within the system body. Consequently, holes are drilled into both the inner and outer pots utilizing a drill press. For the creation of hinge holes on the wooden outer cases, hand drills are used. These drilling operations are conducted within the Engineering Student Machine Shop. Figure 7 illustrates the perforations made in the outer pot using a drill press.

Figure 7: The drilled holes in the outer pot

2.3.4 Mixer Blade Extension

The original blade attached to the motor for mixing is short in length and is angled upwards. This blade was not effective in mixing the food especially when there was not much food content. To address this, a second mixing bar was designed to reach the food further away from the center and closer to the bottom of the pot. Figure 8 below shows the 3D model of the mixing bar design. This design was sent to EMS as a commission, to fabricate the stainless-steel sheet as desired. The detailed mechanical drawing of the mixing bar can be found in Appendix A.

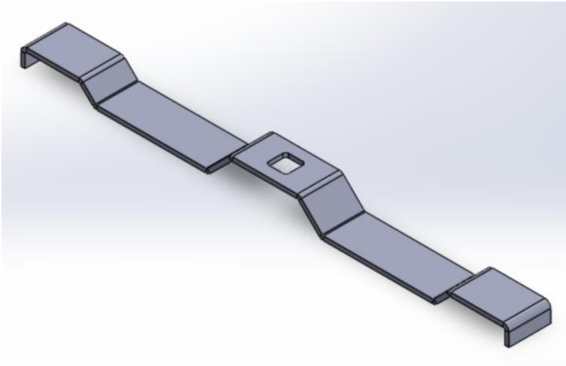


Figure 8: Mixing bar

2.3.5 Insulation

Both thermal insulation and electrical insulation are crucial in order for the system to function. The PTC chips chosen can reach a maximum surface temperature of 190°C (determined from testing), making the system very hot from the inside. To prevent the components from melting or burning from the heat, several insulating materials are used. Under the PTC chips, a ceramic board is placed to thermally insulate the bottom. The middle pot that gets heated is surrounded by a layer of melamine foam to protect its surroundings. Adding these insulating materials keeps the outer surface temperate of the device room temperature, making it safe for the user to operate.

Along with thermal insulation, the system must also be electrically insulated. Perfboards are used to solder the components and wiring of the system. To prevent any chance of shorting the connections on the boards, hot glue is placed on each board to electrically insulate them. Additionally, the sensors placed on the lid are insulated with hot glue to prevent condensation produced during the heating process to short the connections.

2.4 Commissioning

This section of the report covers the testing of subsystems before the final system is assembled. This includes the heating system as well as sensor integration. This is an important step to ensure that the subsystems are functioning before building the whole system and helps with debugging any problems prior to full integration.

2.4.1 Heating Subsystem

To ensure that the heat generated by the selected heating method (PTC chips) is appropriate for the goal of the system, it is first tested on its own. The PTC chips purchased are rated for 12V and are reported to reach 220°C [9]. To evenly distribute the heat along the bottom of the inner pot, at least two chips would need to be used. The chips are connected in parallel using bus bars to the power supply set to 12V maximum voltage and 4A maximum current as seen below in Figure 9.

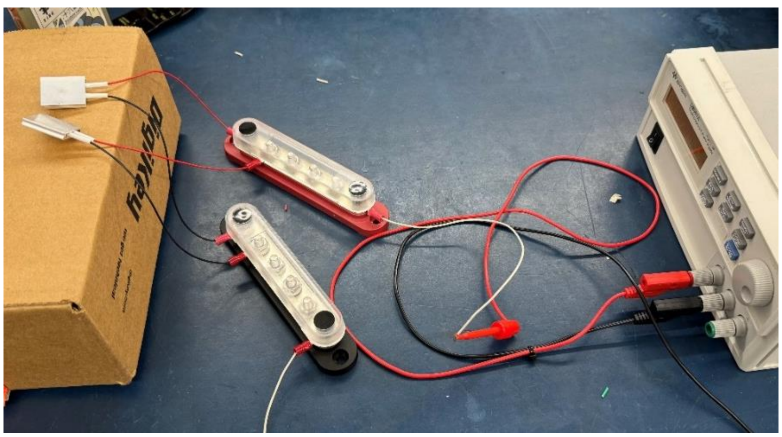


Figure 9: Heating subsystem testing with power supply

The results of testing two chips in parallel are summarized below in Table 2.

Table 2: PTC testing results

Time elapsed (minutes)	Voltage (V)	Current (A)	Temperature (°C)	Notes
1	5	2.75	70	-
2	6	3.5	80	Reached current limit of 4A
3	7.15	4	145	Current rapidly dropping
8	12	2	160	Current change slows down, still decreasing
9	12	1.85	160	-
11	12	1.69	190	PTCs reach stability, current only fluctuates a little bit

The PTC chips can heat up quickly, reaching 70°C in one minute. When they are first heated, the current spikes up to the maximum limit of 4A but eventually drops to 1.69A where it stabilizes. This process was repeated for three PTC chips in parallel but with the current limit set to 5A instead (the maximum current the power supply can output). However, with this configuration, the current spikes up to 5A and does not decrease after 30 minutes. Since the chips do not stabilize when three are put in parallel, only two chips will be used for the heating system.

