A STUDY ON SMART FOOD WASTE RECYCLING SYSTEM USING BLACK SOLDIER FLY LARVAE

ASHLEY CHUA JUN HONG

INNOVATION & DESIGN PROGRAMME

NATIONAL UNIVERSITY OF SINGAPORE

2024

A STUDY ON SMART FOOD WASTE RECYCLING SYSTEM USING BLACK SOLDIER FLY LARVAE

ASHLEY CHUA JUN HONG

A THESIS SUBMITTED FOR THE DEGREE OF

BACHELOR OF ENGINEERING (ELECTRICAL ENGINEERING)

INNOVATION & DESIGN PROGRAMME

NATIONAL UNIVERSITY OF SINGAPORE

DECLARATION

I hereby declare that this thesis is my original work and it has been written by me in its entirety.

I have duly acknowledged all the sources of information which have been used in this thesis.

Additionally, I disclose that a paraphrasing tool was employed to assist in constructing sentences and enhancing the clarity of the text, ensuring adherence to academic integrity and the scholarly presentation of the work.

ASHLEY CHUA JUN HONG

30 March 2024

Acknowledgements

The team wishes to express our profound gratitude to our project supervisor, Dr Elliot Law, along with our co-supervisors, Ms Wong Kah Wei, and Mr Adrian Fuhrmann, for their invaluable guidance and mentorship throughout the course of this project. Their constructive insights, generous sharing of knowledge, and thought-provoking ideas have not only enriched our project but also steered us toward effective ideation processes. We recognize that their unwavering support and wealth of expertise have been instrumental in ensuring that our learning experience was truly beneficial and that the project achieved its goals.

Special thanks to Mr. Hamilton Toh Boon Pin, our Mechanical Consultant, whose profound knowledge, and innovative approach in mechanical engineering have significantly enhanced the technical robustness of our work. His guidance through complex mechanical challenges has been instrumental in achieving our project objectives.

We are also immensely grateful to our Electronics Consultants, Ms. Annie Tan and Mr. Alvin Poh, whose expertise in electronics have illuminated our path through intricate circuit designs and system integrations. Their meticulous attention to detail, combined with a deep understanding of electronics, has been critical in ensuring the reliability and functionality of our electronic components.

Their collective wisdom and dedication have not only contributed to the success of our project but have also inspired us to push the boundaries of what we thought was possible.

We are honoured to have had the opportunity to work alongside such distinguished professionals.

Table of Contents

Summary

The thesis, "A Study on Smart Food Waste Recycling System Using Black Soldier Fly Larvae," presents an innovative approach to addressing the escalating issue of food waste management in Singapore. Through the lens of sustainability and resource efficiency, the research focuses on the development and implementation of a portable reactor system that utilizes Black Soldier Fly Larvae (BSFL) for the bioconversion of food waste into valuable byproducts such as animal feed and organic fertilizer. This work is set against the backdrop of Singapore's significant food waste challenge, where only a small fraction of food waste is currently recycled, with the majority being incinerated or landfilled, contributing to greenhouse gas emissions and the looming saturation of landfill capacity.

The thesis outlines the environmental and logistical drawbacks of conventional food waste processing methods in Singapore, such as incineration and anaerobic digestion, emphasizing their contribution to greenhouse gas emissions and inefficiency in resource recovery. In contrast, the utilization of BSFL is proposed as a more sustainable and efficient alternative, capable of converting nearly 100% of food waste into useful products, thereby embodying the principles of a circular economy. This approach not only mitigates the environmental impact associated with traditional waste management methods but also supports Singapore's "30 by 30" goal to increase local food production resilience.

Central to the thesis is the design, development, and testing of a BSFL-based reactor system designed for on-site deployment at food waste generation sites such as eateries and hawker centers. The reactor system is conceptualized to be portable, user-friendly, and adaptable

to various urban environments, thereby facilitating the localized processing of food waste and reducing the need for its transportation to centralized facilities. The research thoroughly documents the iterative design process of the reactor, detailing the technical considerations, challenges, and solutions encountered in developing a system that meets the operational requirements of effective BSFL breeding and food waste bioconversion.

Significantly, the thesis provides a comprehensive analysis of the reactor's components, including the container, cage, drawer slides, chassis, and electronics, each carefully selected and optimized for functionality, durability, and ease of use. The study emphasizes the importance of a scalable and flexible design, allowing for the reactor's adaptation to different settings and scales of operation. The narrative of design evolution reflects a meticulous approach to engineering and innovation, grounded in sustainability principles and practical application.

Furthermore, the research highlights the collaborative aspect of the project, involving consultations with experts and stakeholders in mechanical engineering, electronics, and waste management. This multidisciplinary engagement enriches the development process, ensuring that the reactor system is not only technically sound but also aligned with industry needs and sustainability goals.

List of Tables

List of Figures

1. Background

1.1 Food Waste Statistics in Singapore

Table 1. Overall Waste generated in Singapore in 2022 [1].

2022 Waste Statistics and Overall Recycling Table

Waste Type	Total Generated ('000 tonnes)	Total Recycled ('000 tonnes)	Recycling Rate	Total Disposed ('000 tonnes)
Ferrous metal	1,338	1,331	99%	7
Paper/Cardboard	1,064	394	37%	671
Construction & Demolition	1,424	1,419	99%	5
Plastics	1,001	57	6%	944
Food	813	146	18%	667
Horticultural	221	188	85%	32
Wood	419	298	71%	121
Ash & sludge	241	27	11%	213
Textile/Leather	254	5	2%	249
Used slag	169	166	99%	2
Non-ferrous metal	92	91	98%	2
Glass	73	11	14%	63
Scrap tyres	26	25	95%	1
Others (stones, ceramics, etc.)	249	30	N.A.[1]	219
Overall	**7,385**	**4,188**	**57%**	**3,197**

Table 2. Comparison of Food Waste generated in Singapore over five years [3].

Year	Food Waste Disposed of ('000 tonnes)	Food Waste Recycled ('000 tonnes)	Total Food Waste Generated ('000 tonnes)	Recycling Rate (%)
2018	637	126	763	17%
2019	607	136	744	18%
2020	539	126	665	19%
2021	663	154	817	19%
2022	667	146	813	18%

Food waste represents a significant component of Singapore's waste stream. As indicated in Table 1, the year 2022 witnessed the generation of a substantial 813,000 tonnes of food waste, with a mere 18% of this waste being subjected to recycling [1]. To provide a contextual reference, this is equivalent to approximately two bowls of rice per individual per day [2]. The remaining portion is directed to incineration facilities before ultimately finding its way into our landfill. Furthermore, Table 2 illustrates that the recycling rate has demonstrated no significant improvements over the past five years, consistently hovering within the range of 17% to 19% [3].

1.2 Default method of processing Food Waste

Figure 1. Flow of default Food Waste processing [4][5].

At present, the gathered food waste undergoes transportation via large vehicles to four specialized incineration facilities. There are 3 main drawbacks of the default processing method.

Firstly, post-incineration, the food waste is converted into residual byproducts, including ashes and non-combustible materials. Despite achieving a 90% reduction in waste volume post-incineration, the remaining 10% residue necessitates disposal at landfills [3]. Consequently, these byproducts are conveyed to the Pulau Semakau landfill, where they progressively amass, occupying significant landfill capacity over time.

Figure 2. Pulau Semakau landfill comparison [6].

The Pulau Semakau landfill, originally designed to serve until 2045, now faces an accelerated timeline for reaching its capacity, projected to be filled by 2035, due to ongoing food waste management practices [7]. As illustrated in Figure 2, the left side represents the landfill's status in the year 2000, while the right side represents its condition in the year 2020. The cells initially depicted in blue indicated their vacant state, and upon reaching capacity, they are portrayed in green.

Table 3. Types of Greenhouse Gas emission in Singapore, year 2021 [8].

Greenhouse Gas	Emissions (Gg CO2 eq)	Percentage of Total Emissions
CO_2	50,089.9	93.30 %
PFCs	1,787.6	3.33 %
N_2O	579.6	1.08 %
HFCs	522.3	0.97 %
NF_3	464.3	0.86 %
CH_4	114.5	0.21 %
SF_6	131.1	0.24 %

Secondly, As highlighted in Table 3, for the year 2021, carbon dioxide emerged as the leading greenhouse gas emission in Singapore, accounting for 93.30% of emissions [8]. Incineration plants contribute significantly to these emissions, with 15% of carbon dioxide emissions attributed to waste incineration, that means 7.5 million tons of CO_2 [9]. Interestingly, a person is estimated to exhale one ton of CO_2 over a span of approximately 1000 days. Moreover, the transportation of food waste to incineration plants and landfills results in a substantial carbon footprint, enough to fill 39 million passenger buses annually [10].

Figure 3. Singapore's '30 by 30' goal and strategy [11].

Finally, the existing methods of food waste processing undermine our "30 by 30" objective, which aims for greater food resilience by producing 30% of our nutritional needs locally by 2030, despite dedicating less than 1% of our land to farming [11]. Achieving this ambitious goal necessitates innovative approaches to maximize yield from minimal resources, ensuring our agricultural practices are highly productive, climate-resilient, and resource-efficient.

However, with Singapore's population growth at 6 million in 2023 and projected to be 6.4 million by 2050 [12], the demand for food will increase by 50% [12]. This would essentially mean that there will be more food waste being generated in the coming years. With the default method of incineration, food waste in landfills or incinerated represents a loss of potential nutrients that could have been recycled into the soil as compost or used to feed animals, enriching soil health and supporting sustainable agricultural practices in Singapore.

1.3 Alternative methods of Processing Food Waste

Due to the drawbacks of the present approach to food waste management, several other methods are being explored. One of these methods is anaerobic digestion.

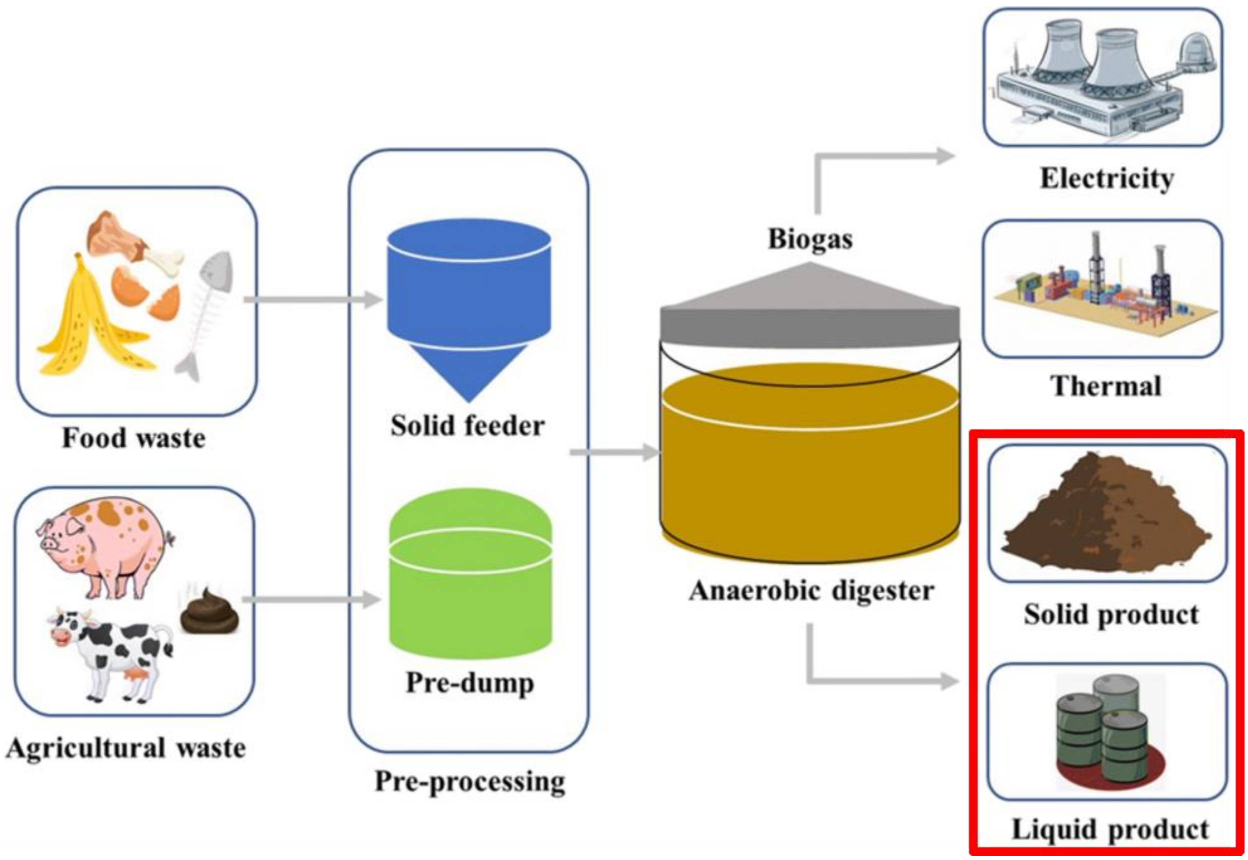


Figure 4. Anaerobic Digestion (AD) Process [13].

Fundamentally, it represents a biological process that enzymatically disintegrates food waste in an oxygen-deprived environment. As shown in Figure 4, microbial breakdown results in the production of biogas, a composite comprising methane and carbon dioxide, as well as a residual substance known as digestate. Biogas can be systematically harnessed and employed as a sustainable energy resource for applications such as electricity generation, heating, and vehicular fuel. Meanwhile, the digestate can undergo additional treatment to yield a valuable crop fertilizer, while any remaining residual waste is directed to landfill facilities [14].

While Anaerobic Digestion may be regarded as a more environmentally sustainable option compared to incineration, there are three key considerations contributing to its limitations:

1. The residual waste generated in the process continue to contribute to the volume of waste in the landfill, potentially accelerating the occupancy of the disposal site.
2. The biogas produced because of Anaerobic Digestion contributes to carbon dioxide emissions in Singapore, thus posing challenges in achieving significant reductions in greenhouse gas emissions.

Figure 5. Anaerobic Digestion of Food Waste from East Coast Lagoon Food Village Pilot project in 2021 [15].

3. Research efforts focused on implementing Anaerobic Digestion as a viable waste management solution are ongoing and have, thus far, primarily been conducted in small-scale or lab-scale projects. As seen in Figure 5, a pilot project at East Coast Lagoon Food Village, spearheaded by researchers from the National University of Singapore (NUS), is innovatively converting food waste into energy and fertilizer. Utilizing an anaerobic digestion system, the project processes food waste from the food village into biogas and bio-fertilizer [15]. This on-site treatment significantly reduces the need for incineration, aligning with Singapore's Zero Waste Masterplan goals. Although this project yields positive data and feedback, there are still considerations and further improvements on this small-scale project.

Figure 6. Insects being considered in Food Waste management [16].

Another approach that is being explored for food waste management is the use of insects. Insects are increasingly recognized as a sustainable and ecologically sound alternative to both anaerobic digestion and incineration for managing food waste. Insects such as black soldier fly larvae as seen in Figure 3 are effective in converting food waste into valuable resources, notably protein-rich insect biomass and nutrient-rich frass, all the while mitigating greenhouse gas emissions. This approach aligns with the principles of a circular economy, where the resulting byproducts are reintegrated into the system to support ongoing production, therefore avoiding the need for disposal in landfills [16].

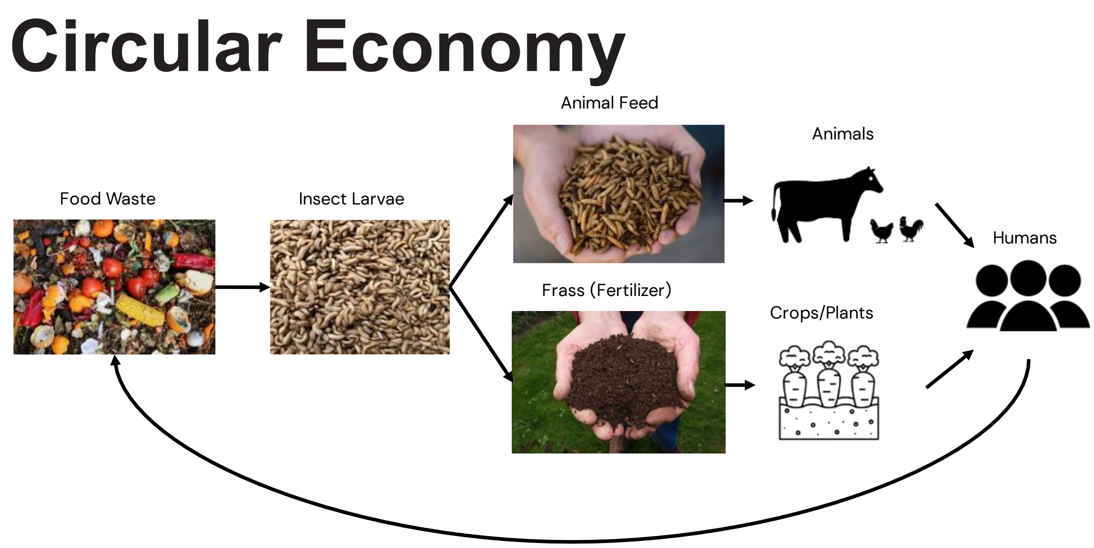


Figure 7. Circular Economy of Insects in Food Waste Management [4][16].

Insects provide a sustainable alternative through the generation of byproducts that can be utilized as protein-rich animal feed and nutrient-rich fertilizers, thereby enhancing livestock nutrition, and facilitating local crop cultivation. Subsequently, the produce and livestock nurtured by these byproducts become part of the human food chain, establishing a circular economy framework.

1.4 Comparison between methods of processing Food Waste

Table 4. Comparison of Food Waste processing methods.

	Incineration	Anaerobic Digestion	Insects
Circular Economy	No	Yes	Yes
Sustainable / Environmentally Friendly	No	No	Yes
Food Security	No	Yes	Yes

Table 4 compared the three aforementioned food waste management approaches in terms of their contribution to creating a circular economy, their environmentally friendliness, and potential for enhancing food security.

Firstly, incineration does not contribute to circular economy as its residual waste that includes ash and non-combustible materials, cannot be effectively recycled and must be transported to landfills. Conversely, anaerobic digestion yields byproducts that can be refined into nutrient-rich fertilizers, facilitating local crop cultivation and hence, has greater potential to create a circular economy compared to incineration.

However, the utilization of insects presents a significantly more sustainable alternative to incineration and anaerobic digestion. This method produces byproducts that serve as protein-rich feed for animals and nutrient-dense fertilizers, which in turn improve livestock nutrition and support local crop production. As a result, the fruits, vegetables, and livestock nourished by these byproducts enter the human food chain, fostering a circular economy.

Secondly, as Table 3 emphasizes, carbon dioxide emissions and their contribution to greenhouse gases remain a critical issue. The incineration of food waste, along with the transportation of these wastes and its residuals, significantly contributes to carbon dioxide production. Similarly, Anaerobic Digestion produces biogas, which contains methane and carbon dioxide, presenting further sustainability challenges. Additionally, the disposal of its residual byproducts in landfills undermines efforts to reduce carbon emissions.

In stark contrast, the insect-based method emerges as a markedly more sustainable solution, notably reducing greenhouse gas emissions. Fundamentally, most of the nutrients from food waste are converted to biomass or frass instead of gaseous products that can harm the environment. Its efficiency in harvesting and repurposing all byproducts ensures that landfill accumulation is prevented, underscoring its environmental benefits.

Lastly, in view of Singapore's constrained land resources and heavy reliance on food imports, which constitute 90% of our food supply, it becomes imperative to prioritize local food production [17]. As seen in Figure 2, the Pulau Semakau landfill is facing an accelerated timeline for reaching its capacity. If Singapore was to allocate more land for waste storage and construction of incineration facilities, it would diminish the opportunities and space available for local crop cultivation and hence, negate the ’30 by 30’ goal. Both incineration and Anaerobic Digestion will contribute to this challenge. In contrast, Insect-based processing offers a solution that does not rely on landfill disposal, ensuring that valuable land resources remain available for food production and enhancing food security.

Therefore, exploring the utilization of insects for food waste management is highly warranted, given its potential to fulfil three key objectives:

1. Circular Economy: This approach ensures the recycling of all byproducts back into the system, effectively minimizing waste and reducing dependency on landfills.
2. Sustainable Food Waste Management: By transforming most nutrients into biomass and frass, this method significantly diminishes our carbon footprint.
3. Enhanced Food Security: Reducing reliance on incineration plants and landfills frees up more space for local crop cultivation, thereby bolstering food security.

1.5 Why Black Soldier Fly Larvae (BSFL)

In the context of using insects for food waste management, various options, including maggots, black soldier fly larvae (BSFL), and mealworms, were considered. Among these options, BSFL is the most promising based on these factors.

1. Accelerated Food Waste Decomposition: BSFL are notably efficient at rapidly decomposing organic matter, highlighting their exceptional ability to expedite food waste processing. Their voracious appetite allows a single BSFL to ingest up to four times its body weight daily [18], leading to the potential reduction of food waste volume by 50% to 80% within just a few days [19]. This efficiency is contingent on the composition of the waste and the density of the larvae population.

   In comparison, mealworms exhibit a more modest consumption rate, capable of ingesting approximately 34% of their body weight per day. This equates to a consumption of 34 to 39 milligrams of food waste daily [20]. On the other hand, maggots are capable of consuming about twice their body weight in food waste per day [21]. This differential in consumption rates underscores the unique efficiency of BSFL in waste management scenarios, setting them apart from their counterparts such as mealworms and maggots in terms of speed and volume of waste they can process.

2. Versatile Digestion of a broader range of Food Waste: BSFL are renowned for their versatile diet, capable of breaking down a wide array of organic waste types, including meats, dairy products, and fats [22]. This broad dietary range is part of what makes BSFL particularly valuable for waste management and composting efforts.

   In comparison to BSFL, mealworms primarily subsist on a plant-based diet and are remarkable in breaking down polystyrene foam [22]. However, they exhibit limited capacity for processing meats and dairy products. Similarly, maggots are adept at decomposing animal tissues. Yet, like mealworms, their ability to handle fats and dairy products is constrained [23]. This distinction underscores the unique adaptability of BSFL in handling a more diverse range of food wastes, including those rich in fats and dairy, setting them apart as a more versatile option in waste management.

3. High-Efficiency Conversion into Valuable Byproducts: BSFL demonstrates an exceptional conversion rate, efficiently transforming 100% of the food waste into biomass (Adrian Fuhrmann, personal communication, October 2023). This

comprehensive process ensures that all food waste and larvae are converted into valuable feed and frass, leaving no residual waste to be disposed of in landfills [22].

Mealworms are recognized for their efficient conversion of certain types of food waste into byproducts, particularly excelling with plant-based materials and unique materials like polystyrene. Their ability to transform these specific wastes into valuable byproducts is notable, though their versatility is somewhat limited to the kinds of waste they digest effectively.

On the other hand, the efficiency with which maggots convert food waste into byproducts is influenced by several factors, including the nature of the waste, environmental conditions, potential for cannibalism, and risks of pathogen transmission [23]. These sensitivities necessitate close monitoring and a more controlled rearing environment for maggots, which restricts their flexibility and application compared to other organisms.

Table 5. Comparison table for different insect types.

Criteria	BSFL	Mealworms	Maggots
Food Waste Decomposition Speed	High (up to 4x body weight daily, reducing waste by 50% to 80%)	Moderate (approx. 34% body weight per day, specific to plant-based waste and polystyrene)	Good (up to 2x body weight daily, dependent on conditions)
Dietary Versatility	Very high (can digest meats, dairy, fats, and more)	Limited (primarily plant-based diet, limited meat and dairy processing)	Moderate (efficient in animal tissue, limited with fats and dairy)
Efficiency in Conversion to Byproducts	Exceptional (100% conversion into valuable biomass)	High for specific wastes (efficient conversion, but limited by diet)	Variable (influenced by environmental conditions and waste type)

Overall, as shown in Table 5, the BSFL stands out in the field of food waste management for their exceptional efficiency in decomposing organic matter, their versatility in digesting a broad range of food wastes including meats, dairy, and fats, and their unparalleled ability to convert nearly 100% of the food waste into valuable byproducts such as biomass and frass. This efficiency is notably higher than that of mealworms and maggots, which have more limited diets and show variable efficiency in waste conversion. BSFL's rapid food waste decomposition speed significantly reduces food waste volume by 50% to 80% in just a few days [19], and their adaptability allows for the processing of diverse food waste types that other insects cannot handle as effectively.

However, the implementation of BSFL in waste management is not without its challenges. The need for specific climate and environmental conditions can limit their use in colder climates without controlled environments, potentially raising the cost of operations. Odor management becomes crucial when processing large amounts of food waste, requiring additional attention to maintain a pleasant environment. Additionally, specialized handling and processing needs, including the timely harvesting of larvae before they become flies and the separation of larvae from frass, adds a layer of complexity to utilizing BSFL. Despite these drawbacks, the benefits of using BSFL in food waste management, particularly their high efficiency and contribution to a circular economy, make them a compelling option compared to mealworms and maggots, warranting further exploration and optimization to overcome these challenges.

1.5.1 Life Cycle of Black Soldier Fly

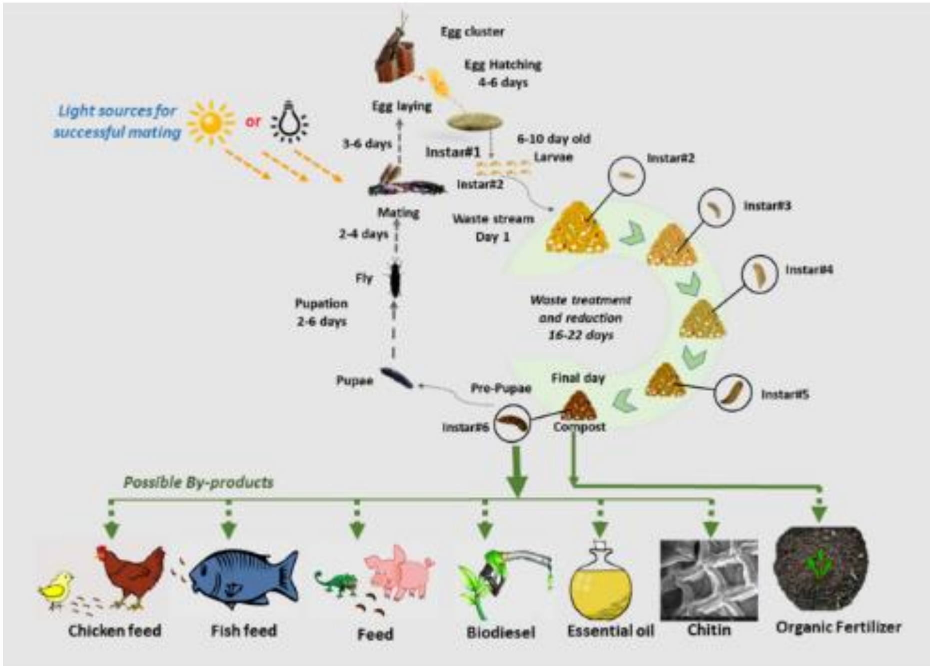


Figure 8. Black Soldier Fly Larvae (BSFL) Life Cycle [24].