The two chip heating system is tested once more for a longer cycle and with an Instant Pot lid to act as a placeholder for the designed lid of the system. Water is placed inside the inner pot and the PTC chips are placed directly under the pot. After approximately 2 hours, visible steam and condensation is produced after removing the lid, as seen below in Figure 10.

Figure 10: Condensation produced from the heating system

Based on the results from testing, the designed heating system can sufficiently heat up the contents within the inner pot and can now be tested with real food scraps once the system is fully integrated.

2.4.2 Sensor Integration

The next subsystem that is tested are the sensors. The system utilizes three sensors to monitor the environment: air quality, humidity, and temperature. An LCD screen is used to display information to the user and buttons are used for the user to interact with the system (start/stop). The sensors and LCD display communicate with the microcontroller using the I2C communication protocol.

The code for testing the sensor subsystem follows the same basic structure of the code for the full system. First, the program waits for the start button to be pressed. Once the start button press is registered, each sensor reads the environment and prints the readings onto the LCD display. If at any point the stop button is pressed, all functions stop running and an estop message is printed to the LCD. Figure 11 shows the setup for testing of the sensor subsystem.

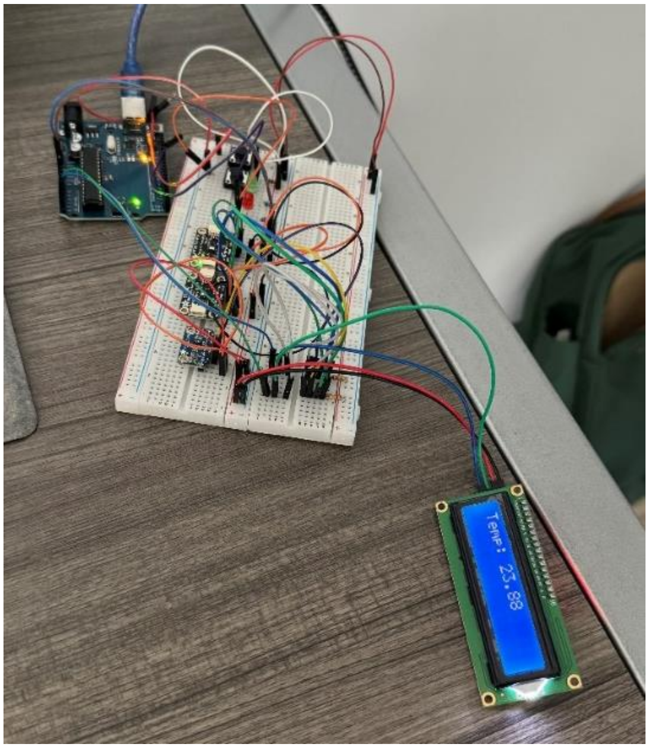


Figure 11: Sensor subsystem testing

Once the heating and sensor subsystems are tested and functioning properly, the full system can now be implemented.

2.5 Testing and Performance

Apple Crisp is incomplete without proper testing of the design specifications it sought to meet. This section explains some of the testing executed and summarizes the overall performance of the system. The design objectives and constraints outlined for the design will be reviewed, while the power consumption of Apple Crisp in comparison to competitors will also be evaluated.

2.5.1 Design Specification Testing

Testing of the system primarily relied on the success of the first objective in the design's formulation, which was to achieve a minimum volume reduction of 50% for processed food scraps. A brief description is also provided of whether each objective and constraint were met.

Objective 1: Minimum volume reduction of 50%

A test to check volume reduction aimed to run the system's drying cycle for a minimum of 6 hours at above 45°C. During the cycle, weigh-in and volume checks were made every 1 to 1.5 hours to monitor changes. A kitchen scale recorded weights to the nearest gram, while volume was measured with measuring cups. Significant heat loss is expected to occur when the lid is opened for these checks. To account for this, a 10-to-15-minute buffer is included for the system to reach temperature before continuing the timer. If a weigh-in takes 10 minutes, and the system needs 10 minutes to get back to temperature, these 20 minutes are not included in the total heating time.

Data from testing a 258g batch of carrot, potato, and apple peels, spinach, celery, and lettuce resulted in the weight reduction summarized in Figure 12.

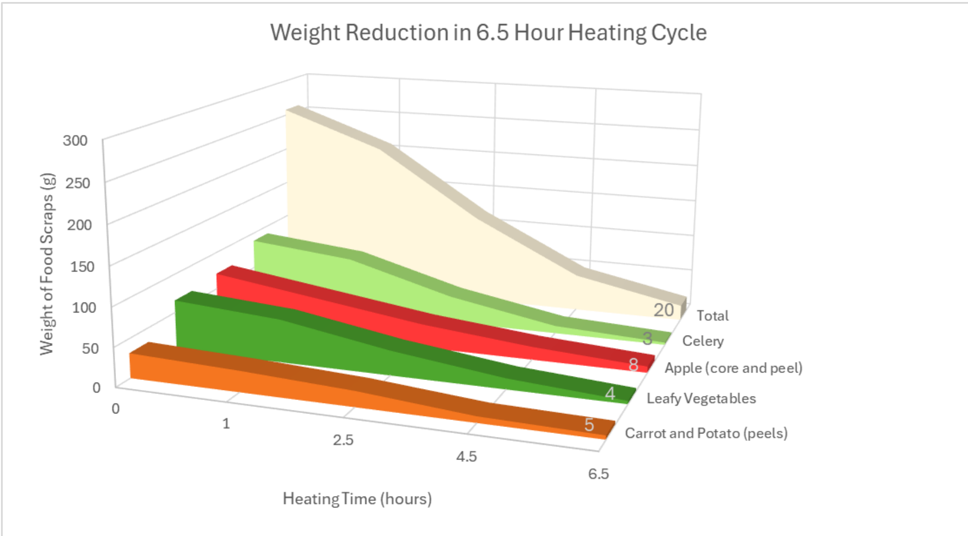


Figure 12: Graph of weight reduction in 258g of food scraps with time

By the end of the cycle the original volume of 3 cups were reduced to ¾ of a cup. The exact numbers are recorded in Table 3 below.

Table 3: Recorded changes in weight and volume during heating cycle

Time (hours)	Celery (g)	Apple (core + peel) (g)	Carrot and Potato (peels) (g)	Leafy Vegetables (g)	Total Weight (g)	Volume (cups)
0	89	71	32	66	258	3
1.5	75	51	27	56	209	2.75
3	36	31	20	32	119	1.5
4.5	10	17	8	14	49	1.25
6.5	3	8	5	4	20	0.75
Percent of Initial	3.4%	11.3%	15.6%	6.1%	7.8%	25.0%
Total Reduction	96.6%	88.7%	84.4%	93.9%	92.2%	75.0%

From the testing results, Apple Crisp has clearly succeeded in achieving minimum volume reduction of 50%. In the 6.5 hours of the heating cycle, the batch of food scraps were reduced by 75% in total volume. This can also be visualized in the progress pictures taken throughout the test as seen in Figure 13.

Figure 13: Changes in food scraps during heating cycle

Objective 2: Less than 1-Day processing time

As demonstrated in the 6.5-hour heating cycle test to prove volume reduction, Apple Crisp successfully meets the objective of processing food scraps within a day. Although the volume placed in the system will ultimately determine the processing time based on how much moisture needs to be evaporated, the test is a proof of concept that there is significant progress in achieving weight and volume reduction efficiently.

Objective 3: Response to user inputs (E-Stop) within 3 seconds

Providing users with a way to interact with the system was implemented via start and stop buttons. Each button's logic considers system safety. If at any point during the cycle the stop button is pressed, all motions and processes would halt. This occurs immediately after the button press – the system's heating mechanisms and motor functions cease within the same second this e-stop is activated.

Objective 4: Budget within $650

The initial budget was set at $600 but as of January 2024, the team revised the budget considering the purchases made and changes to the original design. The budget section will later detail the breakdown of spending. In summary, the build and project costs in the completion of Apple Crisp and symposium preparation did not exceed $600 and met this objective.

Objective 5: Air quality testing under 500ppb in 2m radius

At regular measurements when the system is not in use, the air quality sensor reads around 150 to 300ppb, and maintains this standard throughout the first hour of heating, even during the preheating stage. However, air quality readings exceeded the 500ppb threshold after about 1.5 hours into the heating cycle. By observation, these high levels of TVOC ranging from 600 to 1050ppb occurred only when steam was steadily exiting the lid's vent. Although the system's TVOC levels did not meet the objective, the sensor measures TVOC directly at the vent and fails to consider the potential of dispersion for which if it remains under the safe 500ppb standard, it should not be a cause for concern. Additionally, Dyson has stated that different foods and the method with which they are cooked can produce different levels of these VOCs. Generally, electric heating such as PTC chips would produce less VOCs than gas cooktops [10]. A recommendation in the conclusion section will revisit this design objective and describe ways that this issue can be addressed.

Constraint 1: Contained moving mechanisms

As described in the final design, all motors and hazardous components are located inside of the system. There should be no need for the user to interact with any of these parts. A safety feature on the lid locks the system during the processing cycle to prevent risks.

Constraint 2: System is 20kg or lighter

The final build of Apple Crisp weighed in at 6.3kg, meeting this constraint. It can be moved around a residential unit with ease.

Constraint 3: System dimensions (max. 1 m height, 0.5 m width, 0.5 m depth)

The final dimensions of the system were: 0.356m height, 0.305m width, 0.305m depth, and could be easily stored in a cabinet such as under a kitchen sink.

Constraint 4/5: System external temperatures max. 60°C / Contact points max. 40°C

Courtesy of the insulation internal to the system, the heat is distributed so that external surfaces are safe to touch. From thermometer measurements, the readings for any surface temperature and contact points are consistently under 30°C, meeting the constraint established in design specifications. The only risk is at the top of the vent where hot steam is a risk for burns, like the venting hole of a rice cooker or instant pot.

Constraint 6: System conception within MTE 481 / 482 timeframe

The conception, construction, and building of the Apple Crisp system was completed within the expected timeframe and produced a desirable outcome meeting the design objective and constraints. The symposium and the results presented are evidence of this success.

2.5.2 Energy Consumption

Through multiple tests of the system, the energy consumption of Apple Crisp was calculated to ensure that the system is energy efficient and aligns with its vision for sustainability. The microcontroller, sensors, and servo motor for the mixing mechanism are powered with 5V, while the PTC chips used for heating the system requires a 12V input. 12V power supply has the maximum current draw limited to 5A, therefore these two values are selected for calculations. The system uses one 12V power supply for the heating mechanism, while the Arduino is powered and controlled through a computer. To calculate the power draw from the components powered through the computer, a 5V power supply will be assumed to replace the computer. According to online resources, the Arduino, sensors, and servos are unlikely to reach 200mA, therefore, 200 mA is assumed as the maximum current draw for the 5V power supply [11].

$$P = I_1V_1 + I_2V_2 = (5\ A)(12\ V) + (200\ mA)(5\ V) = 61\ W$$

One example of Apple Crisp's competitor is Lomi, which is a home composter that turns organic waste into dry compost. According to Lomi's product manual, its power draw is rated to be 600W [12]. Comparing to Apple Crisp's power draw of 61W, this comes up to 9.83 times more power consumption.