Figure 8 shows the typical life cycle of BSFL. For food waste management, 5-day-old larvae (5DOL) are normally used as they are ready to commence feeding. Typically, BSFL require approximately two weeks to reach a developmental stage where their feeding ceases, depicted as Instar#5 in Figure 8. At this stage, the larvae can be collected and subjected to dehydration for animal feed production. Harvesting the larvae at this juncture reduces the likelihood of their maturation into adult flies. Concurrently, the resulting frass, comprised of exoskeletons and excrement, proves invaluable as a high-quality fertilizer resource.

1.6 Current state of BSFL solutions in Food Waste Management

Figure 9. BSFL Research Laboratory in the National University of Singapore (NUS).

In Singapore, current initiatives leverage the utilization of Black Soldier Fly Larvae for food waste management. However, it is worth noting that these endeavors are predominantly characterized by their limited scale, often taking the form of small-scale or laboratory research that are typically situated within centralized facilities.

For example, one such collaboration, involving institutions like the Swiss Federal Institute of Technology Zurich (ETH Zurich), National University of Singapore (NUS), and Nanyang Technological University (NTU), is dedicated to researching and implementing the application of BSFL in the context of food waste management and sustainable food production within urban environments. As illustrated by Figure 9, the research project is conducted on a laboratory scale, featuring specialized reactors meticulously designed to provide the most conducive conditions for the feeding period of BSFL. These reactors are equipped with an array of sensors and monitoring equipment, allowing for adjustments to the internal environmental parameters (Adrian Fuhrmann, personal communication, October 2023).

Figure 10. Insectta, A local company that adopts the use of BSFL [25].

Another example is, Insectta, a company based in Singapore that focuses on insect farming, specifically utilizing BSFL technology to convert food waste into valuable byproducts. Insectta aims to tackle food waste by transforming it into high-value biomaterials, such as animal feed, organic fertilizer, and even chitosan—a versatile compound used in pharmaceuticals, cosmetics, and more. Their approach not only addresses the issue of waste management but also contributes to the creation of sustainable, circular economies by turning waste into resources [25].

Insectta is part of a growing industry that recognizes the potential of insect farming in sustainable agriculture and waste management. Their work includes research and development into new applications for the byproducts of insect farming, exploring ways to maximize the impact of this technology on sustainability and waste reduction efforts globally.

However, Insectta's core mission revolves around leveraging BSFL technology not merely for the management of food waste but primarily for the transformation of such waste into valuable byproducts. Their focus extends beyond establishing facilities for waste processing in Singapore. Instead, Insectta concentrates on innovating methods to convert food waste into a range of useful products [25]. The emphasis is on exploring the potential applications of these byproducts, identifying how they can be utilized across various industries to create sustainable solutions.

Figure 11. Protix, a Netherlands company that adopts the use of BSFL [26].

Protix is a notable company based in the Netherlands that specializes in the cultivation of BSFL for sustainable protein production. Protix is at the forefront of developing technologies and processes for converting food waste into high-quality protein, fats, and other valuable byproducts using BSFL. Their work is geared towards creating sustainable food systems by providing an alternative protein source for animal feed, aquaculture, and pet food industries [26].

The company aims to address some of the world's most pressing sustainability challenges, such as the need for more sustainable food production methods and the reduction of waste. By harnessing the efficiency of BSFL in breaking down food waste and converting it into nutrient-rich biomass, Protix contributes to creating a circular economy where waste is minimized, and resources are used more efficiently [26].

While Protix in the Netherlands exemplifies the innovative use of BSFL for sustainable food waste management, Singapore's unique context presents distinct challenges. Given Singapore's limited land availability, the large-scale facilities that Protix operates are not feasible within the constraints of our small country. This necessitates a shift towards decentralized facilities, which can be integrated into the urban landscape without requiring extensive land use.

Furthermore, our approach also prioritizes minimizing the carbon footprint associated with transporting food waste. Centralized facilities, while efficient on a large scale, often necessitate longer transportation distances, leading to increased emissions. By adopting a decentralized model, we can process food waste closer to its source, significantly reducing transportation needs and associated carbon emissions.

Given these differences in goals and circumstances, directly transplanting Protix’s model to Singapore is not viable. Instead, we must tailor our approach to align with Singapore’s specific conditions, focusing on decentralized waste management solutions that address both land use limitations and the desire to lower our environmental impact.

As a decentralized facility, there are 3 main benefit it can bring about:

1. On-site waste processing: Decentralized facilities can process food waste close to its source, reducing the need for long-distance transportation of food waste. This can significantly cut down on carbon emissions associated with the transportation of food waste.
2. Resilience and Flexibility to disruptions: Decentralized facilities can be more resilient to disruptions. If one facility faces challenges, others can continue to operate simultaneously, ensuring the overall system's stability. This flexibility allows for the testing of different approaches and adaptations to on-site environmental conditions, where the weather and capacity of food waste varies from different facilities.
3. Community Engagement and Awareness: By training and involving the community to facilitate this decentralized facility, it can increase awareness about food waste management and sustainability practices. This can foster a greater sense of responsibility and participation in sustainable food waste management practices.

However, there are some complexities in implementing a decentralized facility:

1. Specialized training and Knowledge: Operating BSFL facilities requires specialized knowledge and skills. Ensuring that staff at all decentralized locations are adequately trained can be an additional operational challenge.
2. Oder management and Public Perception: Decentralized facilities, being closer to communities, must stringently manage odors and address any public concerns about hygiene and safety.
3. Standardization and Quality Control: Ensuring consistent standards and quality of output (e.g., larvae biomass and frass) across decentralized facilities can be

challenging. Quality control mechanisms and best practices must be established and maintained.

4. Adjustments and Adaptability of decentralized equipment: Decentralized BSFL projects necessitate a careful balance between standardization and flexibility in equipment and operational practices. In small-scale and laboratory settings, equipment is meticulously calibrated to control environmental conditions, ensuring the viability and optimal growth of BSFL while facilitating data collection and experimentation. These controlled conditions are crucial for understanding the specific needs and behaviours of BSFL in various stages of food waste processing.

   Transitioning to decentralized facilities introduces the challenge of replicating these ideal conditions across multiple sites, each with its unique environmental and logistical constraints. Unlike the controlled, uniform settings of laboratory projects, decentralized systems must adapt to variations in climate, food waste types, and operational capacities. This necessitates not only the ability to adjust and customize equipment and processes to local needs but also requires ongoing testing and refinement to achieve optimal results.

In essence, while the benefits of BSFL food waste management are clear, the transition from small-scale, laboratory-centric projects to larger, more decentralized facilities will introduce a new range of considerations and complexities. Successfully navigating these challenges will be pivotal in achieving a more sustainable and widespread solution for food waste management in Singapore.

2. Proposed Solution

2.1 Our Vision

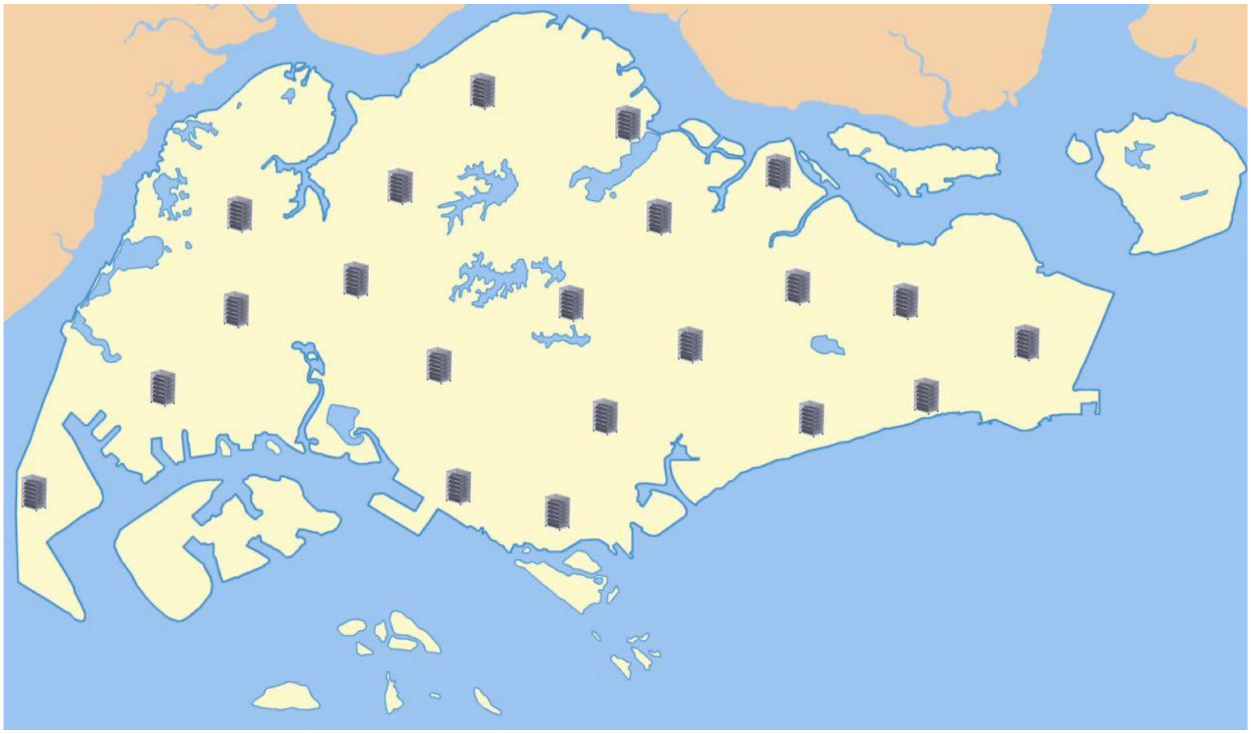


Figure 12. Our vision of our solution deployed across Singapore.

To facilitate the seamless integration of BSFL into food waste management, we envision a broader-scale deployment strategy, shifting away from the conventional centralized facility model. Depicted in Figure 7, our vision entails the establishment of numerous autonomous reactors distributed across various locations throughout Singapore, including eateries and hawker centres. This approach is designed to enable on-site food waste processing, concurrently reducing the necessity for large-scale transportation. Moreover, considering land scarcity concerns in Singapore, the decentralized facility model significantly alleviates the requirement for extensive treatment areas.

The core concept underlying our vision is to decentralize the food waste management process, enhancing its efficiency and sustainability. By installing independent reactors at the source of food waste generation, such as restaurants and food stalls, we can significantly reduce the carbon footprint associated with transporting waste to a central facility. This approach not only minimizes transportation costs but also decreases the overall carbon emission.

The adoption of on-site reactors significantly enhances the immediate handling of food waste, enabling timely and efficient management. This approach not only exemplifies the principles of a circular economy but also ensures that the byproducts from these reactors are seamlessly integrated into the local ecosystem for repurposing and recycling. This promotes resource efficiency and bolsters environmental sustainability.

Furthermore, recent legislation mandates that developers incorporate space for on-site food waste treatment systems in their design plans for new buildings. This requirement has been in effect since January 1, 2021 [27]. Additionally, the enforcement of food waste segregation and reporting standards will be phased in, with specific mandates for new constructions starting from January 1, 2024 [27]. Such regulatory measures significantly bolster our vision, making it increasingly relevant and in demand.

By decentralizing food waste management and deploying autonomous reactors at various key locations, our vision strives to create a more robust and eco-friendly system for handling food waste in Singapore. This transformative approach holds the potential to revolutionize the way we manage food waste, reduce transportation-related emissions, and contribute to a more sustainable urban environment.

2.2 Our Objective and Scope

Therefore, the aim of this project is to engineer an upscaled, deployable reactor for on-site food waste treatment. The three main objectives are as follows:

1. Achieving Circular Economy: Develop the reactor to not only process food waste but also to convert it into valuable byproducts, such as nutrient-rich fertilizer or protein-rich animal feed. This approach ensures that food waste is transformed into resources, exemplifying the principles of a circular economy where the end-of-life of one product becomes the input for another.
2. Promoting Environmental Sustainability: By processing food waste on-site, the project significantly cuts down on the greenhouse gas emissions associated with the transportation of food waste to centralized facilities. Additionally, the use of BSFL for waste processing requires less energy compared to traditional incineration or anaerobic digestion methods.
3. Enhancing Food Security: This project proposes an innovative approach to food waste management by enabling the on-site processing of waste across multiple facilities. By significantly reducing the dependency on incineration plants, not only do we free up valuable land, but we also pave the way for utilizing these spaces to cultivate local crops. Such a strategic shift not only addresses the pressing issue of waste management but also enhances Singapore's food security.

Thus, to achieve our objective, we started to scope, design, and test a prototype of a portable BSFL reactor that will aid researchers at the NUS BSF Laboratory, but can be easily deployed at food waste generation sites across Singapore. This reactor will serve as a foundational tool for future research and optimization of BSFL-based food waste management, considering both the biological needs of the larvae and the operational requirements of various waste-producing establishments.

2.3 Target Venue

Figure 13. BSFL Research Laboratory in the National University of Singapore (NUS) [28].

Our project is poised to take a significant step forward by situating the initial development and testing phases within the BSF Research Laboratory in the National University of Singapore (NUS), as shown in Figure 13. This strategic decision to use the NUS lab as our primary venue for early-stage development underscores our commitment to rigorous scientific research and innovation. Within this controlled environment, our team aims to design and develop a prototype of a deployable reactor for on-site food waste treatment. This endeavour not only leverages the advanced research facilities and intellectual capital available at NUS but also aligns with our broader objective to contribute substantively to the field of sustainable waste management.

Our focus within the NUS lab setting is to iterate and refine our prototype, ensuring it meets the highest standards of efficiency, sustainability, and scalability. This phase is critical for laying the groundwork for future research, allowing for comprehensive testing, analysis, and optimization of the reactor design and its operational parameters. By adopting this meticulous approach, we aim to address and overcome potential challenges, thereby enhancing the reactor's performance and its applicability across diverse settings.

The goal of conducting this preliminary phase at NUS is to establish a strong foundation for the reactor's success in real-world applications. Post-validation and optimization within the lab environment, our vision is to roll out the reactor to the public, targeting various food waste generation sites across Singapore. This phased approach ensures that when the reactor is introduced to the market, it is fully equipped to meet the demands of on-site food waste processing, aligning with our vision of promoting a circular economy, enhancing food security, and contributing to a more sustainable urban ecosystem.

2.4 Value Proposition

These are the potential benefits for various stakeholders that could arise from the proposed solution:

1. Food Establishments: Our project introduces a valuable alternative for food establishments. The implementation of our reactor enables these establishments to derive value from their food waste through the sale of its byproducts.
2. Local Farms: The primary beneficiaries of these byproducts are local farms. They can harness the nutrient-rich frass as an organic fertilizer to enhance soil quality and nutrient content. Additionally, the larvae generated in the process serve as a nutritious and sustainable source of animal feed, contributing to livestock nutrition and local produce growth.
3. Government: Our project has a direct impact on government waste management efforts, reducing the volume of food waste destined for landfills or incineration facilities. This not only extends the lifespan of the Pulau Semakau landfill but also curtails waste management expenditures. Furthermore, by promoting the utilization of BSFL, it aligns with the agenda of sustainable agriculture, diminishing the necessity for food imports and fostering self-sufficiency.

2.5 Design Requirements

Table 6. Design Requirement Table.

Criteria	Requirements	Rationale
Size	Maximum Width of 85cm	Given that we have a decentralized application, our solution has to be portable. With the full derivation of the Size and Weight criteria in Section 6.2 – Sizing Constraints
	Maximum Depth of 120cm	
	Maximum Height of 200cm	
Weight	Maximum Weight of 400kg (when fully loaded with food waste and BSFL)	
Optimal Bioconversion Performance	Achieve moisture content of 70 – 80%	This is the ideal moisture content range of food waste for BSFL
	Achieve relative humidity of 40 – 70%	The mortality was 62%, 26% and 3% at a relative humidity of 25%, 40% and 70%, respectively
	Achieve environmental temperature of between 25 - 30°C	This is the optimum temperature range for the growth of BSFL
	Ensure Light Intensity of 0 Lux	Presence of light can affect the feeding rate of the BSFL which will affect its developmental growth
Reduction in Organic food waste mass	80 – 90% reduction in organic mass 50 – 80% volume reduction	Effective and sustainable means of food waste management by reducing cost and carbon footprint due to waste transportation as well as designated land for waste management facilities and landfill

Table 5 outlines the essential prerequisites that our proposed solution must meet. These requirements have been derived from comprehensive research data and current industry practices, serving as the foundation for optimizing the setup conducive to the thriving of Black Soldier Fly Larvae and achieving the most favourable byproduct outcomes. These initial values will guide our testing phase; however, we will also collect proprietary data following the testing process to determine the most suitable parameters for our specific context.

Figure 14. Lift Dimensions in NUS Engineering Block E2.

Figure 15. Door Dimension in NUS Engineering Block EA.

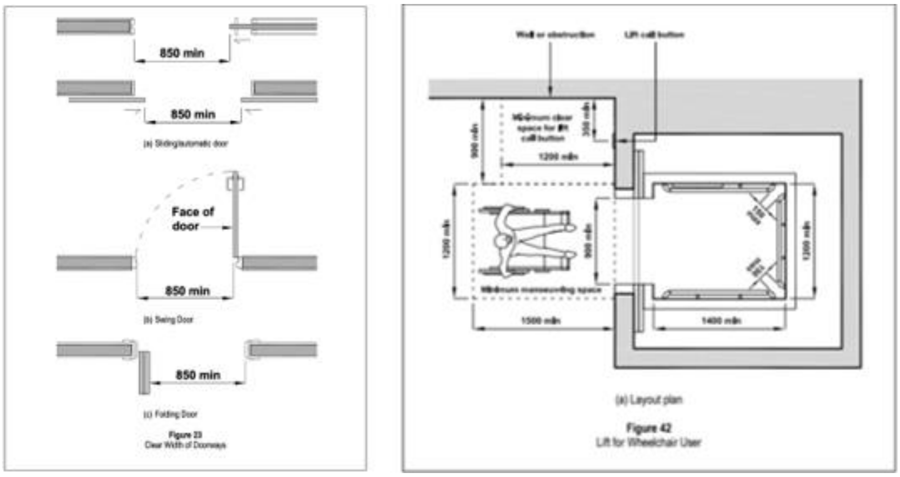


Figure 16. BCA Guidelines for Doors and Lifts [27]. (Refer to Appendix 7.1)

1. In developing the sizing criteria for our reactor, meticulous research was conducted to ensure seamless integration within the physical infrastructure of NUS and, by extension, potential deployment sites across Singapore. Recognizing the critical importance of navigability and compatibility, our team embarked on a comprehensive survey within NUS, measuring the dimensions of corridors, doors, lifts, and walkways—essentially, any pathway our reactor might traverse. These measurements are meticulously documented in figures 14 and 15.

   To ensure our reactor adheres to not just the specific requirements of NUS but also to broader standards that would facilitate its future deployment across varied locations, we consulted the guidelines set forth by BCA Singapore, in figure 16. This step was crucial in aligning our design with the most common sizes for corridors, doors, and lifts as defined by BCA, setting a standard for our reactor's dimensions that anticipates and mitigates potential logistical challenges in transportation and installation [27].

   After our findings, we arrived with a reactor size of 2m by 1.2m by 0.85m.

Figure 17. Food Waste calculation per food court per day (based on weight). (Refer to Appendix 7.2)

2. To accurately determine the operational capacity required for our reactor to effectively process food waste, we selected the food court at the NUS UTown as a case study. Through conducting targeted interviews with the cleaning staff at the UTown food courts, we gained invaluable insights into the volume of food waste generated daily. It was revealed that each day, the food court accumulates a full bin of food waste, quantitatively measured at approximately 120 liters.

   Recognizing that food waste density can vary significantly from one location to another, it was imperative to establish a general density value to guide our reactor's design specifications. By consulting existing literature on the subject, we identified an average density of 1.565 Kilograms per liter for food waste. This figure, when applied to the daily volume of food waste collected from the UTown food court, results in an estimated total mass of approximately 187.8 Kilograms of food waste per day.

3. Determining the optimal environmental conditions under which BSFL can thrive and efficiently convert food waste is a critical component of our project. To establish these vital parameters, we have grounded our approach in a comprehensive review of existing literature and valuable insights from field experts. A pivotal source of knowledge in this endeavour has been our collaboration with Adrian Fuhrmann, a dedicated researcher within the NUS BSF Laboratory.

   Adrian's ongoing experiments, which utilize reactors similar to our project's focus, are instrumental in uncovering the precise conditions that maximize BSFL bioconversion performance. As highlighted in Figure 9, these reactors serve as a testbed for understanding the environmental needs of BSFL, including temperature, humidity, and food waste composition.

   Based on the synthesis of findings from the literature and Adrian's empirical research, we have defined a range of optimal conditions crucial for the survival and productivity of BSFL [28]. These parameters are tailored to ensure that our reactor not only supports the life cycle of the larvae but also optimizes their ability to process food waste effectively.

4. In our quest to evaluate the efficacy of Black Soldier Fly Larvae (BSFL) in food waste reduction, we conducted an extensive review of the literature and closely observed the experiments conducted by Adrian Fuhrmann in the NUS Black Soldier Fly Laboratory. Adrian's pioneering work suggests that BSFL have the remarkable capacity to convert 100% of food waste into biomass, indicating their potential as a

highly efficient bioconversion solution. However, our review of broader scientific literature indicates a more conservative estimate, suggesting an 80-90% reduction in food waste mass when processed by BSFL [29].

Given the variance in reported outcomes, our team has decided to undertake our own empirical research to accurately determine the conversion efficiency of BSFL in our specific context. To begin, we have set a conservative target for the reduction of food waste mass. This approach allows us to establish a baseline understanding of BSFL's bioconversion capabilities within our operational parameters. Our objective is to verify through firsthand experimentation the extent to which BSFL can reduce food waste mass, thereby providing a solid foundation for our project's expectations and goals.

3. Concept Design

3.1 Overall process of Reactor

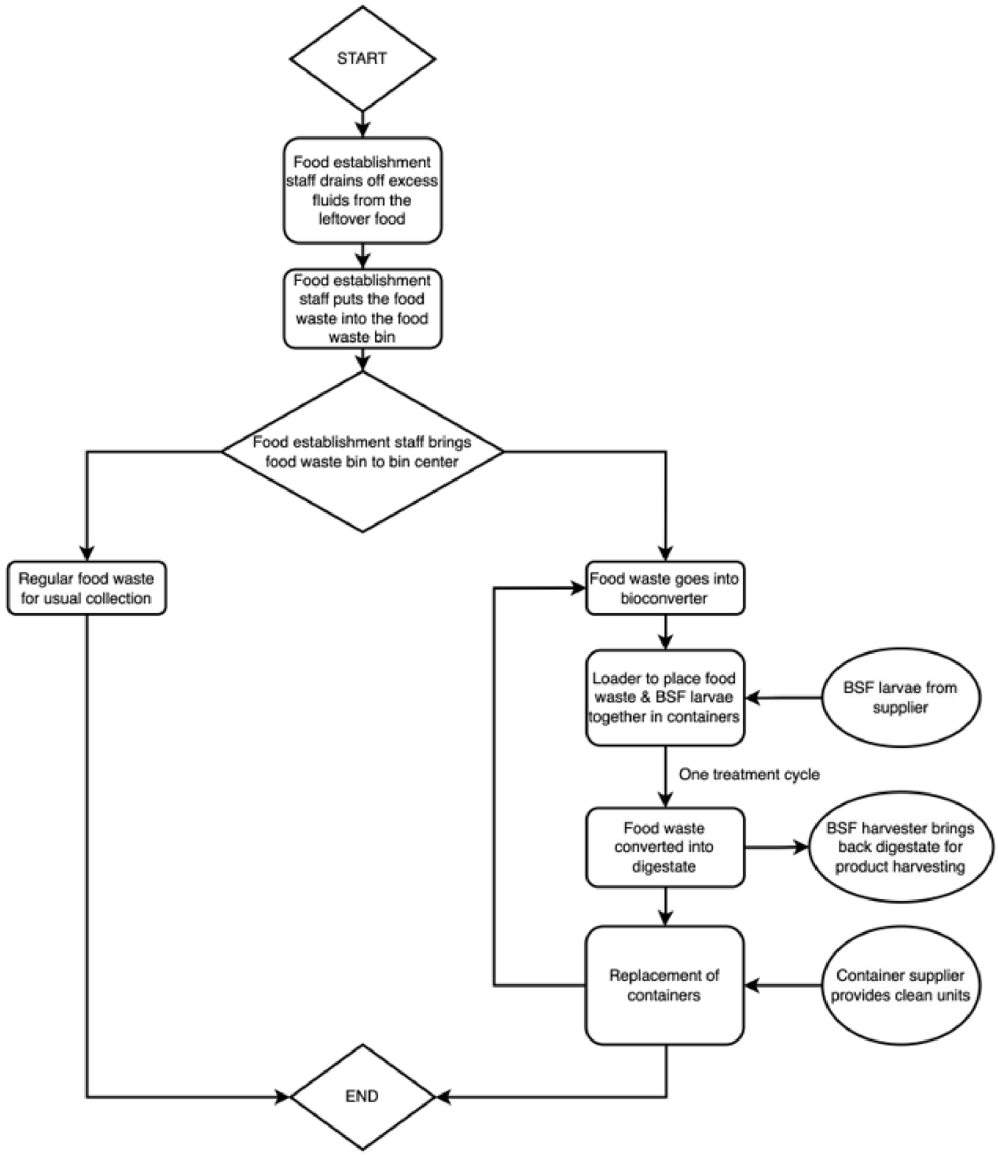


Figure 18. The overall flow of how the envisioned reactors will work.

Figure 18 illustrates the operational concept of our envisioned solution in contrast to the existing treatment approach. Within our proposed reactor system, upon the entry of food waste, the generated byproducts are systematically recycled back into the system as valuable feed or fertilizer components. This design ensures a closed-loop system, where nothing is left unused or wasted, thereby promoting a sustainable and efficient utilization of resources.

3.2 Overall Concept Design

Figure 19. Rack used in BSF Research Laboratory in NUS.

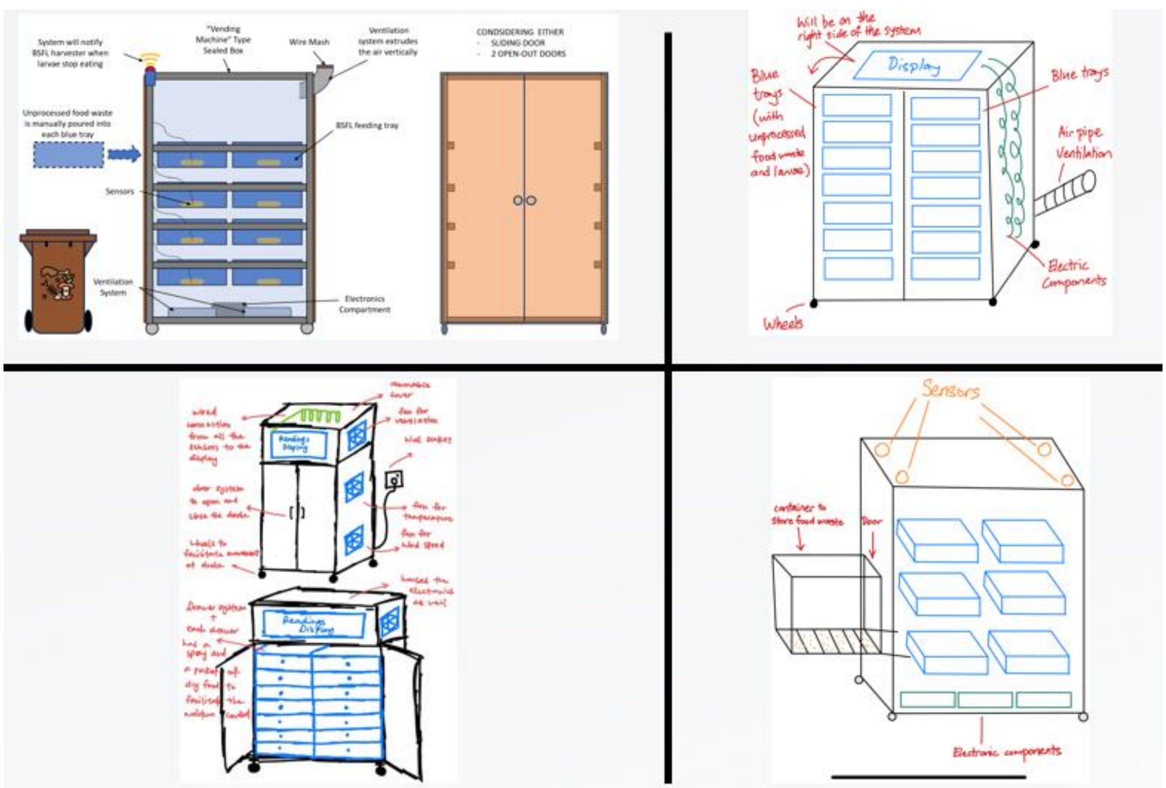


Figure 20. Concept ideas.

As a team, we drew inspiration from the current reactor (Figure 9) and rack (Figure 19) employed in the laboratory setting to ideate on concepts for our envisioned reactor design (Figure 20), aligning with the prescribed dimensions and guidelines set forth by the BCA. Upon consolidating our ideas, we observed that the proposed concepts predominantly revolved around the utilization of multiple containers for storing food waste. These containers are envisioned to be stacked on various levels within the system, encapsulated by an outer shell enveloping the entire structure.

3.3 Sub-Systems

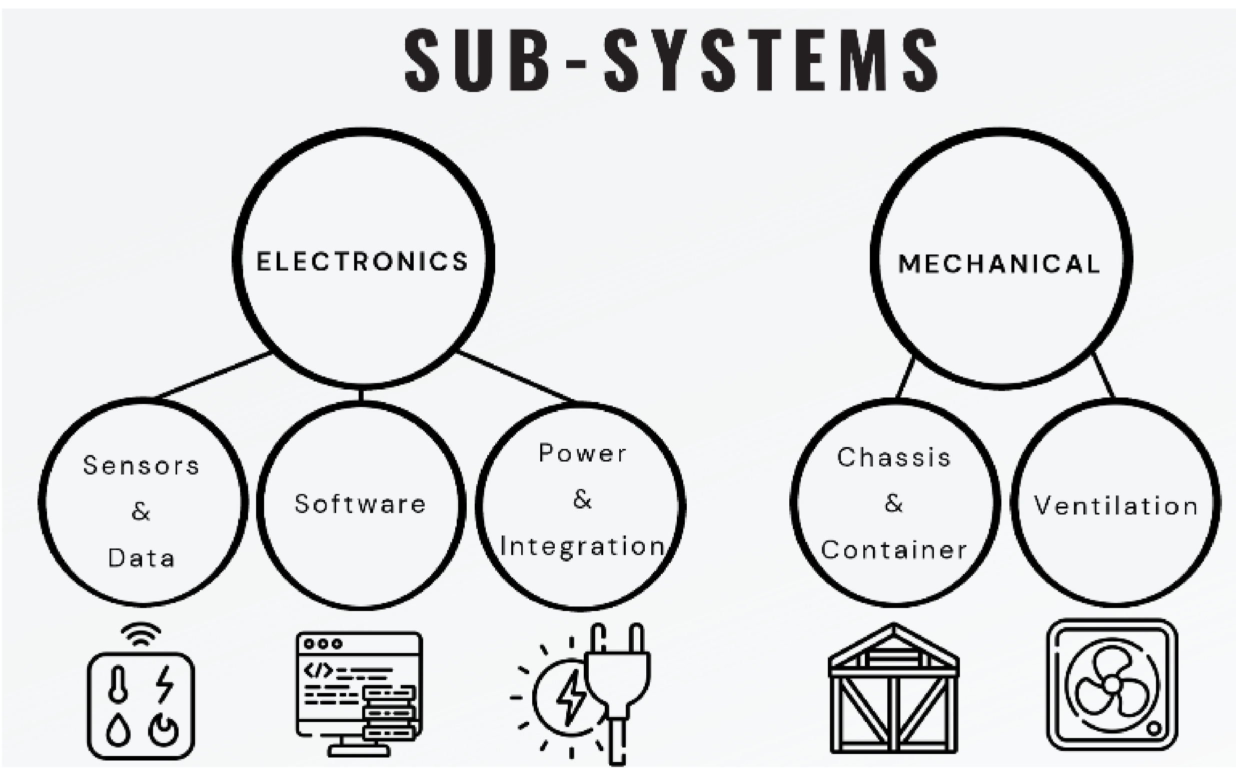


Figure 21. Sub-systems identified for our project.

Based on the above concept design, figure 21 shows the subsystems within our project. We have organized the electronics segment into three distinct sub-systems, each serving a specific purpose:

1. Sensors and Data: This sub-system encompasses the selection and calibration of sensors, as well as the extraction of critical data. It plays a fundamental role in ensuring precise monitoring and data collection within the system.
2. Software: The software sub-system is responsible for programming and automation, enabling the internal conditions of the system to be adjusted seamlessly. It forms the intellectual core of our project, facilitating real-time adjustments for optimal performance.
3. Power Supply and Electronics Integration: This final sub-system is tasked with the power supply management and overall integration of electronic components. It ensures the cohesive operation of all electronic elements.

Subsequently, within the mechanical segment, we have categorized it into two sub-systems to address different aspects of the project:

1. Chassis and Container Design: The first sub-system is focused on the design and construction of the chassis and container. The chassis is the foundational structure that supports the entire body of the structure and the systems within, while the containers are what holds the food waste and BSFL. This segment ensures the structural integrity and physical housing of our reactor.
2. Ventilation: The second sub-system is dedicated to ensuring the proper ventilation within our reactor. It plays a vital role in maintaining the environmental conditions necessary for the efficient operation of the system.

3.4 Mechanical systems goal

From the mechanical team's perspective, our primary objective is to maximize the reactor's portability and user-friendliness. While our immediate aim is not deployment to the public but rather to equip researchers with a versatile tool for laboratory experiments, we are designing with the eventual widespread adoption across Singapore's food establishments in mind. By focusing on creating a device that is easily maneuverable and straightforward to use, we ensure it can adapt to a variety of settings. This approach not only facilitates the current research phase, allowing for the adjustment of parameters and internal conditions with ease, but also lays the groundwork for a smoother transition to public use. Designing with the end goal in sight, our prototype aims to offer a seamless, practical solution for on-site food waste management that minimizes operational challenges in diverse environments.

3.5 Sizing of Chassis

As outlined in Section 2.5, under design requirements, our chassis sizing strategy was informed by two critical considerations: the dimensions of walkways, lifts, and doors within NUS, and the stipulations set forth by the Building and Construction Authority (BCA) of Singapore. For detailed insights into how these factors influenced our design, please refer to Section 2.5, Point 1.

3.6 Current Storage used in BSF Laboratory in NUS

Figure 22. Current containers used on the racks in NUS BSF research laboratory.

The initial phase of our research involved an in-depth examination of two distinct containers employed within the BSFL research laboratory. The first container, in tandem with the racks (shown in Figure 22), possesses a shorter stature and a layered configuration with discernible gaps.

Figure 23. Current containers used in the reactors.

Conversely, the second container, designed explicitly for the reactor (shown in Figure 23), boasts taller dimensions, and incorporates perforations in the additional height to promote improved airflow.

The key distinction between the two types of containers, as illustrated in Figures 22 and 23, lies in their respective usage environments. The container shown in Figure 22 is used in non-controlled environments, whereas the container depicted in Figure 23 is specifically used within the reactor. This latter container is optimized for vertical stacking in the controlled conditions provided by the reactor setup, enabling efficient space utilization and environment management.

However, a notable practical challenge emerges from the direct stacking of these reactor containers: accessing the lower containers necessitates the removal of those situated above. Moreover, the current reactor design can only accommodate three containers, prompting us to explore an alternative internal rack system capable of housing multiple containers while preserving an enclosed structure like the existing reactor setup. This adjustment aims to optimize containment capacity without compromising the integrity of the established enclosure system.

3.7 Current Loading and Unloading of containers

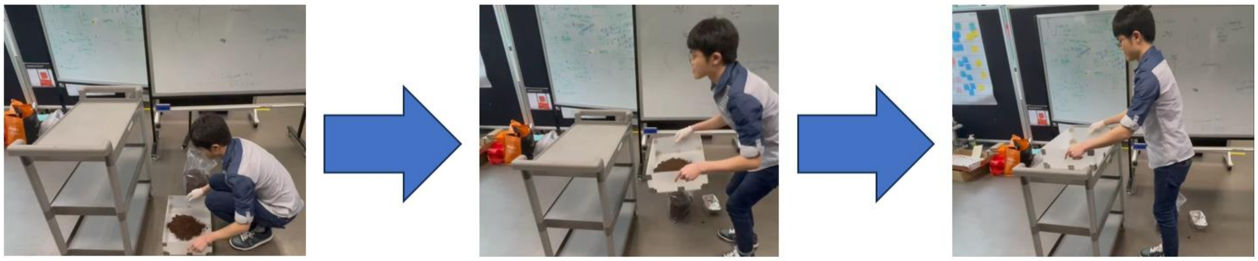


Figure 24. Current method of loading containers.

Figure 25. Current method of unloading containers.

Following our investigation, we scrutinized the current procedures utilized by researchers for loading and unloading containers onto and off from the racks. Our findings highlighted a demanding and repetitive process that requires a significant level of physical endurance from the staff involved. This method involves the repetitive lifting of containers, each weighing approximately 8 kilograms, necessitating continuous lifting, and lowering throughout the process, as evidenced in both Figure 24 and Figure 25. Given these insights, we acknowledged the necessity to develop more user-friendly approaches for loading and unloading within our reactor system. This initiative aims to mitigate the physical strain imposed on users during these tasks.

3.8 Loading and Unloading Concept designs

3.8.1 Loading Concept designs

During the preliminary phase of our loading concept designs, our team explored the feasibility of integrating a top opening in the reactor to streamline the intake of food waste. The objective was to facilitate the even distribution of food waste into designated containers within the reactor. However, this approach presented notable challenges primarily due to the intricate mechanisms required, potentially leading to excessive complexity and impracticality within our operational context.

Figure 26. Pump to transfer food waste into the containers.

Following this, our attention pivoted towards investigating an alternate solution involving the utilization of pumps directly within the food waste bin. The proposed concept aimed to pump the waste directly into designated containers under the guidance of a staff member wielding the nozzle, presenting a more viable and simplified approach for waste distribution, as illustrated in Figure 26.

However, the notion of employing a food pump was ultimately dismissed due to four reasons:

1. Substantial cost implications - Initial setup costs for a food pump system will be high. This includes not only the cost of the pumps themselves but also installation, integration and ongoing maintenance.
2. Reduced flexibility of handling varying food waste - Fixed pumping systems may lack the flexibility to handle varying amounts of waste or waste of different types and consistencies.
3. Sanitation concerns - Mechanical systems can harbor bacteria and require regular cleaning and sanitation to ensure that they do not become a source of contamination, especially in food handling areas.
4. Mechanical complexity – The need for trained personnel to operate and maintain the pumps, may not always be feasible for all establishments.

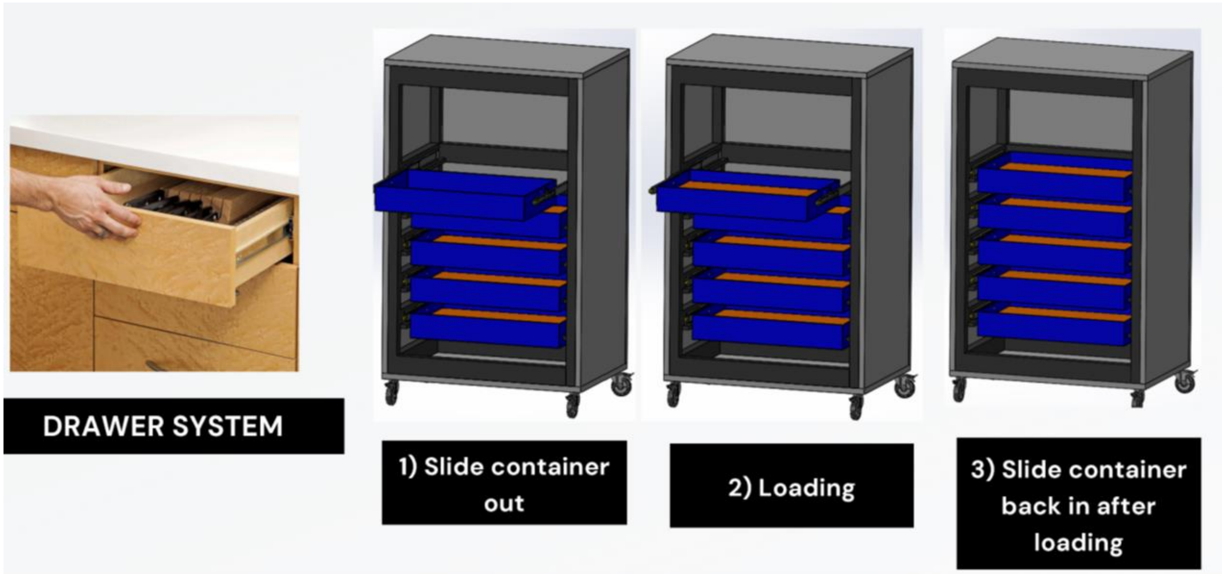


Figure 27. Drawer system loading concept.

As a result, our attention turned towards formulating a drawer-style system where the containers can be affixed directly to the reactors. This design permits staff to load food waste directly onto the containers, obviating the requirement for subsequent transportation of the containers onto the reactor, as depicted in Figure 27.

The two main reasons why a drawer system is favoured:

1. Control over Weight and Distribution: Individuals responsible for loading the food waste into containers gain precise control over the weight and distribution of the waste within each container. This careful management ensures an even spread, optimizing the capacity and balance of the containers.

2. Ergonomic Efficiency: The process is designed ergonomically, with the food waste positioned at waist level. This arrangement significantly reduces the need for the loader to bend down to pick up loaded containers, thereby minimizing strain and enhancing comfort during the loading process.

3.8.2 Unloading Concept Designs

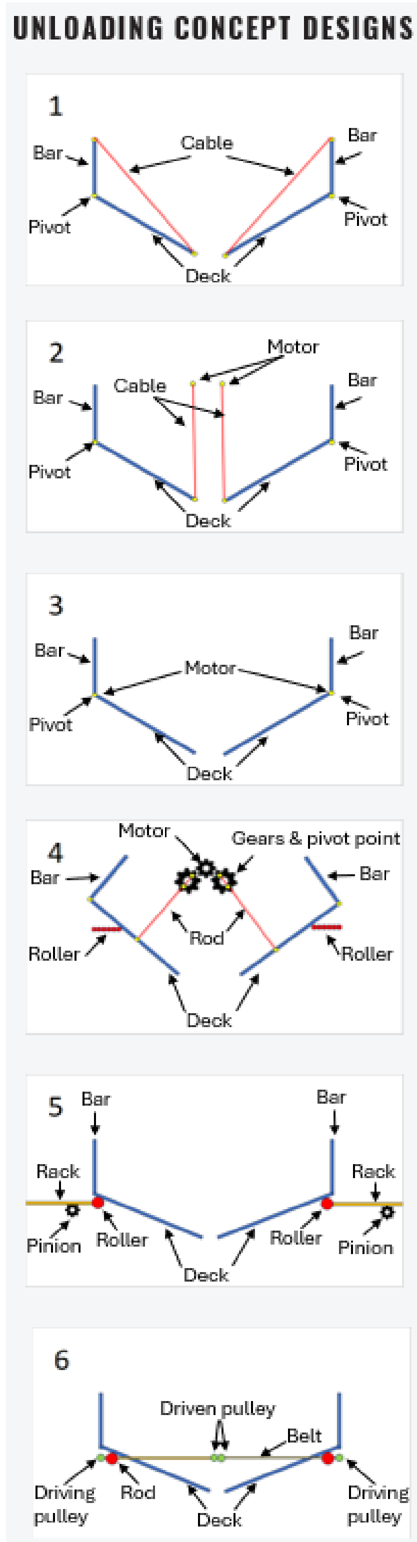


Figure 28. Unloading concept designs.

In the initial phase of conceptualizing our unloading mechanism, multiple concepts were generated, primarily aligning with two predominant trends. The first approach involves elevating the container's sides, thereby creating a void at the base to facilitate the release of frass and larvae, as illustrated in figure 28 under design 4. Alternatively, another method involves creating a separation between the bottom sections of the container, as evident in the remaining designs. Subsequently, a subset of these concepts, considered most suitable for our context, was selected for rapid prototyping. This approach aims to enhance visualization and determine the most promising direction for further exploration and refinement.

3.8.3 Unloading Concepts Prototyping

In the development of our prototypes, we employed cardboard to fabricate the containers, incorporating holes to facilitate the securing of strings to these containers. To simulate frass and larvae, we utilized blue bottle caps as substitutes. The dimensions of this prototype adhere to a one-to-three scale in comparison to the actual intended size, ensuring a detailed and proportionate representation for testing and demonstration purposes. This approach allows us to refine design elements and operational mechanisms before scaling up to the full-size version.

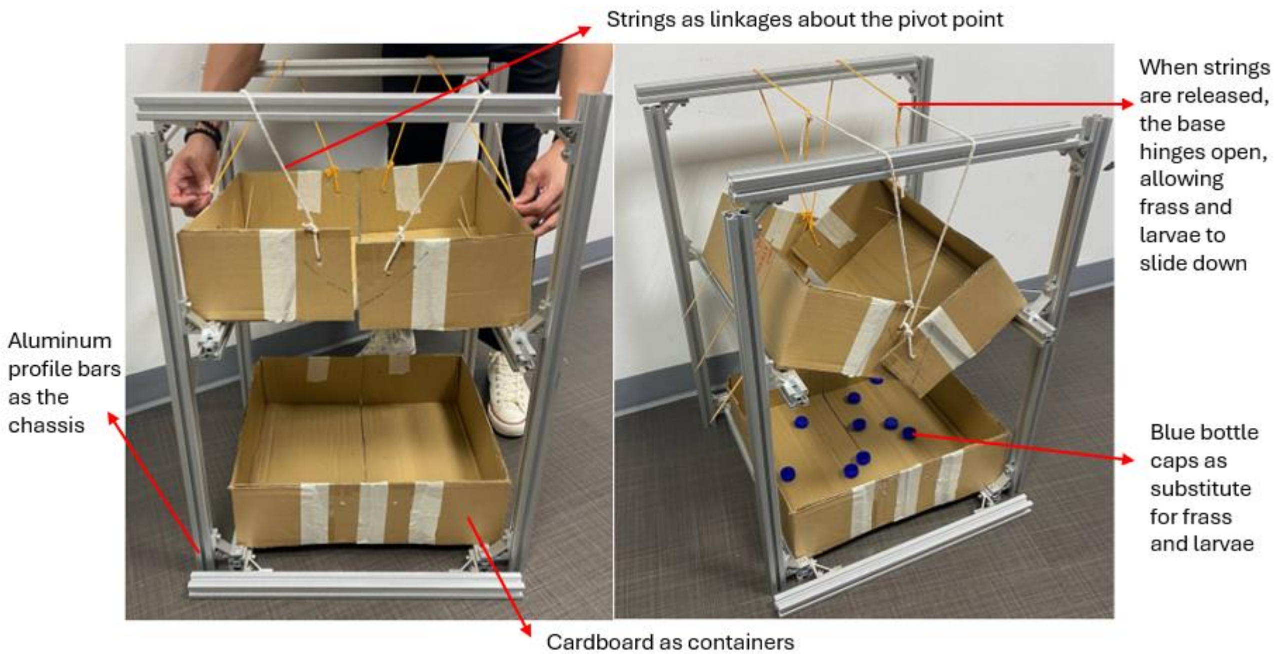


Figure 29. Prototyping of design one.

In the execution of design one, we utilized a configuration incorporating strings and wooden sticks to secure both containers onto the aluminum profile frame. Using manual manipulation through string pulling, we successfully closed the containers. Releasing the tension on the strings facilitated the inward collapse of the containers, intentionally generating a gap at the base. This aperture enabled the controlled descent of frass and larvae, represented by blue bottle caps, guiding their transfer into the subsequent container positioned below.

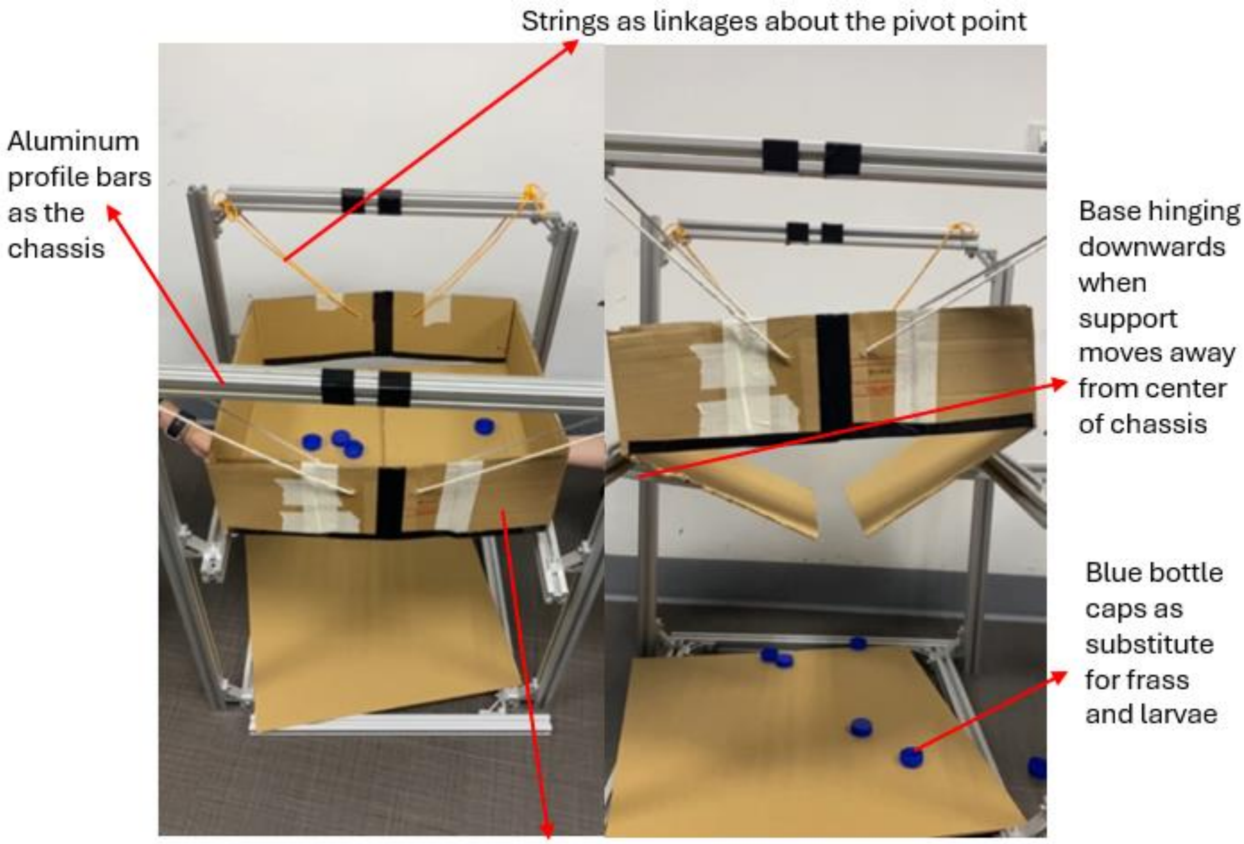


Figure 30. Prototyping of design three.