The energy consumption rates vary depending on the time of electricity usage. Table 4 below summarizes the electricity cost from running Apple Crisp for 1 cycle (8 hours) using different electricity rates for the Region of Waterloo [13]. The cost of running Apple Crisp one cycle ranges from 1.37 to 8.88 cents, thus, it can be concluded that the system is affordable to run.

Table 4: Electricity cost calculation [13]

Period	Time	Rates (¢/kWh)	Energy Cost, 1 cycle - 8 hours (¢)
Overnight	11 p.m. – 7 a.m.	2.8	1.37
Off-Peak	7 p.m. – 7 a.m.	8.7	4.25
Mid-Peak	11 a.m. – 5 p.m.	12.2	5.95
On-Peak	7 a.m. – 11 a.m., 5 p.m. – 7 p.m.	18.2	8.88

3.0 Schedule and Budget

The schedule of milestones achieved, and deliverables are compiled in a Gantt Chart and table of deadlines. Allocated budgets and the incurred costs are also compared to evaluate the overall success of the project.

3.1 Schedule – Gantt Chart, Deliverables

Below, in Figure 14, is a visual timeline in the form of a Gantt Chart, depicting the progress of tasks. In relation to the original schedule prepared at the end of November, all tasks were completed on schedule. There are only slight tweaks from the original schedule, resulting from resource availability and official MTE 482 deadlines. Budgeting costs were revised on various occasions to review incurred costs and to re-allocate funds to different parts of the build. The same was done with component selection and parts ordering to accommodate for deviations from the initial design.

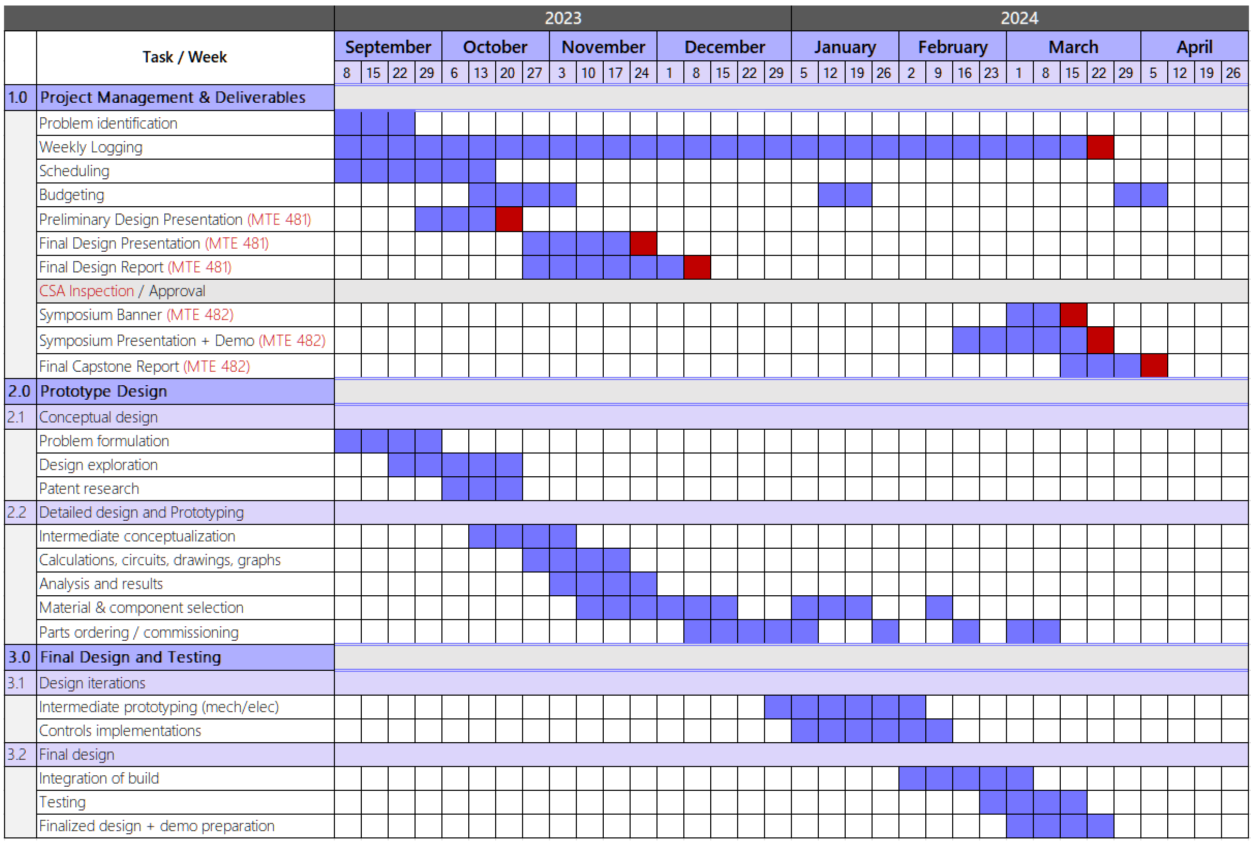


Figure 14: Gantt chart schedule

Internal goals and official course deadlines are listed in Table 5. At times, deadlines of goals were adjusted, to accommodate joint team efforts but overall, the goals were successful in encouraging consistent progress towards the completion of the final system. In both the Gantt chart schedule and deadlines below, the team no longer had to account for CSA inspection with the final solution since the wattage would be under the 100W maximum – this provided flexibility in changing deadlines of internal deliverables for the team.