To prototype the third design, we simulated the base of the container to pivot downward on both sides, employing hinges positioned at the container's far ends. This mechanism facilitates the opening of the base, enabling the controlled descent of frass and larvae (illustrated by blue bottle caps), guiding their transfer into the subsequent container located below.

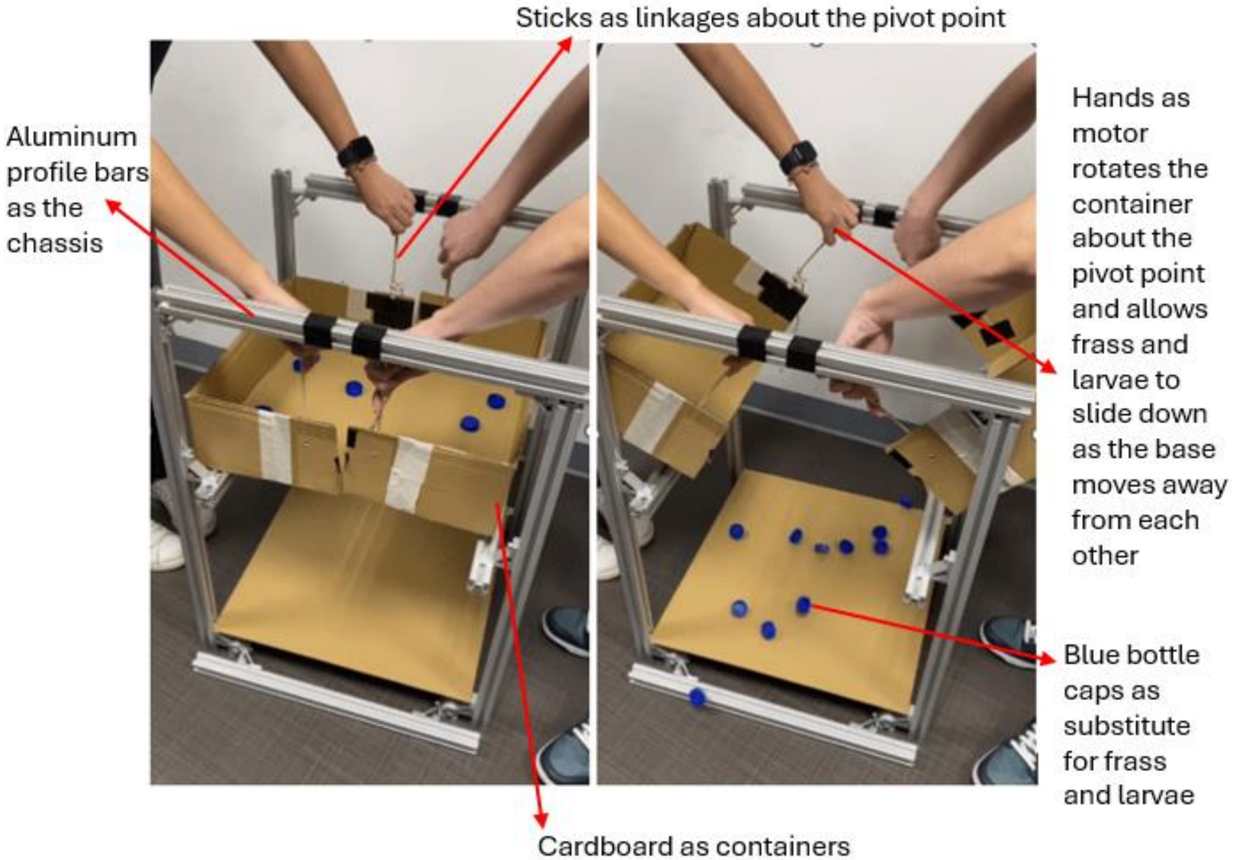


Figure 31. Prototyping of design four.

For design four, manual manipulation was employed to handle the containers, pivoting them apart to establish an opening at the base. This deliberate opening facilitated the controlled movement and descent of the frass and larvae, symbolized by blue bottle caps, guiding their directed drop into the subsequent container positioned below.

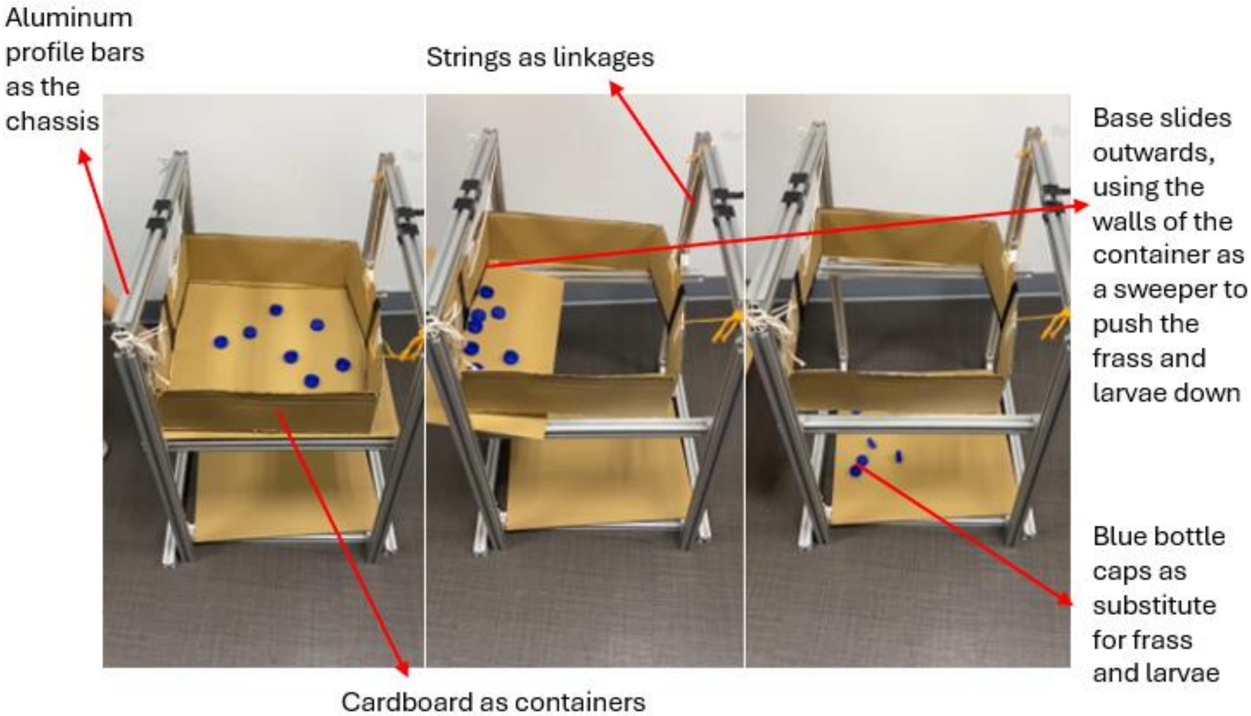


Figure 32. Prototyping of design six.

To prototype design six, a key feature entails a completely detachable bottom section integrated into the container. This feature initiates during the unloading process by manually extracting the bottom section from the container's side. This action enables the controlled movement of frass and larvae (represented by blue bottle caps), guiding their gradual descent toward the lower container situated underneath.

3.8.4 Unloading Concept Design Evaluation

Referenced in Section 3.8.2, our examination of unloading design concepts revealed two primary trends: elevating the container's sides and separating the container's base. To enhance our design visualization and decision-making process, we employed computer-aided design (CAD) software. This tool enabled us to meticulously explore and refine these concepts, ensuring a comprehensive understanding of their mechanisms and potential integration into our final design.

3.8.4.1 Elevating Container’s sides (Pivot system)

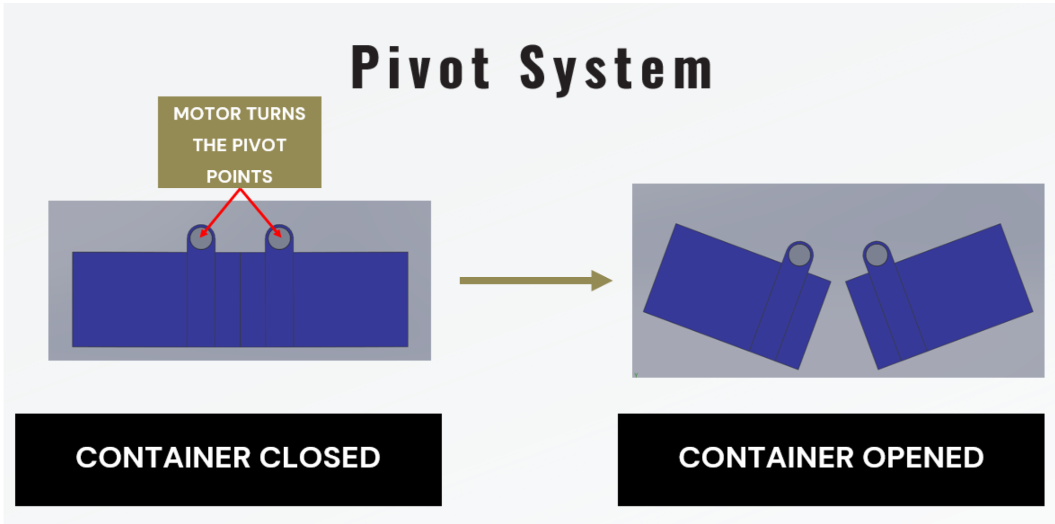


Figure 33. Elevating container's sides for opening and closing.

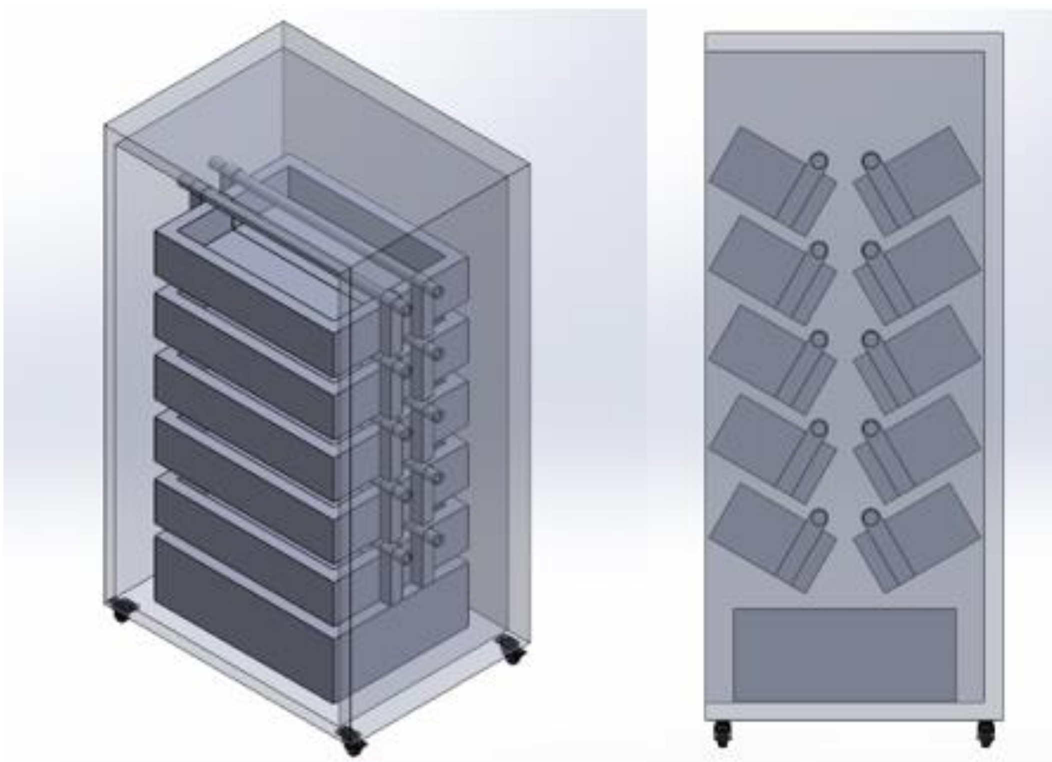


Figure 34. CAD design for pivoting system.

During our rapid prototyping phase, several cardboard prototypes were created to evaluate various options' feasibility. We directed our focus towards exploring design four, featuring a pivot system enabling the controlled manipulation of container openings and closures, illustrated in figure 32. Furthermore, to offer a comprehensive visualization of the reactor's overall structure, a Computer-Aided Design (CAD) model was developed specifically for design four.

3.8.4.2 Separation of Container base (Roller system)

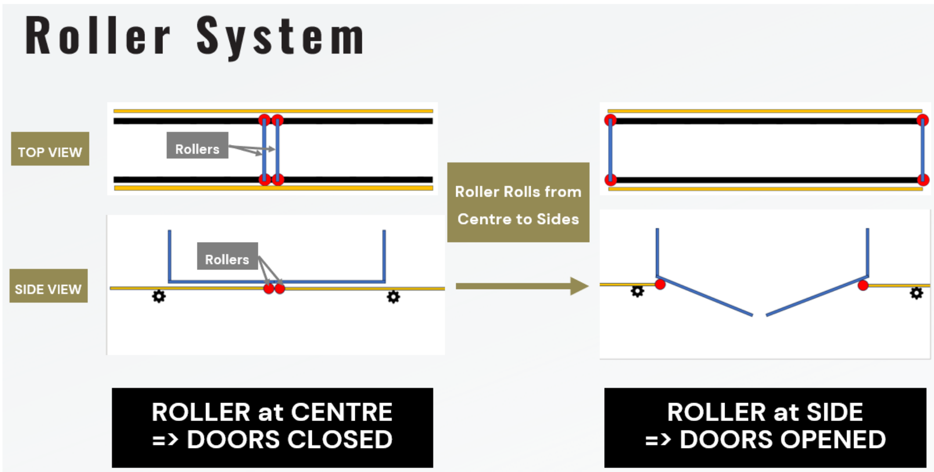


Figure 35. Roller system opening and closing.

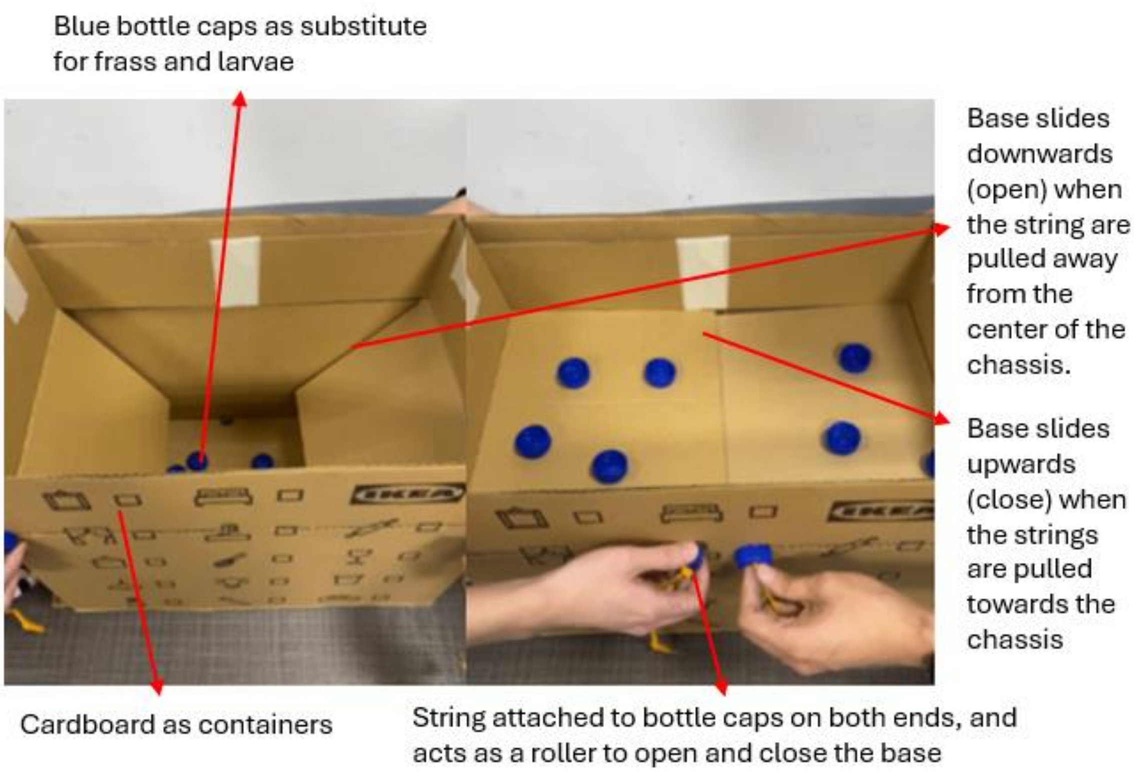


Figure 36. Roller system prototyping.

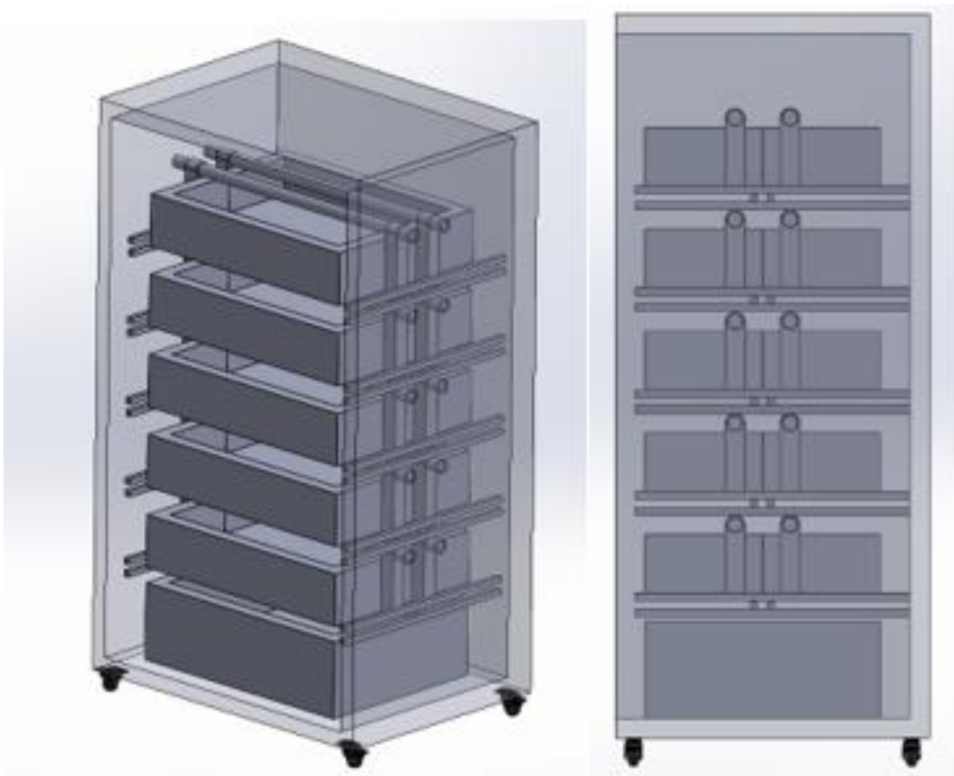


Figure 37. CAD design for Roller system.

After conducting calculations (refer to Appendix 7.3), it became apparent that implementing the pivot system would be impractical due to the torque needed to move the container from the motor, posing a constraint within our limited project budget. Consequently, we shifted our focus towards exploring an alternative design that requires reduced torque, allowing the use of a cost-effective motor if needed. This redirection led us to investigate the roller system, utilizing a roller-type system to enable the container bottom's movement, facilitating the required gap.

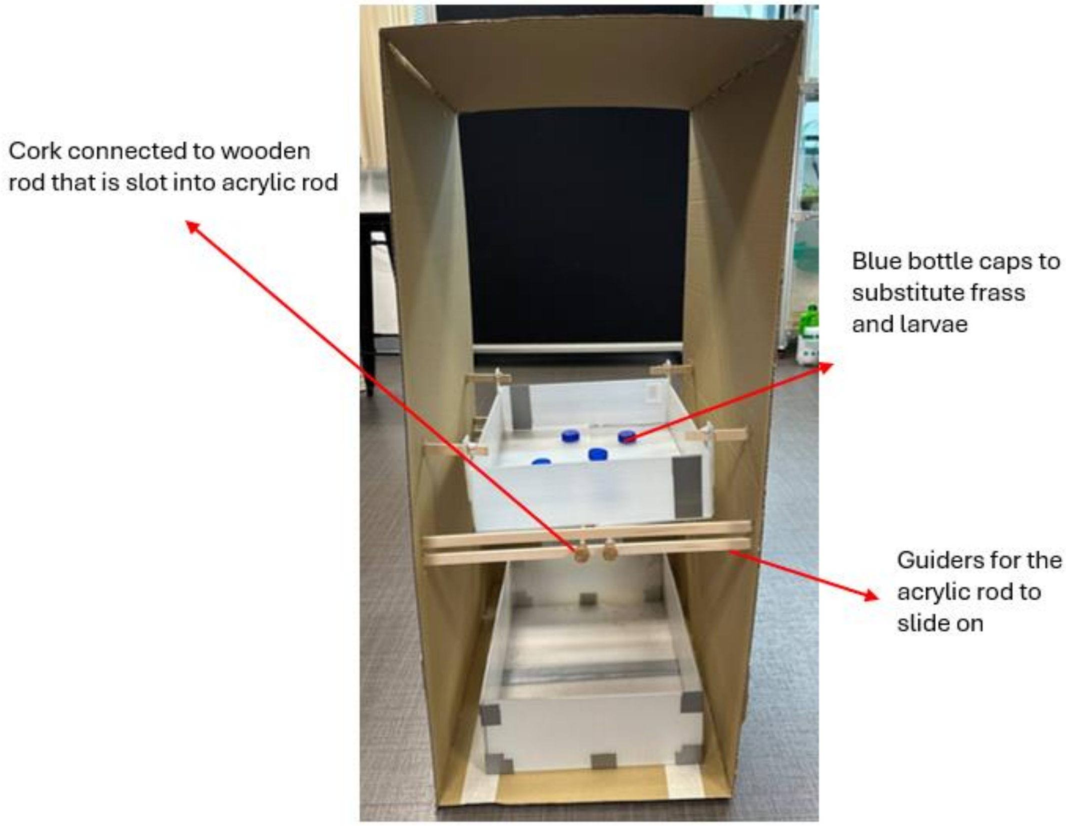


Figure 38. 1:2 scale prototype of Roller system.

In our pursuit, we crafted a 1:2 scale prototype to conduct meticulous and practical evaluation of the design's capabilities and addressing potential obstacles. Employing corrugated board for the containers aligned with our criteria, given its robustness, durability, waterproof nature, and smooth surface conducive for the seamless movement of frass and larvae. To simulate the roller system more accurately, we implemented a wooden solid rod inserted through an acrylic rod, allowing for slight movement with cork stoppers on either side. This configuration closely emulates a rolling pin, minimizing friction between the rollers and the container's base. Such a mechanism reduces the effort required for roller actuation by enabling a turning motion rather than dragging, enhancing the efficiency of the system.

3.9 Angle of Tilt Experiment

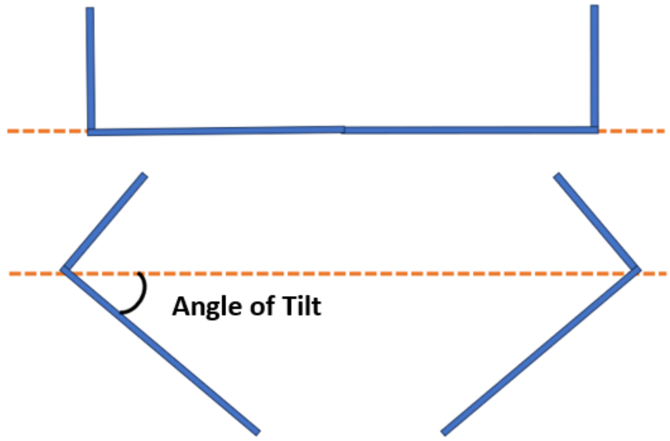


Figure 39. Angle of tilt of container.

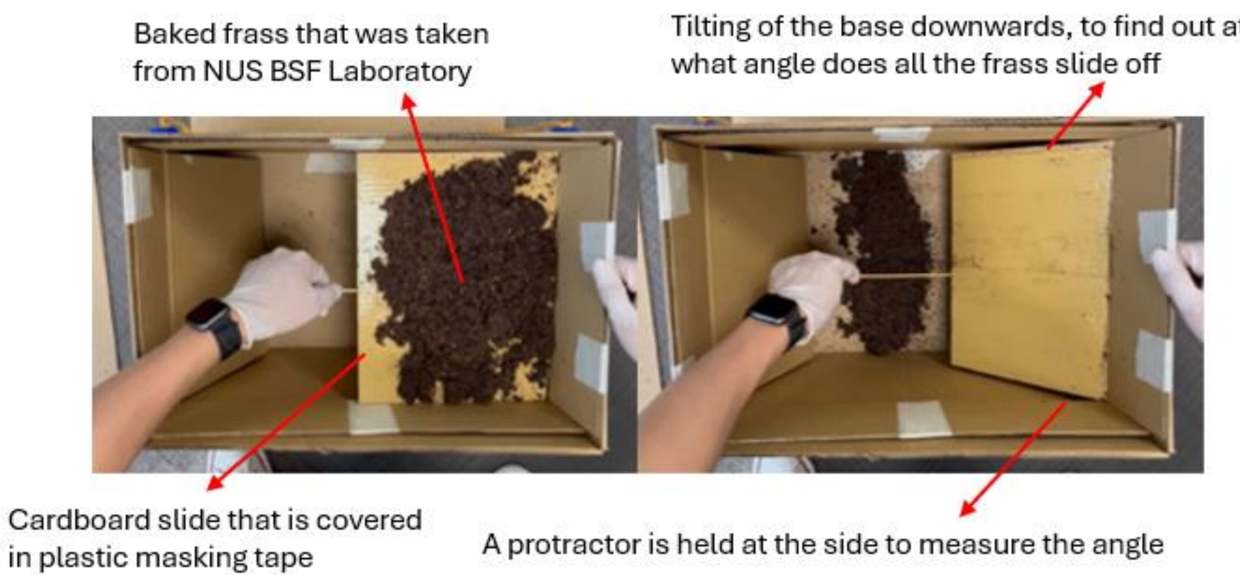


Figure 40. Angle of tilt experiment.