Table 5: List of internal and external deadlines

Course / Internal	Deliverables	Due Date
Internal	Weekly Blog Posts – Summarize Meeting Notes	Ongoing until Symposium
Internal	Finalize problem, goals, specifications, criteria	October 6, 2023
Internal	Finalize alternative design and patent search for MTE 481 #1 PDP	October 14, 2023
MTE481 #1	**Preliminary Design Slides + Presentation**	**October 16, 2023**
Internal	Evaluation of First Iteration Detailed Design	October 30, 2023
Internal	Evaluation of Second Iteration Detailed Design	November 10, 2023
Internal	Finalize Design (CAD, schematics, control states) for MTE 481 #2 FDP	November 17, 2023
MTE481 #2	**Final Design Slides**	**November 20, 2023**
	Final Design Presentation	**November 27, 2023**
MTE481 #3	**Design Log Website**	**December 3, 2023**
MTE481 #4	**Final Design Report**	**December 5, 2023**
Internal	Purchase Components Round 1	December 8, 2023
Internal	Begin design iterations with mech / elec prototypes	January 1, 2023
Internal	Test & calibrate components, Purchase components round 2	January 8, 2023
Internal	Finalize designs for mech / elec prototypes	January 20, 2023
Internal	Begin construction of mechanical components	February 1, 2023
Internal	Complete testing of individual heating & mixing subsystems	February 23, 2023
Internal	Submit majority of fabrication requests to RPC / EMS	February 26, 2023
Internal	Begin integration and build of final system	February 28, 2023
Internal	Begin final testing to gather results for symposium banner	March 4, 2023
MTE482 #1 / Internal	**Supervisor Demos** / Results from testing ready for symposium banner	**March 15, 2023**
Internal	Completed symposium banner / Submitted for printing	March 20, 2023
MTE482 #2	**Symposium Day**	**March 25, 2023**
MTE482 #3	**Final Report Due / Symposium Poster Submitted**	**April 8, 2023**

3.2 Budget Costs

The expenditure allocated and incurred in constructing the system is summarized in Table 6: Allocated budget and actual incurred costsTable 6 below. Expected material and resources given a budget for spending, for which the actual incurred cost can be seen in the column next to it. New listings added after 11/2023 do not have a projected cost and since the budget was revised 01/2024, the available budget had more flexibility for purchases not considered initially.

Table 6: Allocated budget and actual incurred costs

Category	Materials/Supplies	Projected Cost (11/2023)	Actual Costs (04/2024)	Diff	Revised budget (01/2024)	Incurred Costs (04/2024)
Configuration Build	3D printer	0.00	0.00	0.00	200.00	169.94
	3D printer filament	60.00	0.00	60.00		
	Manufactured casings (metal)	200.00	58.16	141.84		
	Thermal insulation	10.00	73.69	-63.69		
	Manufactured casings (non-metal)	0.00	21.91	-21.91		
	Carbon Filter	30.00	9.48	20.52		
	Assembly (screws, bolts, etc.)	-	6.70	-		
Hardware	Humidity / Temperature Sensor	20.00	26.40	-6.40	300.00	256.06
	Air Quality Sensor	30.00	30.36	-0.36		
	LCD screen	15.00	0.00	15.00		
	Power Supply	70.00	0.00	70.00		
	Heating Element	20.00	45.18	-25.18		
	Microcontroller	0.00	0.00	0.00		
	Mixing Motor	75.00	34.65	40.35		
	Mixing Blade	50.00	51.63	-1.63		
	Relay, wiring, buttons etc.	0.00	0.00	0.00		
	Other electrical connections	20.00	67.84	-47.84		
Miscellaneous	R&D Costs (tested parts, etc.)	-	67.53	-	150.00	130.22
	Poster	-	62.69	-		
Total Costs		600.00	**556.22**		650.00	**556.22**
Remaining Budget		0.00	**93.78**		0	**93.78**

The greatest differences in the budget and incurred costs were in manufactured casings. The decision to purchase existing stainless-steel pots was made as a team in early December, bringing the cost down significantly and providing over $140 to allocate elsewhere. Additionally, the original budget missed the costs of R&D and preparing a poster for the Capstone Symposium. To accommodate this change, the team agreed to increase the budget up to $650: $200 for the build configuration, $300 for the hardware components, and $150 for any R&D costs from testing and for the poster. As discussed in the design objective relating to budget, the flexibility to increase budget to $1000 if necessary, still remained true.