We also recognized the significance of determining the necessary tilting angle for the containers to ensure the efficient discharge of frass and larvae, considering its impact on space requirements between containers and the torque needed to operate the bottom of the container. To address this, we conducted an experiment using the cardboard prototype. This experiment aimed to ascertain the precise degree of tilt required for the effective release of frass and larvae, providing crucial insights into optimizing the design for practical implementation. We concluded that for a smooth surface like plastic, the angle at which 99% of frass slides down to the bottom is 50 degrees. (Refer to Appendix 7.4 for test results)

3.10 First Iteration of Final Design

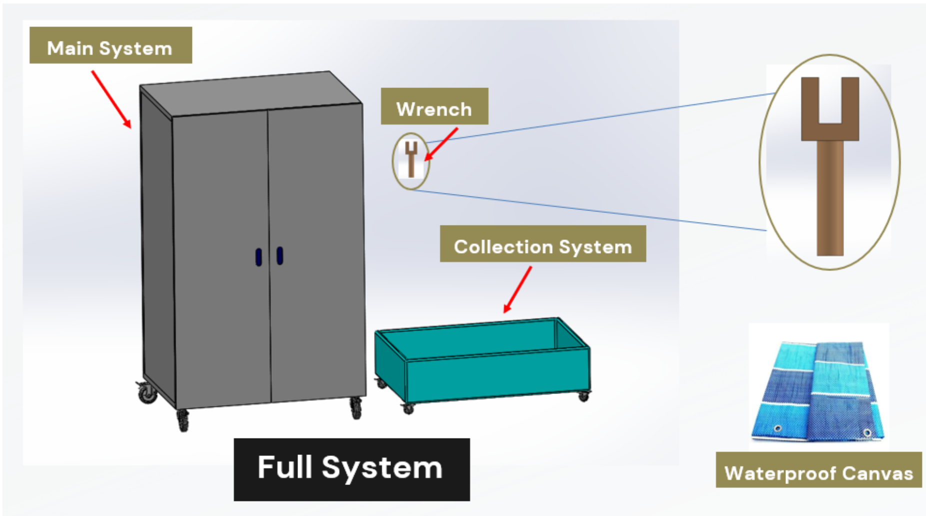


Figure 41. First Iteration of Final Design.

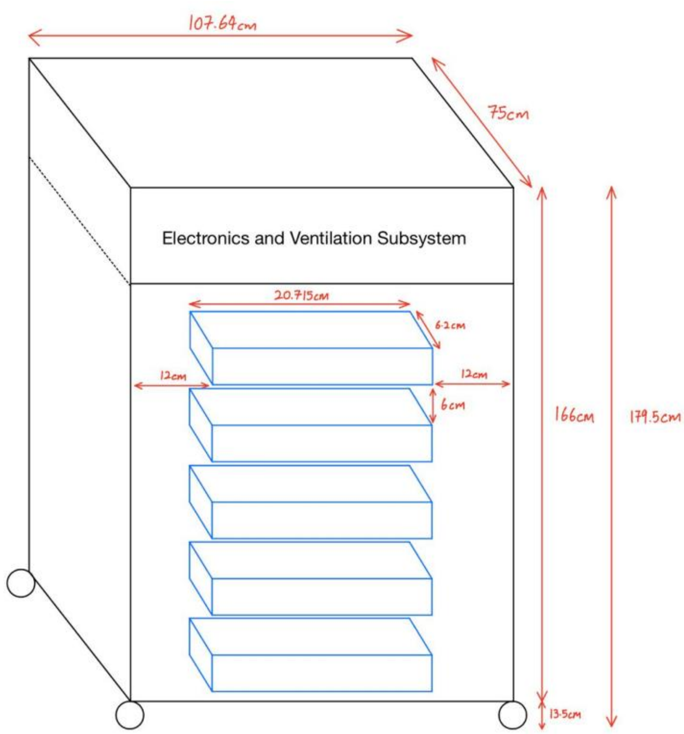


Figure 42. Dimensions for First Iteration.

Despite significant efforts to reduce the required torque to a mere fifth of the original design, the cost implications remain prohibitive and exceed our budgetary constraints. Consequently, we opted for an alternative approach, shifting our focus away from motorized systems to prioritize minimizing physical labour for the workers involved. This redirection led us to devise the schematic depicted above, outlining our envisioned first iteration design for the comprehensive system. The design consists of two subsystems: the primary system comprising the chassis and containers responsible for holding the food waste, and the collection system dedicated to facilitating the unloading of frass and larvae post-treatment. Our proposed solution involves using a waterproofing canvas during unloading, wrapped around the unloading container to effectively channel the frass and larvae into the collection system. (Refer to Appendix 7.5 for calculations)

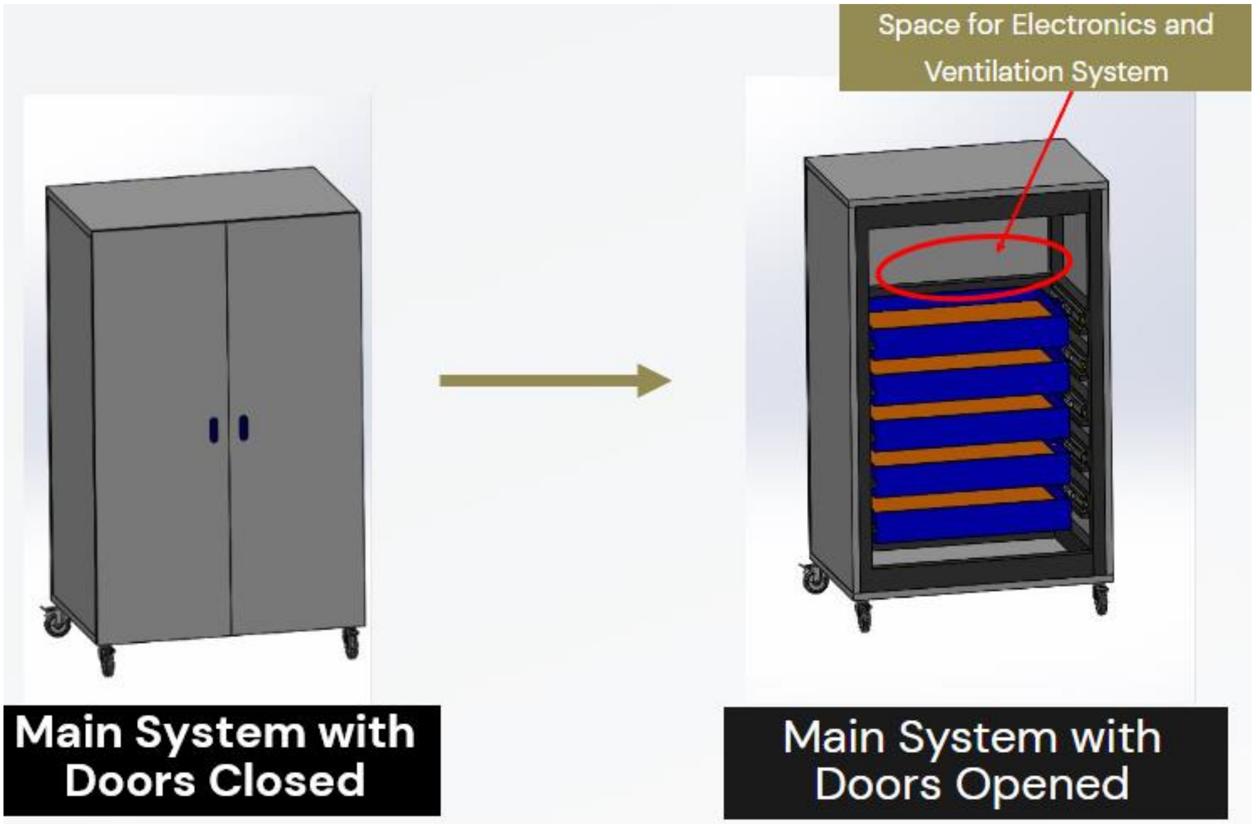


Figure 43. Opening and closing of first iteration.

Within our primary system, once the doors are closed, the internal environment becomes enclosed. The upper space is designated for accommodating electronics and ventilation systems within the reactor. Our electronic system plays a pivotal role in monitoring and effecting necessary adjustments to optimize the environment conducive for the BSFL. This optimization expedites their feeding process, consequently reducing the overall treatment time significantly.

The container's dimensions are constrained by the optimal height necessary to accommodate the food waste, set at 6 cm (Adrian Fuhrmann, personal communication, October 2023), leaving us flexibility only in adjusting the length and width to align with our specific requirements. As a result, our first iteration design comprises five containers housed within the chassis of our main system, measuring 80x50x6cm each. These containers can hold up to 40kg individually, which requires approximately 33,500 larvae per container [30], resulting in a cumulative storage capacity of 200kg for the entire system. (Refer to Appendix 7.6 for calculations)

Figure 44. First Iteration design of loading system.

The loading process onto the container involves several sequential steps. Initially, the reactor doors are opened, followed by the unlocking of the drawers to slide the container out from the chassis. Once out of the reactor, the drawers would then need to be locked in place. Subsequently, the loading of food waste onto the containers, along with the addition of BSFL, takes place. After the containers are loaded, the drawers are unlocked, allowing them to slide back into the reactor, and subsequently, the drawers are locked back into position. Finally, the process concludes with the closure of the reactor doors.

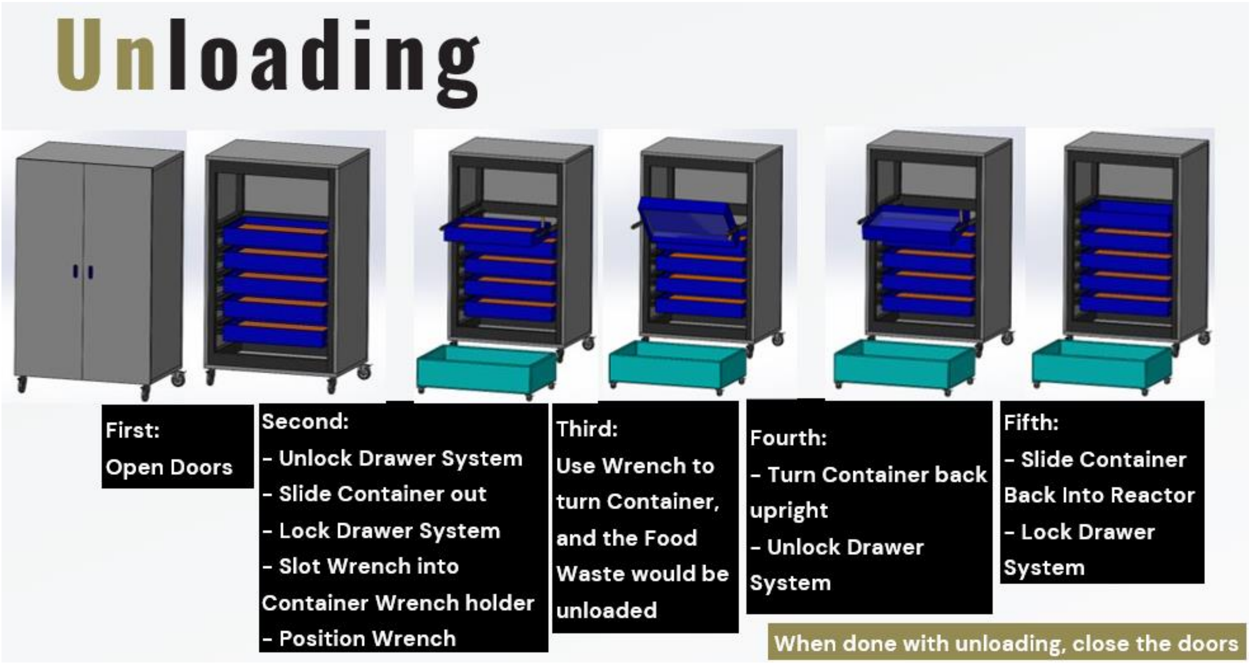


Figure 45. First Iteration design of unloading system.

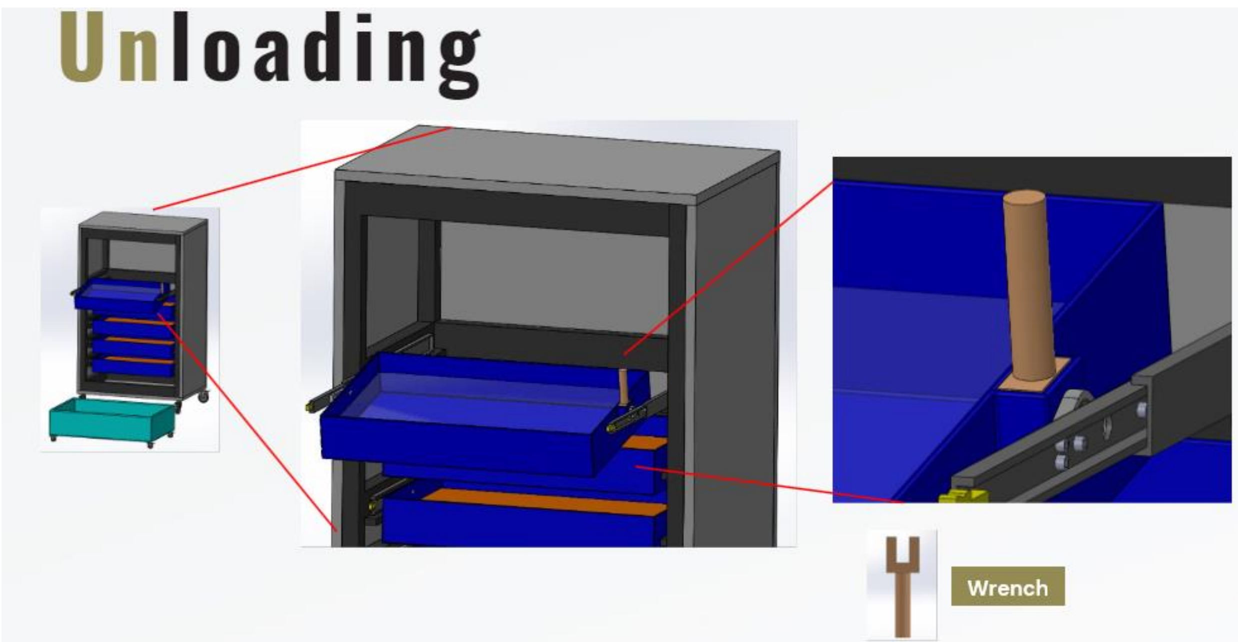


Figure 46. Close up view of wrench system

In our unloading system, the initial steps align with the loading process, requiring the opening of the reactor doors to access the containers. Similarly, unlocking the drawers facilitates sliding the containers out of the reactor, subsequently securing the drawer system in place. However, the unloading procedure diverges at this juncture. Firstly, a waterproof canvas is attached around the container. Following this, a wrench is inserted into a specially designed holder on the container, serving as the pivotal point for rotating the container. This rotation facilitates the controlled unloading of its contents, guided by the waterproof canvas down to the collection system. Subsequently, the canvas is removed, and the container is rotated back to its initial position. By repeating the initial few processes, the container is returned to its original placement inside the reactor with the reactor doors closed to complete the process.

4. Final Design

4.1 Final Design in CAD

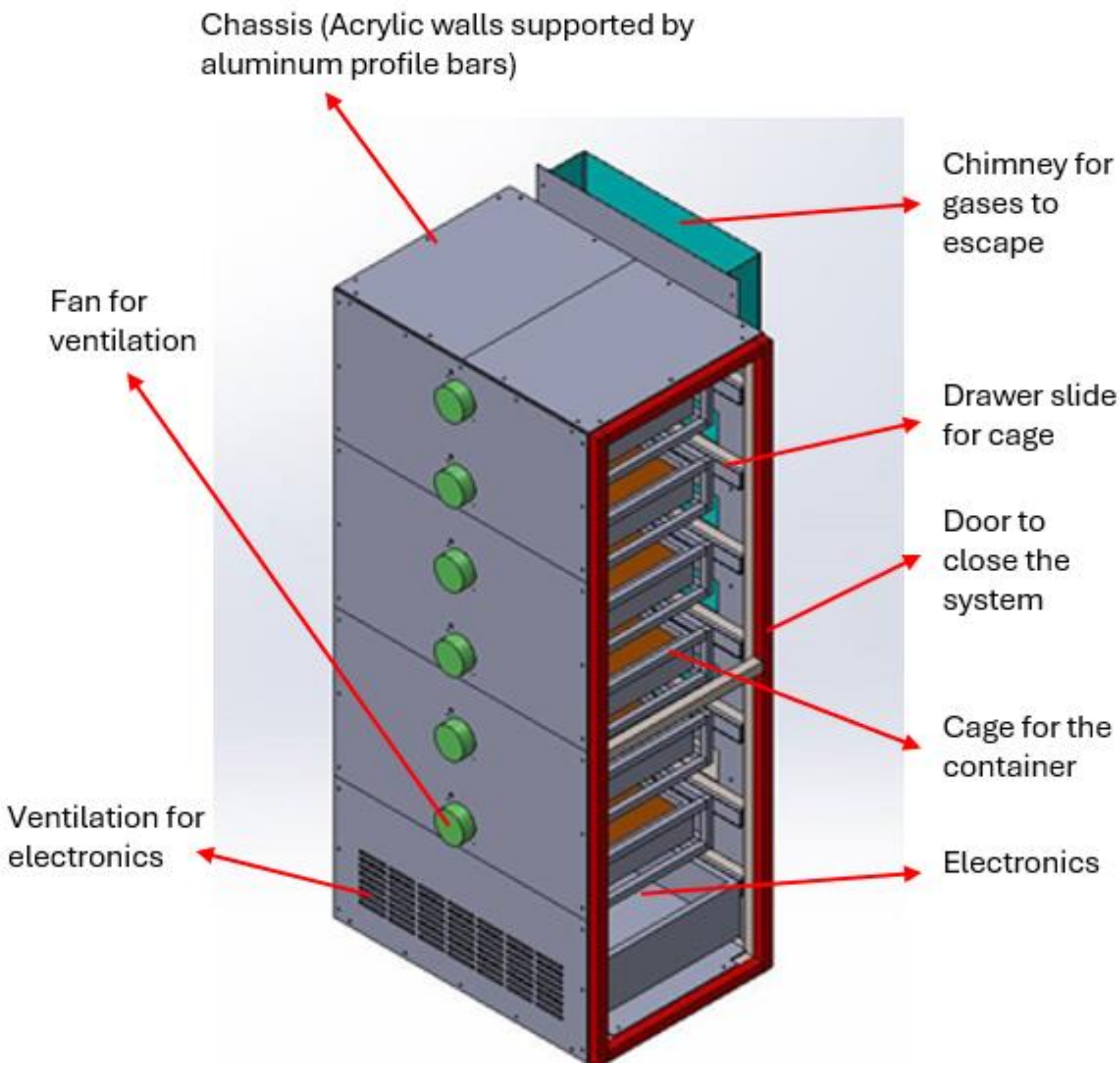


Figure 47. Final Design done in CAD.

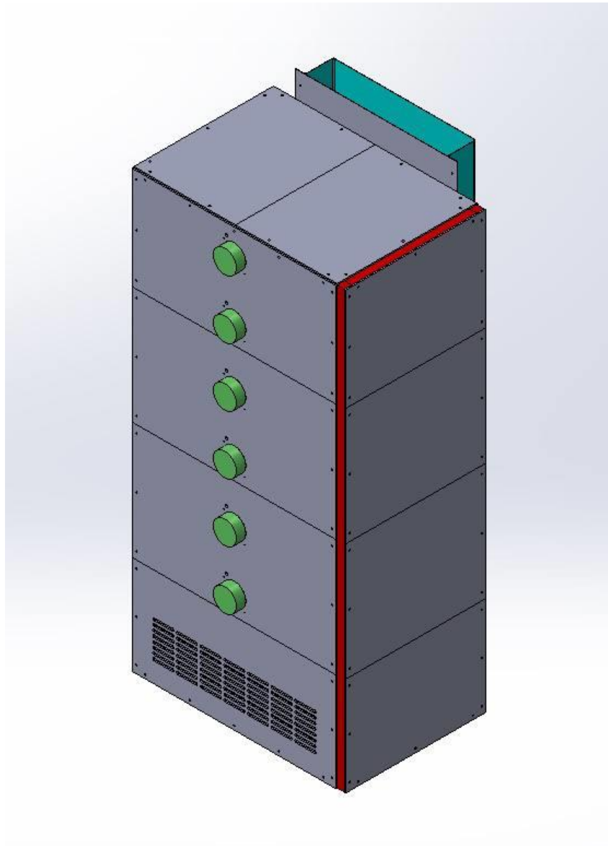


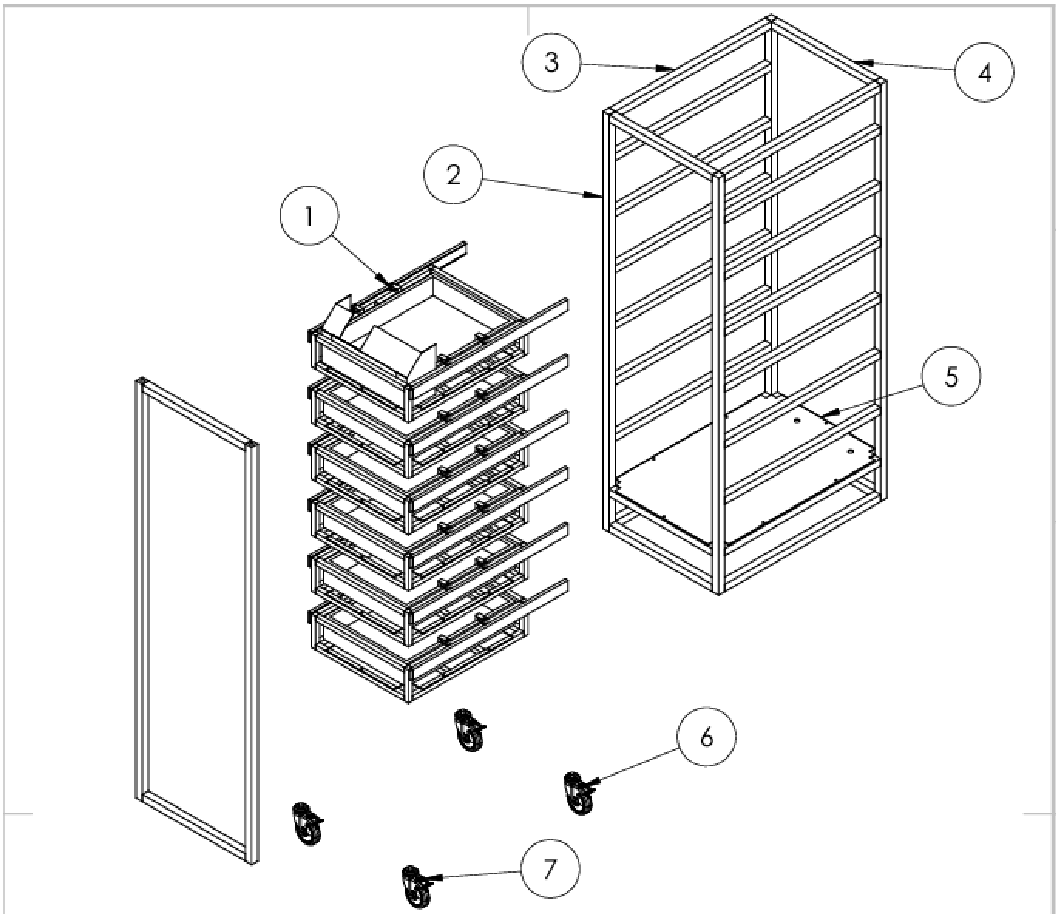
Figure 48. Final Design in CAD (Closed system).

In refining the final design from its initial iteration, several key adjustments were made to better align with the constraints and objectives of our project. The chassis underwent a significant resizing, with the decision to utilize laboratory containers and alter the number of containers employed. This led to the final design being scaled down to one-third of its original size, incorporating six containers. To mitigate the risk of corrosion or malfunction due to rising internal gases such as methane, the electronics were strategically placed at the bottom of the setup.

These modifications were largely influenced by the limited resources available to our team. Specifically, the availability of larvae from the laboratory is constrained by the dual needs of supporting our project and fulfilling the laboratory's own research requirements, given that the larvae are produced on a scale intended for research rather than mass farming. Additionally, the fabrication lab faces its own limitations, needing time to order and produce the materials we require while simultaneously handling requests from numerous other projects.

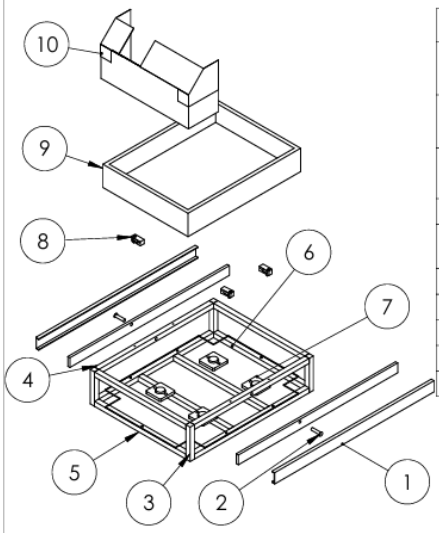
In response to these challenges, we opted to scale down the design of the reactor to one-third of its original size. This decision was driven not only by the need to adapt to the limited availability of larvae and fabrication resources but also by the goal of creating a reactor that serves the research community effectively. By doing so, we ensure that the reactor can be a valuable tool for laboratory researchers, facilitating experiments and data collection aimed at optimizing the reactor's performance. This strategic approach allows us to contribute meaningfully to the ongoing development of sustainable waste management solutions within the constraints we face.