Another notable difference in the costs where the incurred cost was much greater than the allocated budget was thermal insulation, thermoplastic/non-metal casings, electrical connections, and the heating element. Resulting from deviations from the original design, the nichrome wire heating method was replaced with PTC heating. Additionally, there were more components in thermal insulation than expected – the final design included a silicone ring for the top of the pot, insulation between the heating element and rest of the hardware, and melamine foam wrapped around the middle layer of the pot. Non-metal casings were originally believed to be all 3D printed, but the team made the decision to pivot to plywood laser-cut for efficiency reasons. Also included in this cost were resin sensor mounts commissioned to RPC to withstand the heat of the internal system, as opposed to 3D printed material.

The budget and spending charts were updated regularly by the team to ensure there was enough budget to fund a purchase. For any spending that exceeded the allocated budget, there would be brief discussions held among the team to justify the purchase. Overall, the entire cost of the construction and preparation of the project were under the $650 budget by about $90.

4.0 Conclusions and Recommendations

The designed and implemented system was successful based on the outlined constraints and criteria. The first objective is that the system minimizes the volume of the food scraps by 50%. Based on data gathered from testing, batches of food scraps were able to be reduced by 75%, well over the 50% objective. The second objective is that the process must finish within a full day. Based on the amount of food scraps that the system can handle at once and the internal temperature for dehydration, it was calculated that the scraps would finish processing within 8 hours [14]. From testing, it was confirmed that the food scraps were fully dehydrated in 6.5 hours. The next two objectives are the system responding to user input of the estop button within 3 seconds and staying within a budget of $650. Both objectives were met. Finally, the generated steam should be <500ppb within a 2m radius to ensure that the system's output is not harmful to its surroundings. This is the only objective that is not met, with air quality readings directly next to the system with readings ranging from 600-1050ppb.

The first constraint is that moving parts must be contained. The moving mixing blade at the bottom of the inner pot is contained within the outer case and a locking servo is implemented to prevent the user from touching any moving parts. The final system weighs 6.3kg and measured 0.356m in height, 0.305m in width, and 0.305m in depth, meeting both constraint two and three. Due to the use of insulation materials in the device, the external temperature of the device and its contacts points always remained <30°C. Lastly, the system was fully assembled and tested by the time of the symposium, meeting the final constraint.

Although only one objective is not satisfied, the system's ability to fulfill the remaining objectives and constraints render the project a success. While the steam output by the system does not meet the air quality objective, it does not mean that the output is harmful. The generated level of TVOCs from the steam is similar to the steam from cooking. A recommendation for running the system is to turn on the stove's fan during the initial 2-3 hours of the dehydration process where the most steam is generated.

The implemented design required the team to consider multiple aspects of the design which sparks ideas for further improvements. Currently, the dehydration state is hard coded to run for 8 hours. However, depending on the types of food scraps input and the amount, 8 hours may not be a suitable time for dehydration. Further improvements of the system would be determining the time for the dehydration cycle based on the input material. Another improvement of the system given more time, would be to implement a power supply with a smaller form factor to fit within the outer casing. This would make the device more portable for the user and take up less space in a residential unit.