4.2 Breakdown of Individual Components in Final Design



ITEM NO.	DESCRIPTION	QTY.
1	Drawer slide + cage + container	6 set
2	30 by 30 aluminium profile height bar (1750mm)	6
3	30 by 30 aluminium profile length bar (755mm)	18
4	30 by 30 aluminium profile breadth bar (500mm)	8
5	Electronic divider plate	1
6	Light duty caster wheel (with lock)	2
7	Light duty caster wheel (without lock)	2

Figure 49. Exploded view on CAD for overall chassis.



ITEM NO.	DESCRIPTION	QTY.
1	Drawer slide	1 pair
2	Pivot screw	2
3	20 by 20 aluminium profile height bar (140mm)	4
4	20 by 20 aluminium profile length bar (540mm)	4
5	20 by 20 aluminium profile breadth bar (430mm)	6
6	Arcylic plate	1
7	Load cell with holder	4
8	Stopper	4
9	Container	1
10	Guider	1

Figure 50. Exploded view on CAD for the drawer slide, cage, container and guider.

The accompanying illustrations provide detailed exploded views of our project's chassis and the constituent parts of the cage. Each diagram meticulously outlines the placement and specifies the quantity of each component, serving as a visual reference for subsequent sections of this report. In these forthcoming discussions, we will delve into the rationale behind the selection of each component, examining their roles and contributions to the overall design. This analysis aims to offer insight into the decision-making process, highlighting how each part's functionality and characteristics informed our choices, ensuring the system's efficacy and efficiency in its intended applications. (Refer to Appendix 7.7 for detailed dimensions)

4.2.1 Container

Figure 51. Containers from NUS BSF Research Laboratory.

In the preliminary stages of our project, we aimed to customize our containers with an additional wrench holder. This ambition led us to confront the complexities and costs associated with custom designs, particularly the need for unique molds. The expense of these molds, escalating with design complexity, made small-scale customization financially impractical due to high initial costs. Moreover, the process of custom design, from concept to production, is time-consuming and fraught with potential delays due to necessary revisions. Attempts to find manufacturers willing to undertake small quantity customizations were met with resistance, and the few agreeable quoted high prices.

Considering the long-term application of our reactor, we opted for the use of existing lab-standard container boxes, anticipating the scalability of this solution. This approach significantly enhances the feasibility of sourcing materials in large-scale operations, ensuring that these components can be easily obtained as needed. By integrating readily available boxes, we secured the project's sustainability and practicality, capitalizing on their established reliability and efficiency. This strategic decision aligns with our objectives to maintain budgetary and timeline constraints, effectively circumventing the challenges associated with custom fabrication. Thus, this choice not only supports the project's immediate needs but also its future expansion and adaptability.

4.2.2 Cage

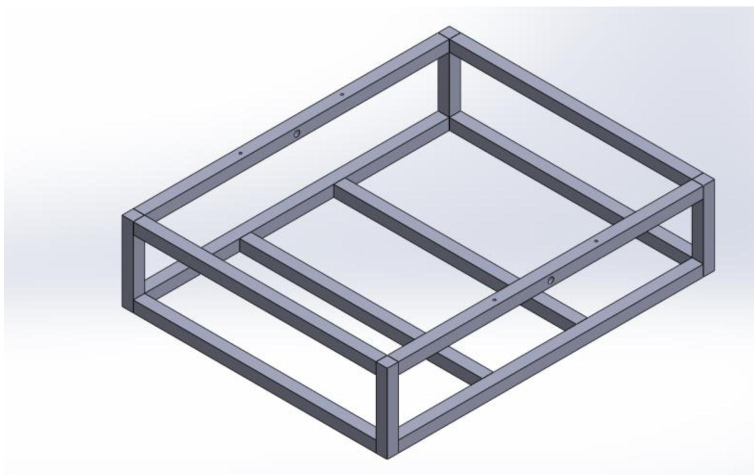


Figure 52. Cage design in CAD.

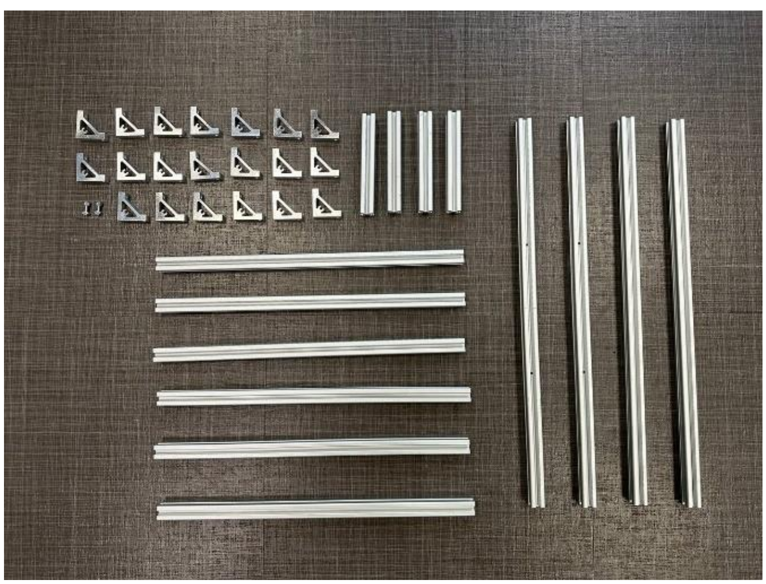


Figure 53. Fabricated parts for the cage.

Figure 54. Side view of assembled cage.

Figure 55. Top view of assembled cage.

Our project then focused on developing a secure yet easily detachable method for attaching the container to the drawer system, aimed at simplifying the cleaning process after each use. Initially contemplating direct mounting, we instead designed a supportive cage. This solution ensured the container remained stable and level during operation, while also enabling easy rotation for efficient unloading. This design innovation facilitated the containers' removal for cleaning, significantly enhancing the system's usability and maintenance efficiency.

In the selection of materials for the construction of the cage, the decision was made to utilize 20 by 20 aluminum profile bars. This choice was informed by the material's comparative lightness against alternatives such as steel, thus facilitating ease of manipulation and assembly. The aluminum's advantageous strength-to-weight ratio was deemed adequate for the demands of our application, ensuring durability without the penalty of increased weight. Moreover, aluminum's amenability to machining processes — including cutting, drilling, and precision shaping — was a critical factor in its selection. This attribute is of particular importance to our project, as it allows for swift and straightforward modifications to be made, should they become necessary. The ease of adaptability and modification provided by aluminum significantly contributes to the overall efficiency and flexibility of the design process.

For the construction of the surrounding structure, a total of eight aluminum profile bars were utilized, with an additional two bars strategically placed in the center to evenly distribute the container's weight within the cage. The dimensions of the laboratory-provided container are as follows: length 53 cm, width 40 cm, and height 9.5 cm. In contrast, the dimensions of the designed cage measure 58 cm in length, 47 cm in width, and 14 cm in height. This discrepancy in width between the container and the cage is deliberate, designed to accommodate the pivot screws. The inclusion and function of these pivot screws within the cage's design will be elaborated upon in subsequent sections.

4.2.2.1 Load Cell and Acrylic mounting plate

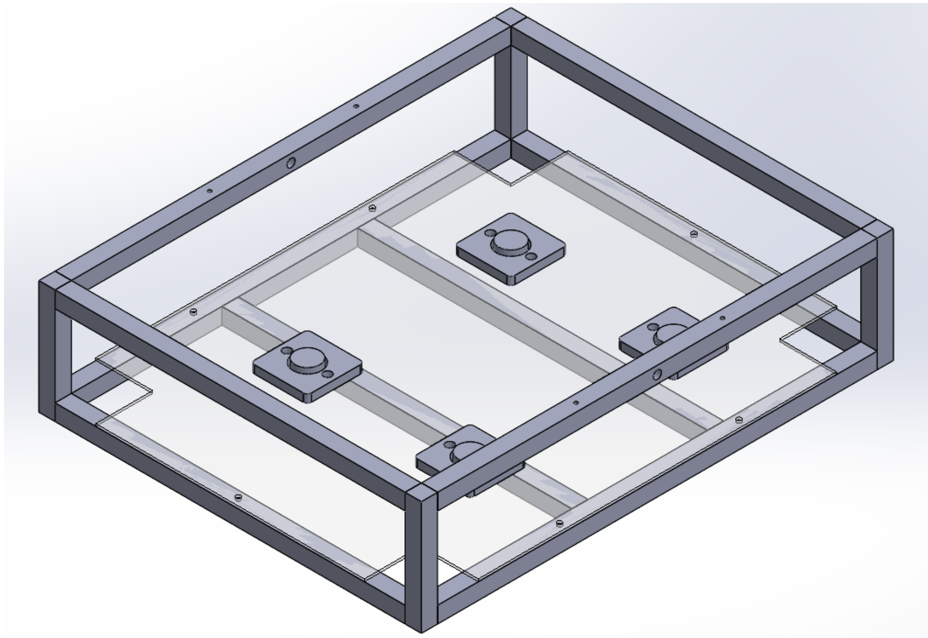


Figure 56. Load Cell with Acrylic Mounting plate with cage design in CAD.

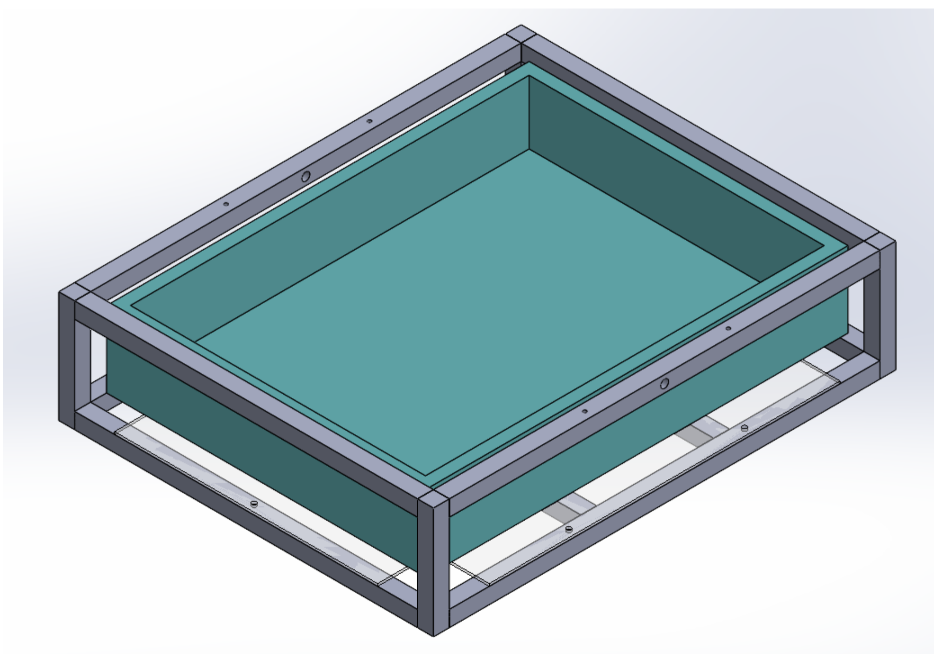


Figure 57. CAD of container in the cage with Load Cell.

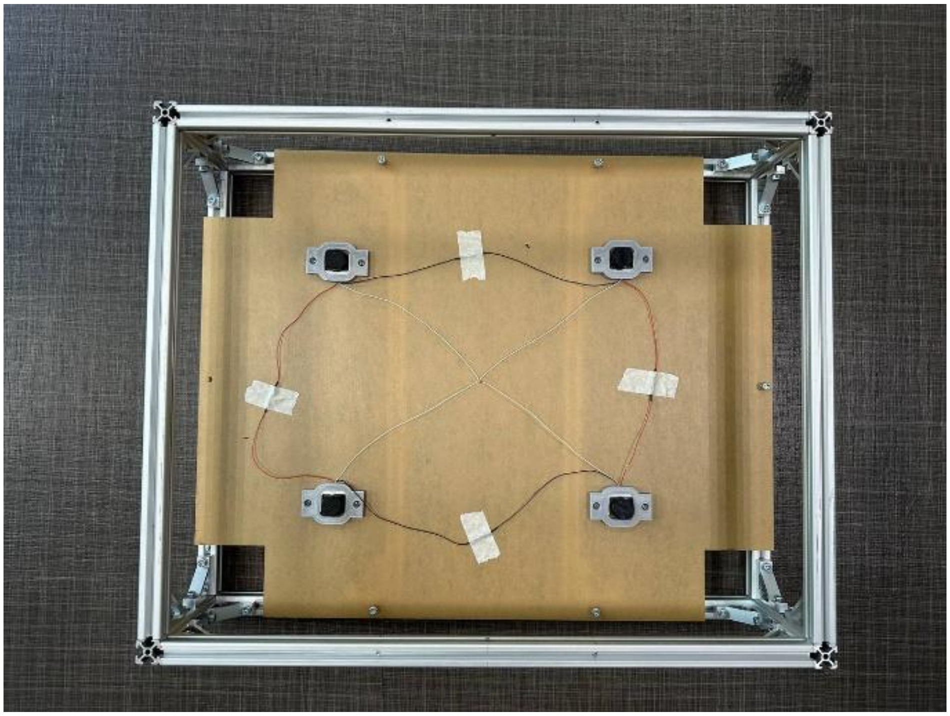


Figure 58. Assembled cage with load cell and acrylic mounting plate.

Figure 59. Assembled cage with load cell and fitting of container.

In the pursuit of precise efficiency assessment of our reactor, our team collaborated with the electronics department to identify the most effective method for monitoring the container's weight during the treatment process. The consensus was that the integration of load cells presented the most feasible strategy, enabling it to double as a precise weighing scale by facilitating uninterrupted weight measurement. This necessitated a design adjustment to the cage, specifically an increase in its height, to accommodate the installation of an additional acrylic plate. This plate is tailored to support the installation of four load cells and their holders, a setup that not only secures the assembly within the cage but also ensures the even distribution of the container's weight across the structure.

4.2.3 Drawer Slide

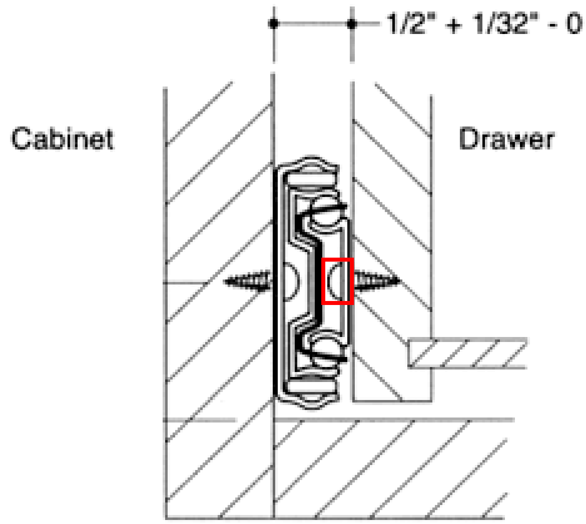


Figure 60. Cross section view of how drawer slide is connected.

Upon examining the finalization process for pivoting the cage, it became evident that our initial concept of employing a stainless-steel pivoting bar was flawed. The primary challenge lay in securely attaching the bar to the drawer slide, a task complicated by the minimal gap available for such an integration. For instance, when considering the cross-section of a standard drawer slide, as depicted in an earlier illustration, the highlighted red box indicates the maximum space available for affixing the bar to the drawer slide [31]. Any attempt to exceed this spatial allocation would interfere with the drawer slide's mechanism, rendering it impossible to extend the drawer. This realization prompted a reassessment of our approach to ensure the functionality of the drawer mechanism while accommodating the necessary pivot feature of the cage.

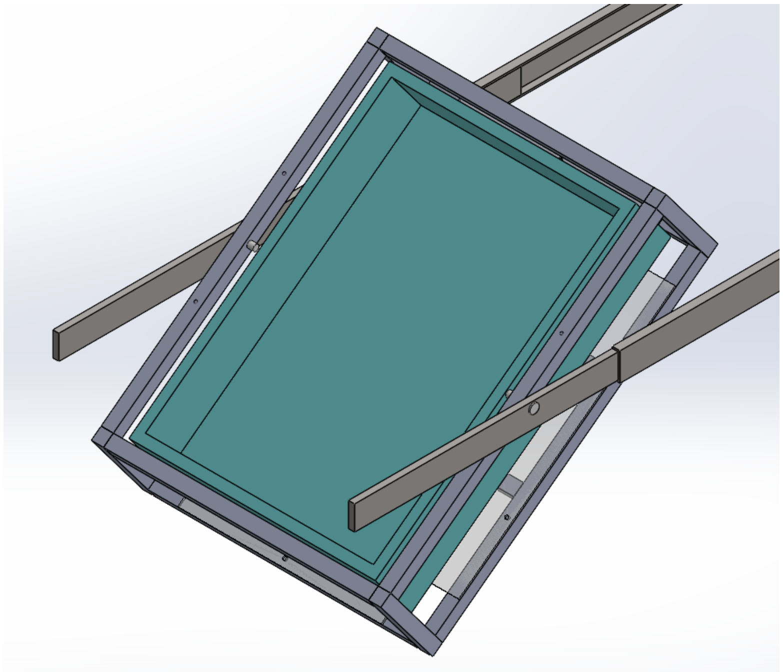


Figure 61. Drawer Slide connected to cage in CAD.

Figure 62. Drawer Slide connected to cage (external view of pivot point).

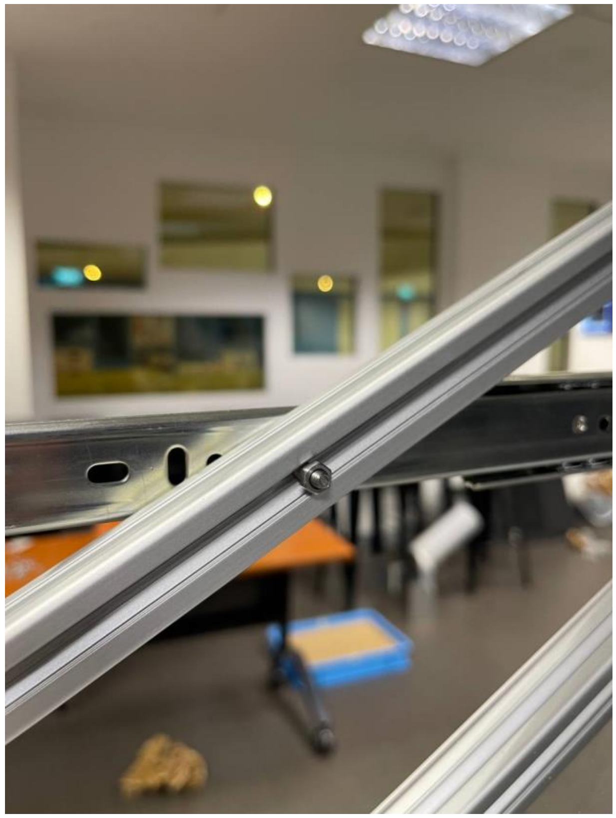


Figure 63. Drawer Slide connected to cage (Internal view of pivot point).

Consequently, our team opted for a pivot mechanism utilizing two screws to facilitate the cage's rotation on the drawer slide, a method detailed in the accompanying photo. This approach, favoring screws over rods, allows for the screw heads to be easily positioned on the side of the drawer slide, requiring only the securing of the screw's other end with two nuts. The feasibility of this method is further supported by the load-bearing capacity of the screws: a single M4 screw can withstand up to 214.7 kg, effectively doubling to 429.4 kg with two screws [32]. The cumulative weight of the cage (approximately 2.332 kg), the acrylic plate with a thickness of 3mm (approximately 0.91 kg), the container (approximately 0.5 kg), and the food waste within the container (approximately 8 kg) totals to about 11.742 kg. This total weight falls well within the load-bearing capacity of the two screws, ensuring their adequacy in supporting the cage. Detailed calculations supporting this conclusion are provided in the appendix for further reference, affirming the practicality and safety of the chosen pivot mechanism.

Figure 64. Different lengths and material drawer slide for comparison.

Figure 65. Mounting of drawer slide on aluminum profile.

In the process of selecting an appropriate drawer slide for our project, we prioritized two key factors. Firstly, the drawer slide needed to extend beyond the length of the cage to ensure unobstructed rotation, preventing any potential collisions with adjacent cages and allowing for a more compact arrangement. Secondly, the slide must possess the structural integrity to support the combined weight of the cage and container, which amounts to approximately 11.742 kg. By applying a Factor of Safety (FOS) of 2 to accommodate any unforeseen excess stress, the required weight capacity escalates to about 23.5 kg [33]. Therefore, the selected drawer slide must have a maximum weight capacity of 23.5 kg to meet our project's specifications and ensure reliable operation under the anticipated load.

During the procurement phase, we acquired two distinct types of drawer slides for evaluation: the first, a 76cm variant constructed from cold rolled steel, and the second, a 66cm option made from polyester [34] [35]. Despite the first drawer slide's advantages in terms of length and cost—being notably less expensive than its counterpart—its load-bearing capacity, ranging only between 10-15kg, raised concerns regarding its safety and suitability for our needs. Conversely, the polyester-made drawer slide, though more costly, boasts a substantial maximum weight capacity of 45kg. Given its alignment with our project's stringent safety and functional requirements, the decision was made in favor of the polyester drawer slide.

4.2.4 Chassis

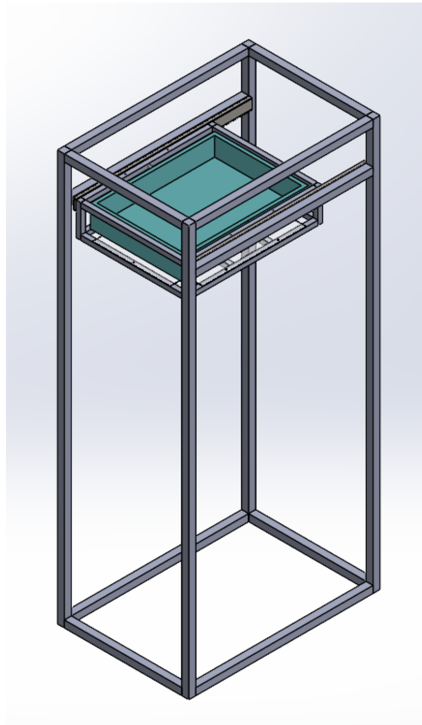


Figure 66. Structure of Chassis with one attached drawer slide, cage and container in CAD.

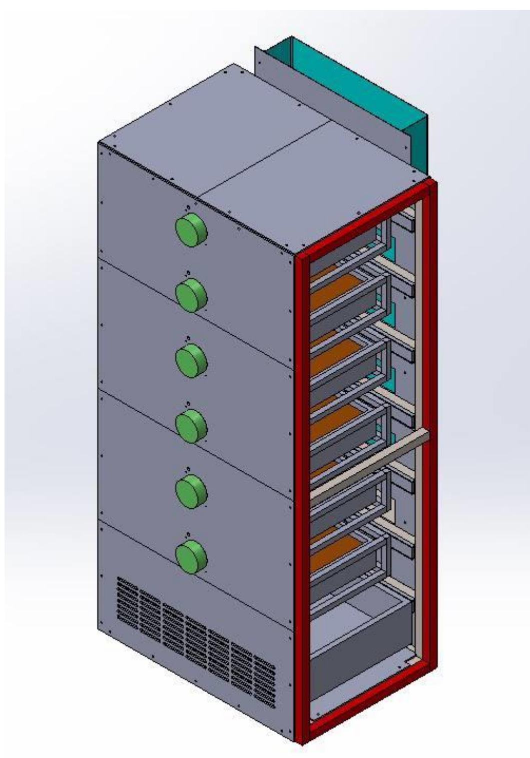


Figure 67. Configuration 1 (larger distance between cages).

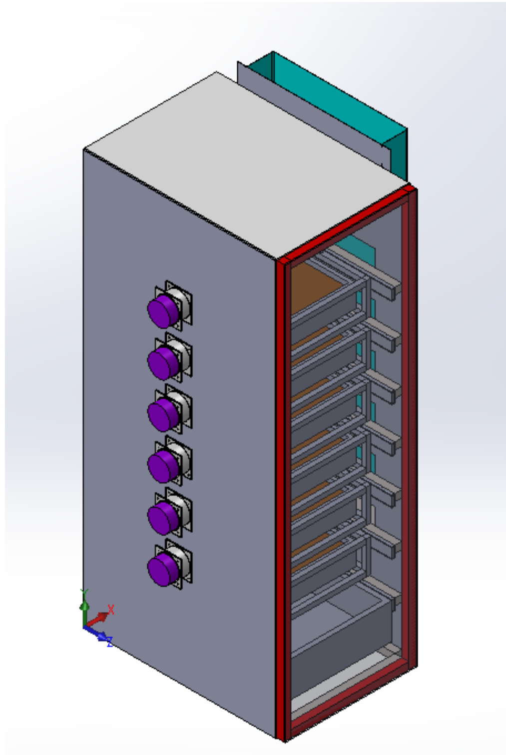


Figure 68.Configuration 2 (smaller distance between cages).

In the design of the chassis, our choice fell on 30 by 30 aluminum profile bars, selected for reasons akin to those guiding our use of 20 by 20 aluminum profile bars for the cage construction. The larger dimensions of these bars not only provide structural integrity but also significantly enhance the flexibility of our design. This flexibility is especially pertinent in the placement of drawer slides, which, thanks to the adjustable nature of the aluminum bars, can be modified as needed without being confined to a fixed height. Moreover, aluminum's inherent ability to form a protective oxide layer renders it resistant to corrosion, an attribute of paramount importance for our reactors. Given the potential exposure to corrosive gases produced by the BSFL over extended periods, the corrosion resistance offered by aluminum ensures the longevity and durability of the chassis, underscoring the material's suitability for our project's specific needs.