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Appendix

Appendix A – Mixing Blade Extension

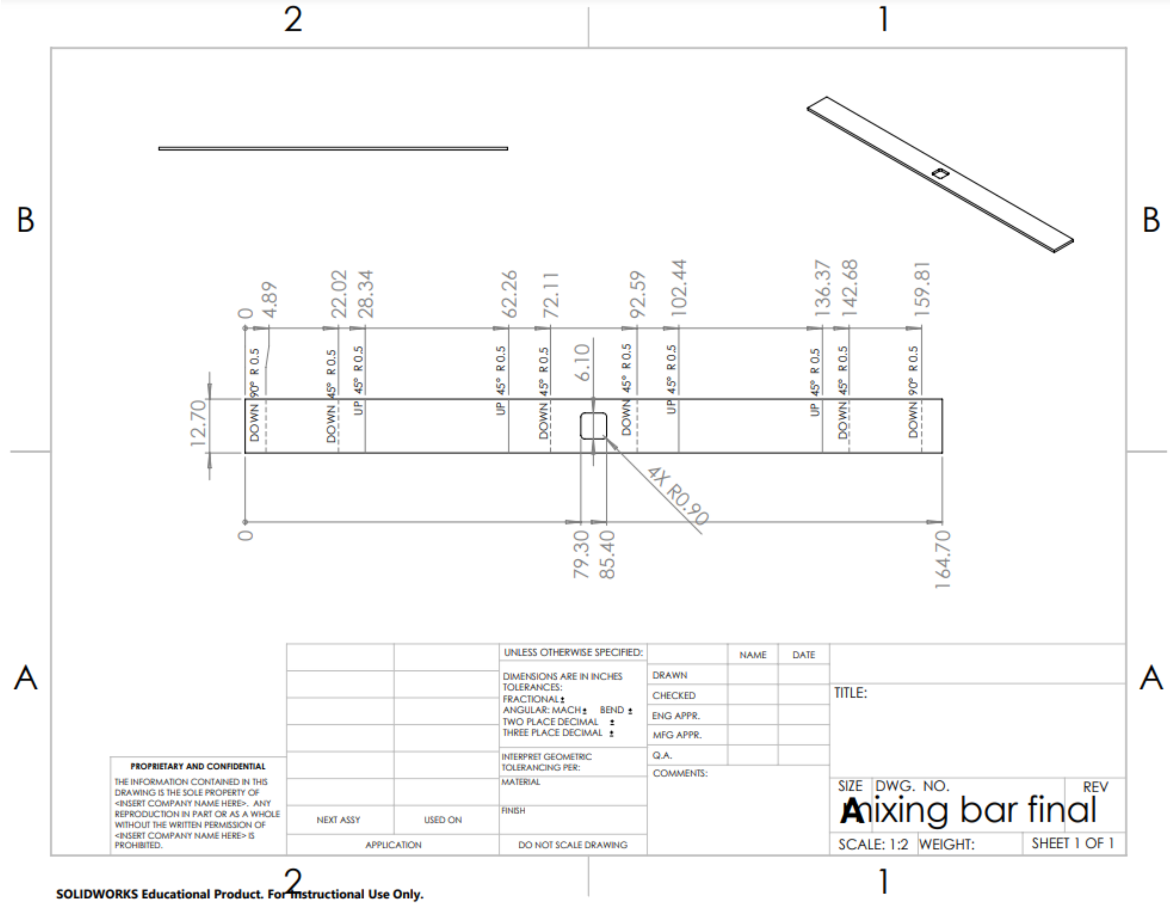

Figure 15: SolidWorks Drawing of the mixing blade extension

Appendix B – 3D Print Components

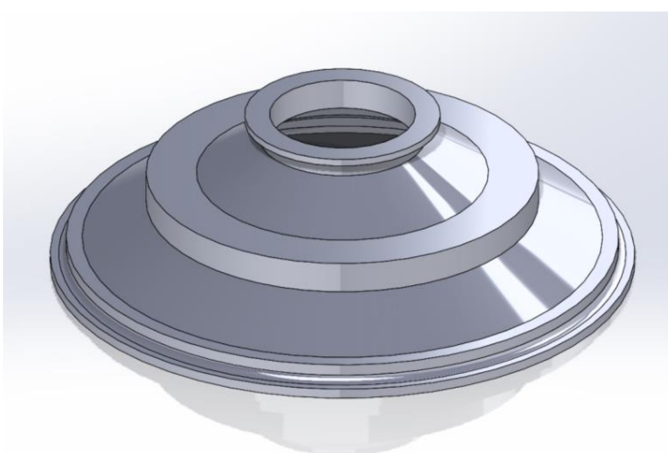

Figure 16: 3D model design of the system lid

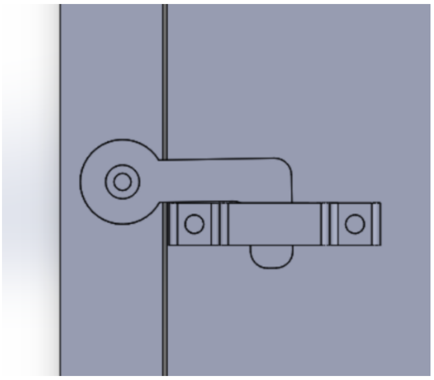

Figure 17: Door lock design

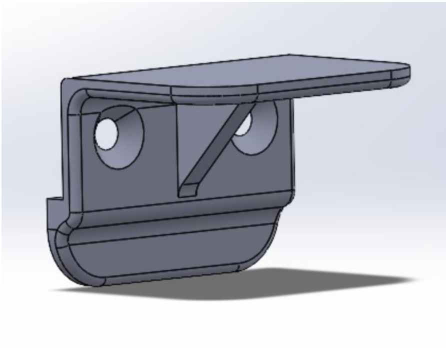

Figure 18: 3D model design of hinge restrictor

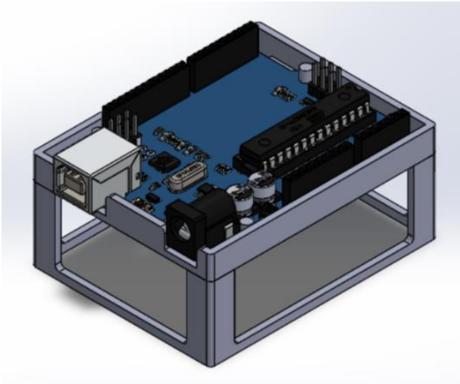

Figure 19: 3D model assembly of Arduino mount

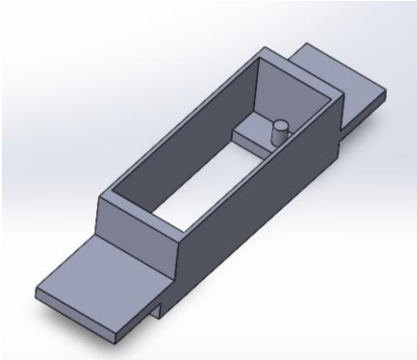

Figure 20: 3D model design of SG90 servo mount

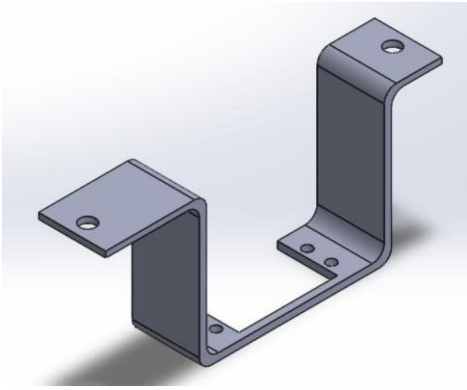

Figure 21: 3D model design of motor mount

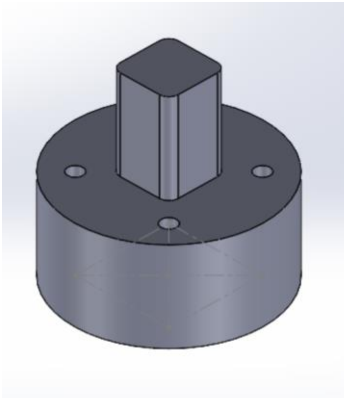

Figure 22: 3D model design of motor to blade socket shaft

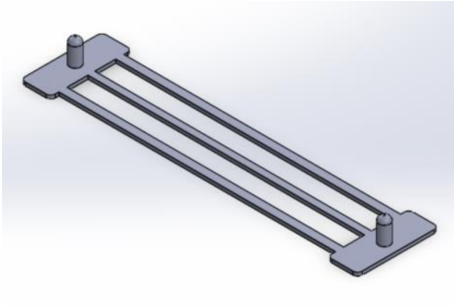

Figure 23: 3D model design of bus bars mount

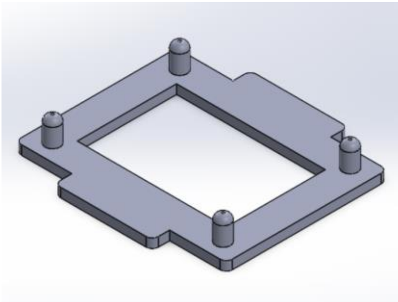

Figure 24: 3D model design of control relay mount

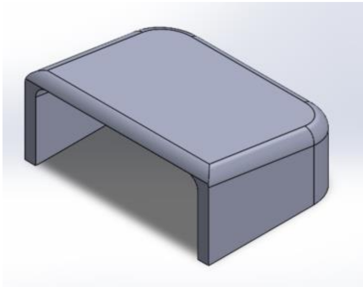

Figure 25: 3D model design of air quality sensor cover

Appendix C – System Program

Idle state: Waiting for user to press the start button to begin the cycle. Lock the lid once button is pressed.

```
if (IDLE == 1 && INTERRUPT == 0) {
  while (!buttonPressed(BUTTON_START) && INTERRUPT == 0){}

  digitalWrite(LED_START, 1);
  digitalWrite(LED_IDLE, 0);
  printLcd("Starting!");
  delay(1000);
  // assume start button pressed only after lid is closed
  Lock();
  IDLE = 0;
  PREHEAT = 1;
}
```

Preheat State: Turn on the relay and begin heating the system until 45°C is reached.

```
if (PREHEAT == 1 && INTERRUPT == 0) {
  delay(8000);  // delay 8s before start
  heatOn();
  printLcd("begin heating");

  while (AT_TEMP != 1 && INTERRUPT == 0) {
    printTemp(readTemp());
    delay(500);
    double temp = readTemp();
    if (temp > 45.0) { // expected to be ~30 minutes
      printLcd("reached temp");
      PREHEAT = 0;
      AT_TEMP = 1;
    }
    else {
      delay(10000); // check temp every 10s