In further refining the design of our reactor, a deliberate decision was made to orient the cages on their longer side within the chassis, a modification aimed at achieving a slimmer profile. This adjustment facilitates the compact arrangement of multiple reactors when stacked side by side, an essential consideration for optimizing space utilization. This design choice was influenced by the necessity to adhere to the spatial constraints commonly encountered in lifts and pathways, leading to the establishment of specific dimensions for the chassis: a length of 81.50 cm, a width of 56 cm, and a height of 175 cm. These dimensions were meticulously calculated to accommodate six cages within the chassis, enabling us to explore two distinct configurations. This experimental approach was underpinned by preliminary simulations conducted by our team members, which suggested that the spacing between cages has a negligible impact on airflow distribution. Such findings prompted further investigation into how the chassis design could be optimized to house an increased number of cages without compromising on the environmental conditions essential for the reactors' operation, thereby enhancing our understanding of spatial efficiency in relation to reactor performance.

4.2.5 Cage Locking Mechanism

4.2.5.1 Iteration 1

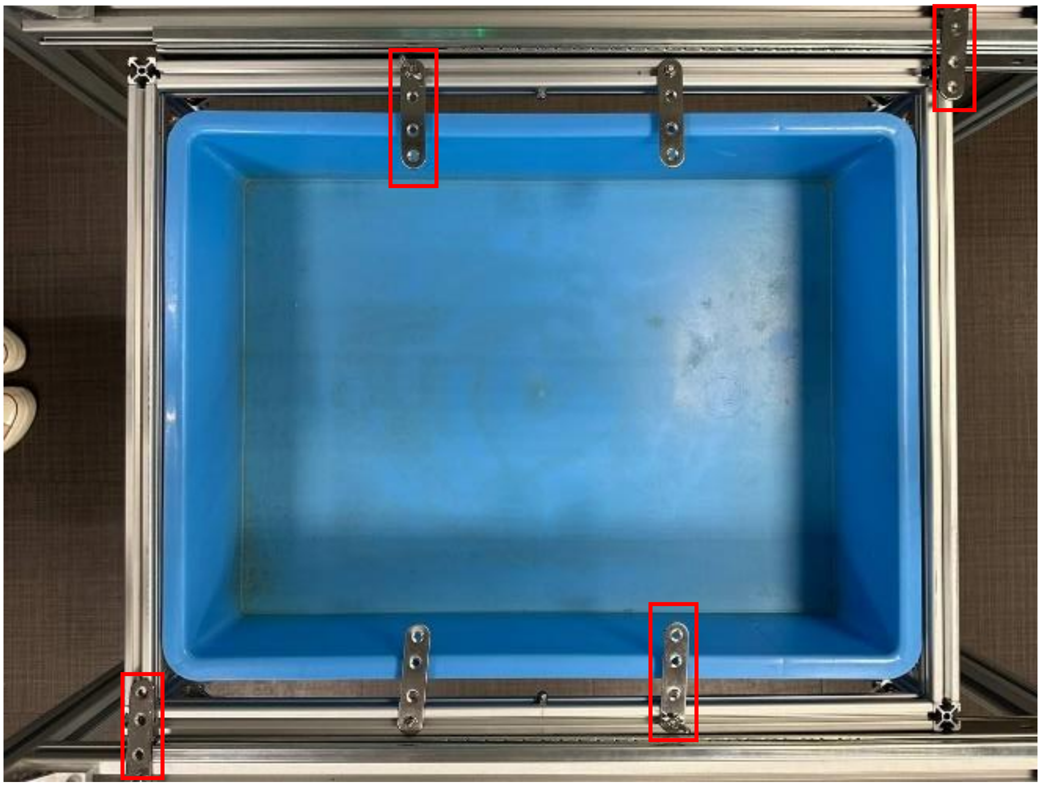


Figure 69. Top view of container locked in cage and cage locked on drawer slide (Iteration 1).

In designing our cage locking mechanisms, we concentrated on two main objectives. Firstly, it was imperative to ensure that the container remains securely within the cage during the rotation process involved in unloading, preventing the container from inadvertently falling out. Secondly, we sought to maintain the cages' stability after loading, ensuring they did not tilt and remained level within the chassis. In the first iteration of our design, as depicted in the provided photograph, we employed six steel straight brackets for this purpose. Four of these brackets were strategically positioned to secure the container during the unloading process, while the remaining two were utilized to stabilize the cage within the chassis, preventing any undesirable tilting movement.

Figure 70. Wingnut locking mechanism (locked container on the left, unlocked on the right).

Figure 71. Locking the cage in place.

For the rotation of the steel straight bracket to be accomplished, the wingnut must initially be loosened. This action enables the bracket to be rotated and adjusted to the preferred orientation. After making this adjustment, it is crucial to retighten the wingnut, securing the bracket firmly in its new position to ensure the bracket remains stable and does not shift out of alignment.

For the arrangement of the two outer brackets, it is feasible to keep the bracket furthest from the door in a fixed horizontal position, while the bracket closer to the door must be designed to be movable. The necessity for the nearer bracket to be adjustable stems from the requirement to withdraw the cage smoothly: this bracket must be shifted to avoid the wingnut on the cages from making contact with it, thereby ensuring the cage can be pulled out without encountering any obstructions.

4.2.5.2 Iteration 2

Figure 72. Custom spring-loaded stopper mechanism (left is unlocked, right is locked).

Figure 73. Custom spring-loaded stopper side view (unlocked).

Figure 74. Custom spring-loaded stopper side view (locked).

In our second iteration, we achieved a significant improvement by developing a custom stopper mechanism, fabricated using a Computer Numerical Control (CNC) machine from the central workshop. This innovative design introduces a more user-friendly and secure method of operation. With this advancement, the necessity to loosen a wingnut to adjust the bracket is eliminated. Instead, users can simply lift the stopper and rotate it to achieve the desired adjustment. The mechanism incorporates a spring to secure the stopper in its new position, and features an extrusion designed to interact with the crevices of the profile bar, ensuring it locks securely back into place. This enhancement, as illustrated in the accompanying photo, streamlines the process, making it quicker and safer while enhancing the overall user experience.

4.2.5.3 Final Iteration

Figure 75. Custom spring-loaded stopper slide view (final iteration).

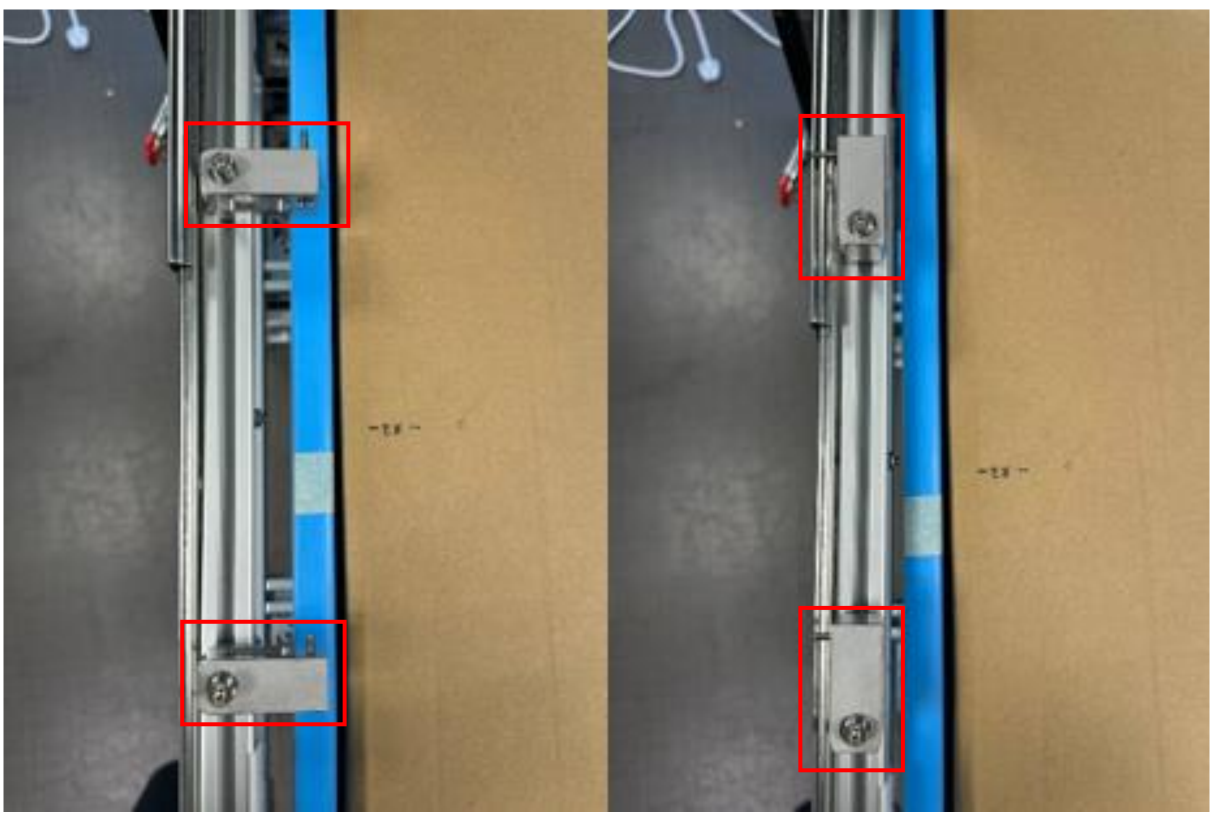


Figure 76. Assembled spring-loaded stopper on the cage (left is to lock the container, right is to lock the cage).

In our final iteration of the stopper design, we aimed to streamline the functionality to address both primary objectives with a single mechanism, thus eliminating the need for additional outer brackets. Unlike the second iteration, where the stopper served its purpose only when positioned horizontally to secure the container within the cage, we introduced a strategic enhancement. By incorporating a screw into the stopper, we effectively leveraged the same device for dual purposes. Now, when the stopper is oriented vertically, it also functions to prevent the cage from tilting within the chassis. This ingenious modification allows us to simplify the assembly from the initial setup—comprising four stoppers and two straight brackets in the second iteration—to a more efficient system with only four stoppers.

Further refining the user experience, we have also incorporated an indentation into the stopper design. This ergonomic feature provides users with an improved grip, facilitating the manipulation of the stopper with greater ease. This adjustment not only elevates the design’s practicality and efficiency but also significantly diminishes the system's complexity and the total number of components required. As a result, the modified stopper mechanism emerges as both more user-friendly and efficient, embodying a considerable advancement in the project's design optimization efforts.

4.2.5.4 Loading and Unloading comparison

Table 7. Comparison table for the different iteration of stoppers while loading.

Loading

1st Iteration	2nd Iteration	Final Iteration
1. Extract the Cage: Begin by pulling the cage out from the chassis to facilitate access.	As with the initial iteration	As with the initial iteration
2. Insert New Container: Place a new container within the cage, preparing it for loading.		
3. Load the Container: Fill the container with food waste and larvae, initiating the treatment process.		
4. Reposition the Cage: Gently push the cage back into the chassis, ensuring it is correctly aligned.		
5. Stabilize the Cage: adjust the outer steel bracket to the preferred position by loosening the wingnut. Once in position, retighten the wingnut to firmly secure the bracket. This adjustment ensures the cage remains stable and does not tilt within the chassis, maintaining consistent stability during the process.		Given the implementation of the stopper mechanism designed to prevent the cage from tilting within the chassis, Step 5 becomes obsolete. The stopper's strategic placement effectively ensures the cage's stability, negating the need for the outer steel brackets.

Table 8. Comparison table for the different iteration of stoppers while unloading.

Unloading

1st Iteration	2nd Iteration	Final Iteration
1. Adjust Outer Bracket: Loosen and then retighten the wingnuts on the outer steel bracket to allow cage extraction.	As with the initial iteration	With the design eliminating the need for outer brackets, the four stoppers are strategically positioned to prevent any tilting of the cage within the chassis.
2. Extract Cage: Pull the cage from the chassis for content access.		As with the 2nd iteration
3. Secure Inner Brackets: Adjust and secure the four inner steel brackets with wingnuts to keep the container in place during unloading.	3. Secure Container: Lift and rotate the stoppers to a horizontal position, effectively locking the container within the cage.	
4. Unload Contents: Rotate the cage to unload contents into the designated container below.	As with the initial iteration	
5. Unlock Container: Return the inner brackets to vertical to release the container.	5. Release Container: To unlock, rotate the inner stoppers back to their vertical orientation, allowing for the container's removal.	
6. Remove Container: With brackets adjusted, easily remove the container from the cage.	As with the initial iteration	
7. Return Cage: Push the cage back into the chassis, readying it for the next cycle.		

The comparative tables presented above delineate the evolutionary trajectory of our cage locking mechanisms across three distinct iterations. These tables not only highlight the specific differences between each version but also provide a clear, step-by-step guide on the operational procedures for engaging and disengaging the stoppers during both the loading and unloading phases. With each successive iteration, we have introduced enhancements aimed at refining either one or both of these critical processes. This iterative development culminated in the third and final iteration, which embodies the culmination of improvements made throughout the project's progression.

4.2.6 Wheels

Figure 77. Wheels without stopper.

Figure 78. Wheels with stopper.

In the development of our reactor, prioritizing portability led us to select light duty caster wheels, specifically chosen for their compatibility with the reactor's height restrictions and load-bearing capacity. The PTF-HS050-TPU model, with a height of just 71 mm, supports up to 50kg per wheel, enabling a combined maximum load of 200kg when utilizing four wheels. To enhance stability and control, we integrated the PTF-HL050-TPU wheels, identical to the HS050 model but featuring a built-in wheel brake to secure the chassis in place when stationary. Strategically positioning these braked wheels diagonally from one another ensures that the chassis can be firmly fixed in position as needed, thereby combining ease of movement with the ability to remain stationary, optimizing the reactor's functionality and user convenience. (Refer to Appendix 7.8)

Figure 79. Side view of wheels mounted to chassis.

Figure 80. Bottom view of wheel mounted to chassis.

To attach the wheels to our reactor, we utilized the central hole present in the 30 by 30 profile bars, employing an M10 x 25 mm countersunk screw for this purpose. This method of installation ensures a secure and stable connection of the wheels to the profile bar, facilitating both the mobility of the reactor and the structural integrity of the wheel assembly.

4.2.7 Electronics Divider Plate

Figure 81. Acrylic divider plate to separate the electronics section (back of chassis).

Figure 82. Acrylic divider plate to separate the electronics section (front of chassis).

In addition to structural considerations, we incorporated a divider plate into our design to isolate electronic components from potential gases emitted during the BSFL treatment process. This protective measure addresses the need to safeguard the electronic systems from the corrosive or potentially hazardous atmospheres that may arise. Furthermore, the inclusion of four holes at the back of the divider plate accommodates cable glands, which facilitate the passage of wires while offering protection. These fittings are essential for protecting delicate electrical wiring from environmental threats such as moisture, contamination, corrosion, and flammable gases, thereby enhancing the safety and longevity of the electronic systems integral to our reactor.

4.2.8 Experiment Profile Bar

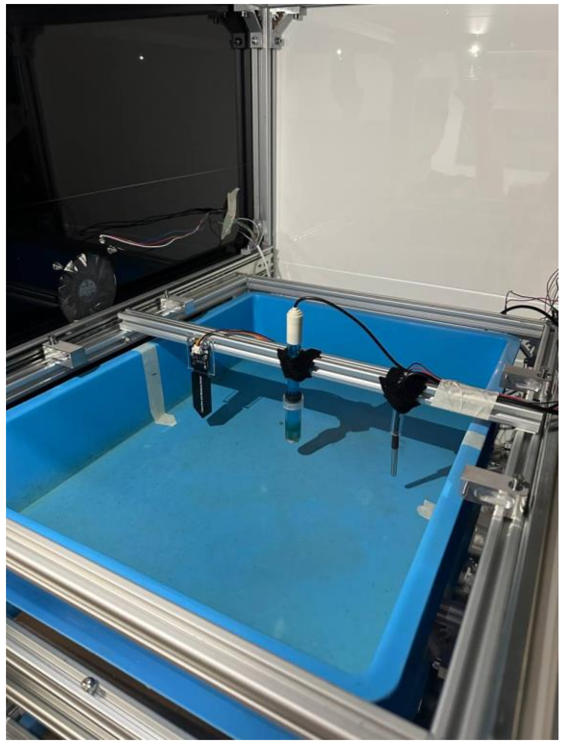


Figure 83. Experiment bar for sensors to be mounted on.

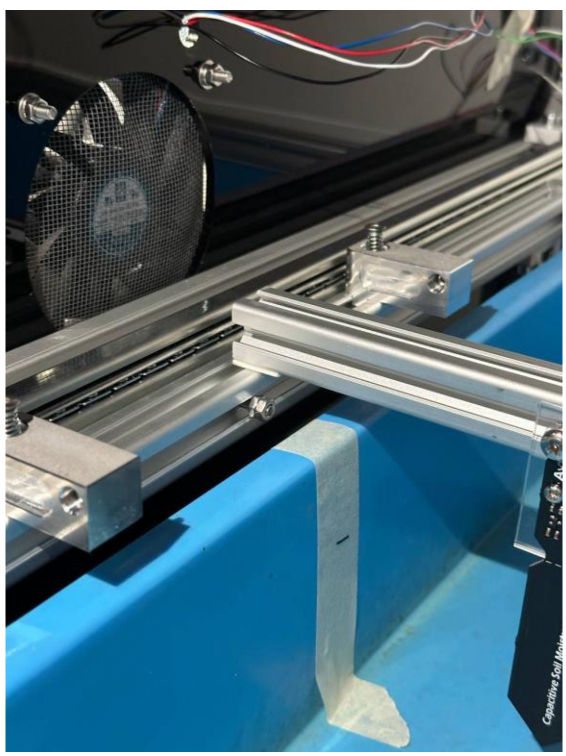


Figure 84. Close up photo of how to experiment bar sits on the cage.

We integrated a 20 by 20 aluminum profile bar into our design, which is strategically positioned along the two edges of the cage. This addition was specifically devised to facilitate the mounting of sensors by the electronics team, thereby significantly enhancing the system's versatility. The design of the profile bar allows for flexible positioning anywhere along the horizontal edges of the cage, accommodating various sensor configurations. Additionally, the sensors themselves can be mounted at any point along the profile bar, offering the electronics team the flexibility to optimize sensor placement based on the requirements of each experiment. This thoughtful integration underscores our commitment to adaptability and precision in the reactor's design, enabling a wide range of experimental setups to be explored and implemented efficiently.

4.2.9 Guider

Figure 85. Prototype guider to test effectiveness.

To enhance the efficiency and cleanliness of the unloading process, the implementation of a guider became essential. This necessity arose from observations during preliminary experiments, where the absence of such a device led to the scattered dispersion of remains, resulting in considerable mess. An initial trial utilizing a simple cardboard piece as a makeshift guider demonstrated that while the majority of the material successfully reached the designated container below, a significant portion missed the target, scattering across the surrounding area. The outcome of this experiment underscored the importance of a more effective solution to direct the contents precisely during the rotation of the cage. Consequently, we opted to design and fabricate a custom guider. This tailored approach aimed to streamline the unloading process, ensuring that the remains are neatly channelled into the unloading box below, thereby minimizing spillage and maintaining cleanliness throughout the operation.

Figure 86. Assembled guider.

Figure 87. Testing the attachment of the guider to the cage.

Figure 88. Testing the unloading of frass using the guider.

Inspired by the functional design of a French fry sorter, we crafted a similar guider with side walls precisely shaped to integrate seamlessly into the container, as demonstrated in the provided photo. The incorporation of an air conditioner duct vent, along with its connector, allowed us to devise a system that smoothly guides frass along the guider's side walls directly into the duct. A pivotal element of this design is the collapsible nature of the duct vent, which significantly broadens the guider's applicability to different cage configurations. This feature enables the duct vent to be adjusted in length to suit cages of varying heights, effectively channelling frass into the designated unloading container below, thereby mitigating spillage.

An additional innovative feature is the use of Velcro for attaching the guider to the cage, which facilitates easy attachment and removal while ensuring the guider remains securely in place during unloading. This inventive design not only facilitates a more efficient unloading process but also minimizes the need for subsequent cleanup by ensuring the frass is confined to a specific route, offering an efficient method for waste management during unloading activities.

4.2.10 Door

Figure 89. Unassembled acrylic door walls and door frame.

Figure 90. Assembled door with hinges.

Figure 91. Side profile of door hinge.

Figure 92. Top profile of door hinge.

For the construction of our door, we assembled a frame using four 30 by 30 aluminum profile bars and affixed acrylic panels on top to enclose the chassis effectively. To hinge the door to the chassis, we employed part PTA-H3030-8, a Plastic Hinge specifically designed for compatibility with 30 by 30 aluminum profile bars [36]. This hinge, combined with four M6 countersunk 16 mm screws and four M6 Rhombus Nuts, allowed us to establish a flush joint, ensuring the door sits perfectly aligned with the chassis without any gaps when closed. To adequately support the door's weight and maintain its alignment, we strategically placed three of these hinges along the door, spacing them equally to distribute the load evenly. This meticulous approach to the door's design and assembly ensures a seamless and secure closure, enhancing the overall functionality and aesthetic of the chassis.

Figure 93. weather foam strip around door frame.

Figure 94. weather foam strip around door hinge.

Furthermore, we incorporated a weather foam strip around the door's perimeter to ensure a tight seal, effectively preventing any gases from leaking through the door. This addition directs gases to exit solely through the chimney, and prevents unintended leakage, thereby maintaining the system's containment measures.

4.2.11 Door Lock

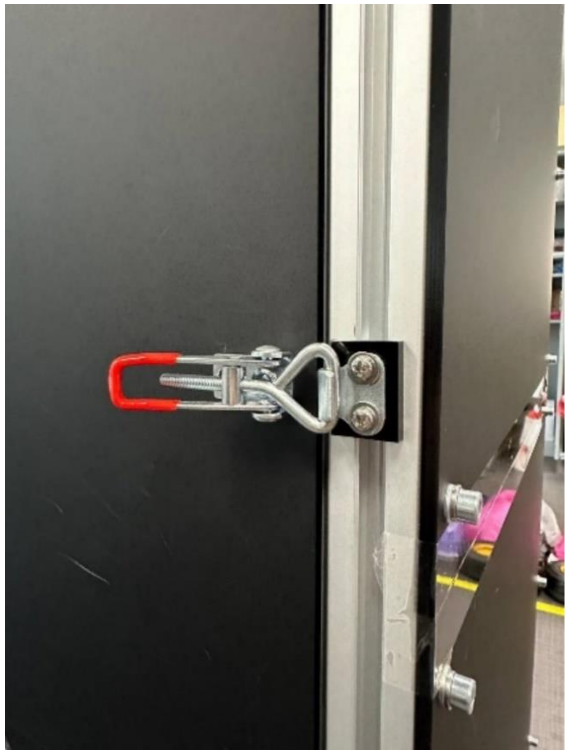


Figure 95. Close up view of attached door lock.

Figure 96. Zoomed out view of door lock.

In designing the door lock mechanism for our system, it was essential to find a solution that could securely close the door against the foam strip, thereby creating a reliable seal. Our selection was an adjustable pull toggle latch clamp, chosen for its ability to draw the door snugly against the chassis and maintain it in a stationary, locked position. This ensures an effective seal, critical for the integrity of the system's internal environment. To facilitate easy access, reopening the door is simply a matter of lifting the red handle upwards, which releases the latch and allows the door to be opened without impediment.

Figure 97. Final iteration of door lock.

Upon implementation, we observed that a single lock positioned at the center of the door was insufficient for ensuring a comprehensive seal due to the door's considerable length. This configuration effectively secured only the central portion of the door, lacking the necessary force to extend the seal to both the top and bottom sections. To rectify this issue, we promptly introduced an additional lock, strategically placing one near the top and the other near the bottom half of the door. This adjustment significantly improved the door's sealing capability, ensuring a uniform and complete seal across the entire length of the door.

4.3 Mechanical Testing

4.3.1 Portability Test

Figure 98. Pushing the reactor in a laboratory setting (smooth floor).

Figure 99. Pushing the reactor in an outdoor setting (rocky floor).

Figure 100. Pushing the reactor into a lift in NUS.

Figure 101. Pushing the reactor into a walkway in NUS.

In assessing the portability of our fully assembled reactor, we conducted practical tests to verify its ease of mobility across different locations. As documented in the accompanying photographs, we successfully demonstrated that a single individual could effortlessly maneuver the reactor. This ease of movement was further corroborated by the reactor's compatibility with common infrastructure, including corridors, alleyways, doorways, and elevators, indicating its design effectively meets the requirements for portability and accessibility within various environments. This testing phase was crucial in ensuring the reactor's functional adaptability and its potential for seamless integration into intended operational contexts.

The reactor has successfully met our primary scope for portability and adaptability, demonstrating its capability to be maneuvered across varied environments within the National University of Singapore (NUS). This portability is essential, as it allows for seamless transportation of the reactor to the research laboratory, where it is slated to undergo the testing and experimentation phase.

4.3.2 Loading Test

Figure 102. Loading baked frass into the container.

Before the Implementation of the Drawer System:

1. Distribution: Begin by evenly distributing food waste into each container.

2. Weighing: Utilize a weighing scale to measure the weight of each container, adjusting the quantity of food waste until the desired weight is achieved.

3. Repetition: This process is meticulously repeated for each container to ensure uniformity.

4. Introduction of BSFL: After achieving the target weights, BSFL are added to each container.

5. Placement: Each container is then manually carried and positioned in its designated rack location, requiring significant labor and time.

After Introducing the Drawer System:

1. Access: Simply pull out the desired cage and insert the container.

2. Weighing and Filling: Add food waste directly into the container until the desired weight is reached, using the cage's built-in load cell for accurate measurement.

3. Addition of BSFL: Introduce BSFL into the container, then push the cage back into the chassis.

4. Efficient Repetition: Repeat steps 1 through 3 for each container as needed, streamlining the process.

Findings for loading test:

Prior to the adoption of the drawer system, the process of preparing containers for BSFL treatment was characterized by its labor-intensive nature, necessitating the frequent lifting and transportation of trays from various surfaces due to the singular availability of a weighing scale. The introduction of the drawer system has fundamentally transformed this procedure by significantly reducing the manual effort and time investment previously essential for the accurate measurement and strategic placement of containers.

4.3.3 Unloading Test

Figure 103. Unloading frass into container.

Before the Drawer System:

1. Manual Retrieval: Containers are manually carried down from each rack.

2. Laborious Repetition: This process is repeated for each container that requires unloading, making it time-consuming and physically demanding.