    }
  }
```

Dehydration State: Turn on mixing servo and print sensors readings to the LCD display.

```
if (AT_TEMP == 1 && INTERRUPT == 0) {
  // 1. hold at temp for set timed duration
  // 2. AT_TEMP = 0; COOLING = 1;
  unsigned long StartTime = millis();
  unsigned long elapsed = 0;
  unsigned long CurrentTime = 0;

  double minute = 480;
  double ms_in_min = 60000;
  double delay_duration = minute * ms_in_min;

  printLcd("Drying...");
```

```
    while (elapsed < delay_duration && INTERRUPT == 0) {
      Blend(10); // blend for 10 seconds
      printTempTime(readTemp(), readHumidity(), elapsed);
      delay(10000);
      printLcd("Drying...");
      delay(2000);
      printAir(readAir2());
      delay(6000);
      CurrentTime = millis();
      elapsed = CurrentTime - StartTime;
    }

    printLcd("Heating done!");
    heatOff();
    delay(3000);
    AT_TEMP = 0;
    COOLING = 1;
  }
```

Cooling State: Once the heat is turned off, wait until the internal temperature is <35°C before unlocking the lid.

```
  if (COOLING == 1 && INTERRUPT == 0) {
    printLcd("Now cooling!");

    delay(1000);  // wait n minutes until beginning to check temp sensor read
    while (CYCLE_FINISHED != 1 && INTERRUPT == 0) {
      float temp = readTemp();
      printTemp(temp);
      if (temp > 45.00) {
        delay(30000);   // wait 30s until next check
        // (reduce check time from 30 seconds -> 10 seconds)
       }
      else if (45.00 > temp && temp > 35.00) {
        delay(10000);
      }
      else if (temp < 35.00) {
        COOLING = 0;
        CYCLE_FINISHED = 1;
      }
    }
  }
```

Cycle Complete State: Print a summary of the sensor readings, prompt the user to open the lid.

```
  if (CYCLE_FINISHED == 1 && INTERRUPT == 0) {
    printLcd("cycle finished");
    delay(10000);
    printLcd("quality summary:");
    printAir(readAir2());
    delay(7000);
    printHumidity(readHumidity());
    delay(7000);

    Unlock();
    delay(5000);
    printLcd("Please open lid");
    delay(10000);
    CYCLE_FINISHED = 0;
    IDLE = 1;
  }
```