After Implementing the Drawer System:

1. Easy Access: Simply pull out the desired cage and attach the guider to the front of the cage to facilitate a directed flow of contents.

2. Preparation for Unloading: Position the unloading container below the cage and adjust the duct vent to aim directly into the container, ensuring a targeted pathway for the contents to follow.

3. Activation of Stoppers: Rotate the four stoppers to their horizontal positions to unlock the container within the cage.

4. Efficient Unloading: Rotate the cage to allow all contents from the container to be efficiently guided out, utilizing the specifically designed guider to direct the flow into the unloading container.

Findings for unloading test:

While evaluating the unloading phase, observations revealed that a certain amount of frass inadvertently escaped through the guider, accumulating on the acrylic plate of the cage. Additionally, it was noted that manual intervention, specifically tapping on the guider, was required to dislodge frass that had congregated near the guider's entrance, facilitating its descent through the duct vent. Despite these challenges, a significant advantage was identified: the elimination of the need to manually remove fully loaded containers from the chassis. The unloading of frass into the designated container was accomplished with relative ease through the simple act of pivoting the cage's end.

4.3.4 Initial Experiment

Figure 104. Food Waste before adding cocopeat.

Figure 105. Food Waste after adding cocopeat.

Figure 106. Weighing the Food Waste to ensure equal weight on each container.

Figure 107. Evening out the Food Waste in the container.

Figure 108. Prepared six containers of Food Waste and six cups of BSFL.

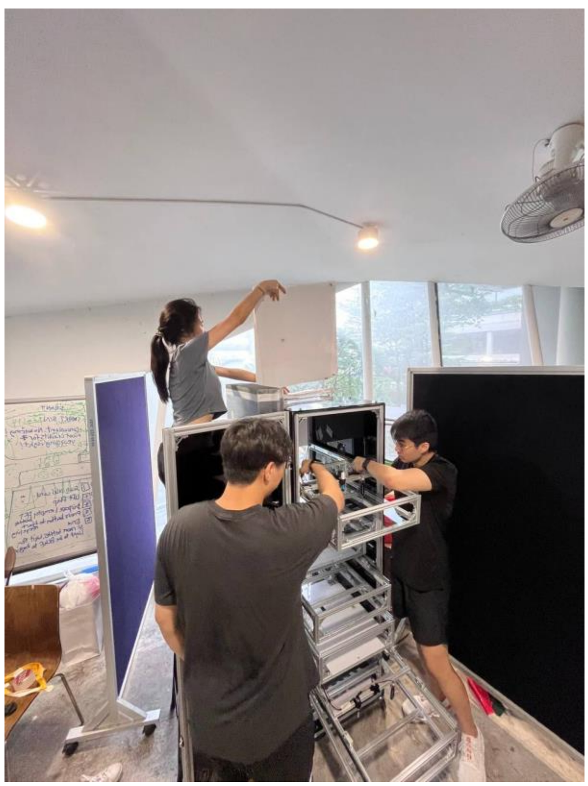


Figure 109. Final touch ups to the reactor.

Figure 110. Loading the Food Waste into the reactor and pouring the BSFL in.

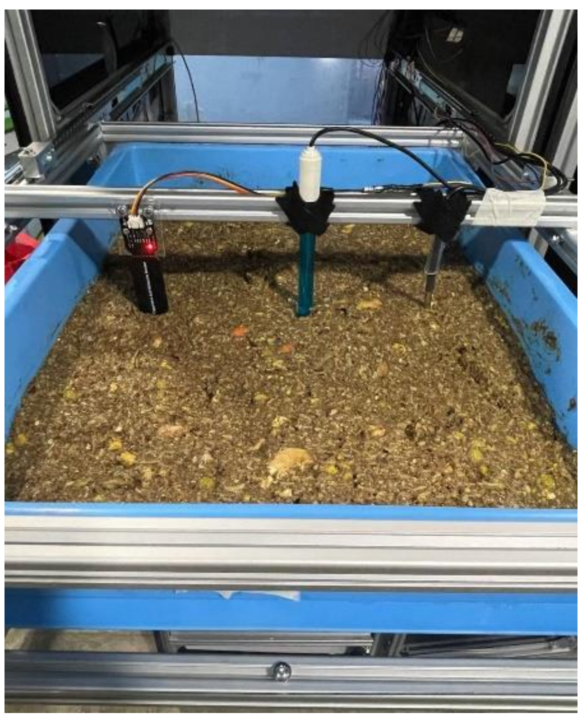


Figure 111. Putting in the sensors before pushing the cages into the reactor.

Figure 112. All containers loaded and all cages secured.

In the conclusive phase of our research, a comprehensive full-scale experiment was conducted within our reactor, necessitating a visit to the laboratory to procure the necessary food waste and larvae. The experimental setup commenced with the preparation of 39 kg of food waste and 1.17 kg of cocopeat, the latter employed to diminish moisture levels within the substrate. Subsequently, these components were thoroughly mixed to achieve a homogeneous substrate mixture. Utilizing a precision weighing scale, each tray was manually filled with the mixture, amounting to a total of 6.695 kg per container, which included 6.5 kg of food waste and 0.195 kg of cocopeat.

Following the preparation phase, the containers were transported to our designated work area, where the reactor will be situated for the experiment's duration. After conducting final adjustments to the reactor, the containers were loaded into it. Prior to reinserting the containers into the chassis, approximately 10,000 larvae were introduced into the mixture, and sensors were strategically placed to commence data collection. With the activation of all fans, the experiment officially began.

At this initial stage of experimentation, we are unable to disclose specific data findings. Nonetheless, it is our intention to provide a detailed analysis and interpretation of the results in future phases of our research. This preliminary experiment lays the groundwork for collecting vital data to assess the efficiency and performance of our bioconversion system within the reactor. As our research advances, we commit to rigorously documenting our observations, challenges, and modifications, aiming to attain an in-depth understanding of the system's dynamics. Through meticulous examination of the gathered data, our goal is to derive significant insights into the system's effectiveness and identify areas for enhancement, setting the stage for further developmental strides in our subsequent experimental endeavors.

5. Future Works

In contemplating advancements for our project, several areas have been identified for improvement to enhance the system's efficiency and practicality further.

1. Wheel Optimization: The current wheel design has shown limitations, particularly when navigating wider floor gaps and transitions, such as those found at lift entrances. To address this, we are considering the adoption of larger wheels. This modification is expected to facilitate smoother mobility over such irregularities, significantly reducing the likelihood of the wheels becoming lodged and thus improving portability.

2. Enhanced Loading Efficiency: While the container loading process has proved effective, there exists potential for further productivity enhancement. Introducing an automated pump system for the distribution of food waste into containers could standardize the process, ensuring a uniform spread across all containers. This automation could drastically streamline the loading phase, minimizing manual intervention and optimizing time efficiency.

3. Guider Design Refinement: Although the conceptual foundation of the guider is solid, practical application has revealed areas for improvement. Primary among these is the necessity to redesign the guider's attachment mechanism to the container, aiming to eliminate leakage during the cage's rotation. Additionally, enlarging the guider's entrance would ensure a more comprehensive collection of contents during unloading tests. Current feedback also suggests that the guider's construction material contributes to its bulkiness and weight, making its handling and placement challenging. Exploring alternative materials

that are lightweight yet durable could render the guider more user-friendly and effective in its role.

These targeted enhancements represent the initial steps in our ongoing efforts to refine and optimize the system's design. By addressing these specific challenges, we aim to not only improve the system's operational efficiency but also its ease of use and overall effectiveness in the BSFL treatment process. Future research and development will focus on implementing these improvements, with a continuous commitment to innovation and practicality at the forefront of our project's evolution.

5.1 Review on current reactor by Researcher (Adrian Fuhrmann)

The initial feedback on our reactor prototype has been largely positive, highlighting its convenience and operability. However, to further refine the reactor and maximize its potential, specific areas have been identified for improvement. The suggestions aim at not only enhancing the reactor's functionality but also its safety and user-friendliness. The following sections outline the proposed enhancements and the research needed to implement these changes effectively.

1. Development of Linked Locks System: Research into the development of an innovative linked locks mechanism that allows operators to secure or unsecure multiple trays simultaneously with a single action. This system should be designed to maintain, if not improve, the current levels of safety and security of the reactor's internal components. Apart from that, it will increase the ease of use of the reactor.

2. Extended Funnel Shielding: Expansion of the current shielding around the funnel to provide a more comprehensive barrier. This improvement aims to prevent frass and larvae from falling outside the intended areas, thus maintaining a cleaner operating environment, and reducing waste.

The feedback received serves as a valuable guide for the next phase of our reactor's development. By focusing on the reduction of manual work involved in tray management and improving byproducts containment, we can significantly enhance the reactor's usability and safety. Each proposed enhancement will undergo a rigorous research and development process to ensure that the solutions are not only effective but also feasible for implementation. The final goal is to develop a reactor that not only meets but exceeds the expectations of its operators and stakeholders in terms of efficiency, safety, and convenience.

6. References

[1] “Waste statistics and overall recycling,” National Environment Agency, https://www.nea.gov.sg/our-services/waste-management/waste-statistics-and-overall-recycling (accessed Sep. 21, 2023).

[2] “Food waste,” Towards Zero Waste Singapore, https://www.towardszerowaste.gov.sg/foodwaste. (accessed Nov. 18, 2023).

[3] “Solid waste management infrastructure,” National Environment Agency, https://www.nea.gov.sg/our-services/waste-management/waste-management-infrastructure/solid-waste-management-infrastructure (accessed Nov. 18, 2023).

[4] “Kerry launches food waste estimator,” Kerry Launches Food Waste Estimator, https://www.kerry.com/about/our-company/news-and-media/2022/kerry-launches-food-waste-estimator.html (accessed Mar. 30, 2024).

[5] “S’pore to reduce 30% of waste sent to Semakau Landfill by 2030,” Mothership.SG - News from Singapore, Asia and around the world, https://mothership.sg/2019/08/singapore-reduce-waste-semakau-landfill/ (accessed Mar. 30, 2024).

[6] H. Auto, “Singapore aims to send one-third less waste to Semakau Landfill by 2030: Amy Khor,” The Straits Times, https://www.straitstimes.com/singapore/environment/spore-aims-to-send-one-third-less-waste-to-semakau-landfill-by-2030-amy-khor (accessed Nov. 18, 2023).

[7] “World’s first offshore landfill constructed from the seabed up is located in Singapore,” TheCivilEngineer.org, https://www.thecivilengineer.org/news/world-s-first-offshore-landfill-constructed-from-the-seabed-up-is-located-in-singapore (accessed Apr. 6, 2024).

[8] “Greenhouse gas inventory,” National Environment Agency, https://www.nea.gov.sg/our-services/climate-change-energy-efficiency/climate-change/greenhouse-gas-inventory. (accessed Sep. 21, 2023).

[9] Cue, “S’pore study on fitting incineration plants with carbon capture Tech set to be completed by Q2 2024,” The Straits Times, https://www.straitstimes.com/singapore/environment/s-pore-study-on-fitting-incineration-plants-with-carbon-capture-tech-to-be-completed-by-q2-2024 (accessed Nov. 18, 2023).

[10] Food waste in Singapore, https://blogs.ntu.edu.sg/hp3203-1920s1-u28/impact-of-food-waste/ (accessed Nov. 18, 2023).

[11] C. SG, “Singapore’s ‘30 by 30’ food security goal and strategies,” CosySingapore Commercial Property Singapore; Office, Shop, Industrial, Medical Suites, Food Factory, or Sale, For Lease, https://cosysingapore.com/singapore-30-by-30-food-security/ (accessed Apr. 6, 2024).

[12] Population outcomes — singapore 2050, https://lkyspp.nus.edu.sg/docs/default-source/ips/exchange-1_the-population-outcomes-singapore-2050-project.pdf (accessed Apr. 6, 2024).

[13] Schematic of the fixed-film anaerobic digester. ..., https://www.researchgate.net/figure/Schematic-of-the-fixed-film-anaerobic-digester-The-anaerobic-digester-was-built-from-two_fig2_318566278 (accessed Apr. 6, 2024).

[14] How does anaerobic digestion work? | US EPA, https://www.epa.gov/agstar/how-does-anaerobic-digestion-work (accessed Nov. 18, 2023).

[15] National University of Singapore, Food waste at East Coast Lagoon Food Village to be turned into energy and fertiliser under pilot project, https://news.nus.edu.sg/food-waste-at-east-coast-lagoon-food-village-to-be-turned-into-energy-and-fertiliser-under-pilot-project/ (accessed Mar. 30, 2024).

[16] M. Igini, “Insect farming: The sustainable future of food production,” Earth.Org, https://earth.org/insect-farming/ (accessed Apr. 6, 2024).

[17] Singapore Food Statistics 2022 - SFA, https://www.sfa.gov.sg/docs/default-source/publication/sg-food-statistics/singapore-food-statistics-2022.pdf (accessed Nov. 18, 2023).

[18] C. Tan, “Researchers develop blueprint for Sustainable Food System using black soldier flies,” The Straits Times, https://www.straitstimes.com/singapore/researchers-develop-blueprint-for-sustainable-food-system-using-black-soldier-flies (accessed Apr. 6, 2024).

[19] Radware bot manager Captcha, https://iopscience.iop.org/journal/1755-1315 (accessed Apr. 6, 2024).

[20] J. Imam, “Styrofoam-eating mealworms might help reduce plastic waste, study finds,” CNN, https://edition.cnn.com/2015/09/30/us/styrofoam-eating-mealworms-plastic-waste/index.html (accessed Apr. 6, 2024).

[21] Maggots could revolutionize the global food supply. here’s how. - The Washington Post, https://www.washingtonpost.com/business/2019/07/03/maggots-could-revolutionize-global-food-supply-heres-how/ (accessed Apr. 6, 2024).

[22] “Mealworms vs. Black Soldier Fly Grubs,” Mealworms vs. Black Soldier Fly Larvae, https://grubblyfarms.com/blogs/the-flyer/mealworms-vs-black-soldier-flies (accessed Sep. 21, 2023).

[23] “How maggots could help Millions,” The University of Sheffield, https://www.sheffield.ac.uk/cbe/research/case-studies/how-maggots-could-help-millions#:~:text=%E2%80%9CThe%20larvae%2C%20or%20maggots%2C,somewhere%20to%20turn%20into%20flies.%E2%80%9D (accessed Apr. 6, 2024).

[24] D. Purkayastha and S. Sarkar, “Sustainable Waste Management using black soldier fly larva: A Review - International Journal of Environmental Science and Technology,” SpringerLink, https://link.springer.com/article/10.1007/s13762-021-03524-7#citeas (accessed Apr. 6, 2024).

[25] “Home,” insectta, https://www.insectta.com/ (accessed Apr. 6, 2024).

[26] “Home,” Protix, https://protix.eu/ (accessed Apr. 6, 2024).

[27] Factsheet updates to Singapore’s food waste ..., https://www.mse.gov.sg/cos/resources/cos-annex-e.pdf (accessed Apr. 6, 2024).

[28] National University of Singapore, Interdisciplinary team to develop blueprint for Sustainable Urban Food Waste Management and food systems using black soldier flies, https://news.nus.edu.sg/interdisciplinary-team-to-develop-blueprint-for-sustainable-urban-food-waste-management-and-food-systems-using-black-soldier-flies/ (accessed Apr. 6, 2024).

[27] “Lifts & escalators,” BCA Corp, https://www1.bca.gov.sg/regulatory-info/lifts-escalators (accessed Apr. 6, 2024).

[28] An optimal feeding strategy for black soldier fly larvae biomass production and faecal sludge reduction | journal of insects as food and feed, https://www.wageningenacademic.com/doi/abs/10.3920/JIFF2018.0017 (accessed Apr. 6, 2024).

[29] Shahida Anusha Siddiqui a b et al., “Black soldier fly larvae (BSFL) and their affinity for organic waste processing,” Waste Management, https://www.sciencedirect.com/science/article/pii/S0956053X22000010 (accessed Apr. 6, 2024).

[30] (PDF) black soldier Fly Biowaste processing - a step-by-step guide, 2nd ..., https://www.researchgate.net/publication/353923113_Black_Soldier_Fly_Biowaste_Processing_-_A_Step-by-Step_Guide_2nd_Edition (accessed Nov. 18, 2023).

[31] “Push to open GS4260 24 inch slide,” TDD Hardware, https://tddhardware.com/shop/all-drawer-slides/ball-bearing-drawer-slides/side-mount-ball-bearing-slides/push-to-open-ball-bearing-slides/gslide-4260/push-to-open-gs4260-24-inch-slide/ (accessed Apr. 6, 2024).

[32] “Minimum ultimate tensile loads,” www.bossard.com, https://www.bossard.com/sg-en/assembly-technology-expert/technical-information-and-tools/technical-information/screws-property-class-46-to-129/minimum-ultimate-tensile-loads (accessed Apr. 6, 2024).

[33] G. Traylor, M. Samiei, and R. Crossno, “How do you choose the appropriate safety factor for different load-bearing structures?,” Choosing Safety Factor for Load-Bearing Structures, https://www.linkedin.com/advice/1/how-do-you-choose-appropriate-safety-factor#:~:text=Safety%20factor%20is%20usually%20expressed,type%20of%20structure%20and%20load (accessed Apr. 6, 2024).

[34] Shopee.sg, https://shopee.sg/3-Sections-Ball-Bearing-Full-Extension-Black-Drawer-Slide-1-pair-i.10214.4050431302 (accessed Apr. 6, 2024).

[35] “Shop fox D3034 26-inch full ext drawer slide 100-pound capacity side mount, pair,” Amazon.sg: DIY & Tools, https://www.amazon.sg/dp/B0000DD4AC?starsLeft=1&ref_=cm_sw_r_apin_dp_B44WRFZCTRWYMBFWPGR9&th=1 (accessed Apr. 6, 2024).

[36] “Home,” Prestech, https://www.prestech.com.sg/house-products/profile-accessories/hinges/product/product/110-hinge-pta-h3030-8 (accessed Apr. 6, 2024).

7. Appendices

7.1 BCA guidelines and dimensions around NUS campus

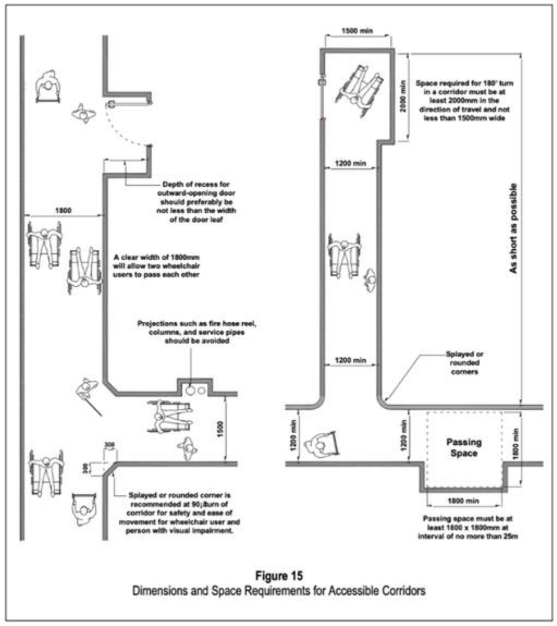


Figure 113: BCA guidelines for corridors.

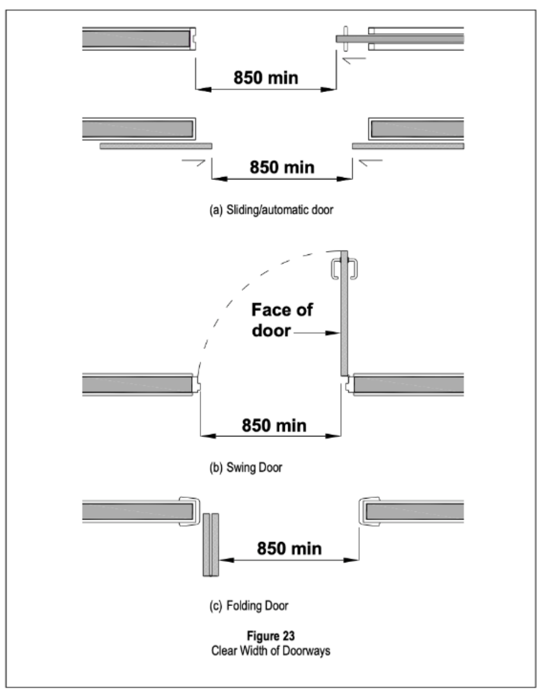


Figure 114: BCA guidelines for doors.

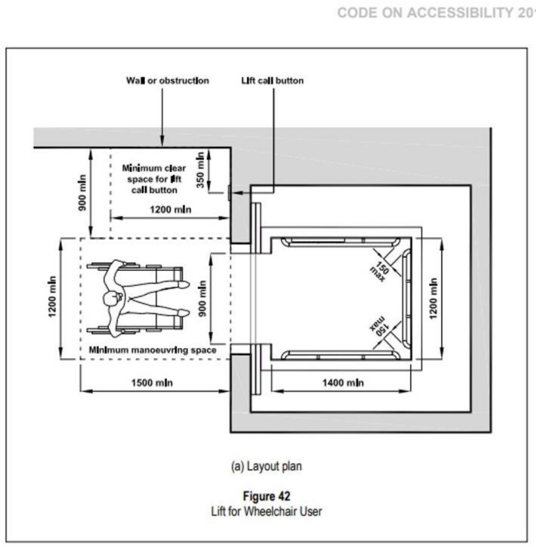


Figure 115: BCA guidelines for lifts.

The figures presented above are derived from the BCA (Building and Construction Authority) guidelines, specifically outlining standards for corridors, doors, and lifts. Our attention was predominantly directed towards these particular areas, as we identified them as potential spaces that could pose challenges for the mobility and manoeuvrability of our reactor system. Understanding and adhering to these guidelines were crucial as they influenced the design considerations to ensure the practicality and functionality of the reactor within various spaces.

Figure 116: Ground level pathway in E2A building, NUS.

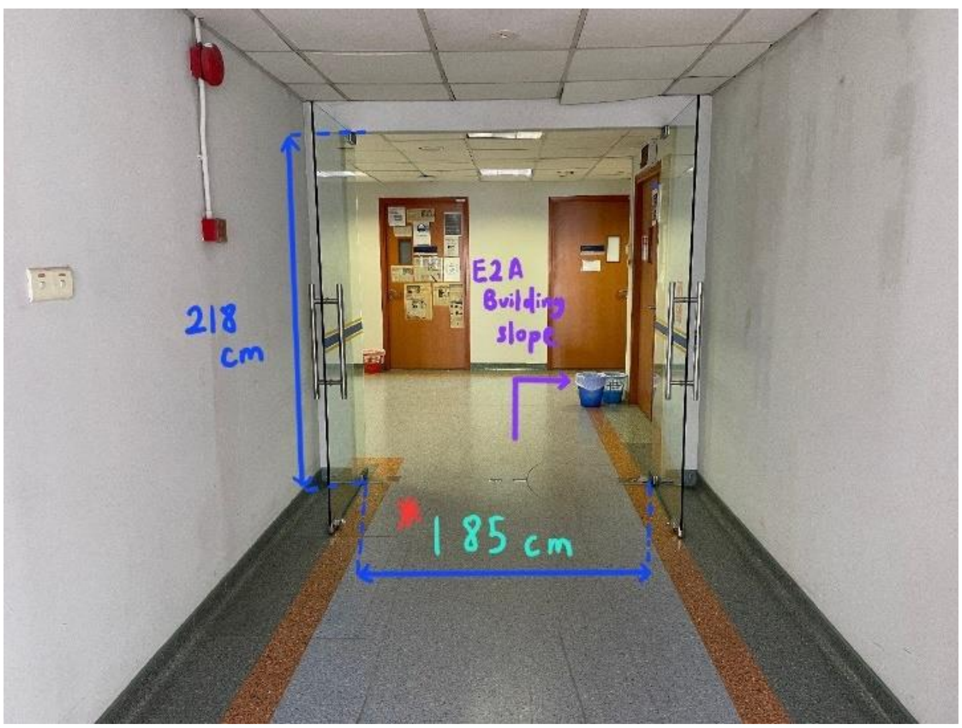


Figure 117: Connecting pathway in E2A building, NUS.

Figure 118: Door in EA building, NUS.

Figure 119: Lift in E2 building, NUS.

Figure 120: Lift in E1A building, NUS.

To validate our design assumptions and ensure accuracy, we conducted a thorough examination of the school campus, precisely measuring various areas and routes pertinent to our reactor's potential mobility. Upon assessment, we confirmed that the dimensions outlined in the BCA guidelines were indeed precise and aligned with the actual spaces within the campus. This validation provided us with the confidence to draft the dimensions of our reactor, referencing the accurate guidelines for optimal compatibility and functionality within these designated areas.

7.2 Calculations of food waste

Figure 121: Food waste calculations per food court per day.

Through interviews conducted with cleaners at UTown food courts, valuable insights were gathered indicating that they produce a full bin of food waste daily, approximately amounting to 120 liters. Acknowledging variations in food waste density across different locations, obtaining an estimate of the density was still essential. Utilizing available literature as a reference, it was found that an approximate density stands at 1.565 Kilograms per liter. Multiplying this density by 120 liters yields an estimated total mass of food waste of approximately 187.8 Kilograms.

7.3 Calculations for pivot system

$$\tau = F \times d$$

$$F_r = m \times g + m \times a$$

Figure 122: Mathematical equations to find torque.

$$\underline{0.124} \times \underline{208.5} = 25.8 \text{ (3sf)}$$

$$25.8 + 25.8 = \underline{\underline{51.6}} \text{ (3sf)}$$

Figure 123: Calculations for torque required per container.

Upon our initial sizing evaluation and conducting approximate calculations, we determined that the torque necessary per container would amount to 51.6 Newton-meters (Nm).

7.4 Test results

Reading	Angle°
1	60°
2	60°
3	60°
4	60
5	60°
6	60°
7	60°
8	60°
9	60°
10	60°

Figure 124: Experiment test results on cardboard.

Reading	Angle°
1	50°
2	50°
3	50°
4	50°
5	50°
6	50°
7	50°
8	50°
9	50°
10	50°

Figure 125: Experiment test results on plastic.

Based on our experimental findings, it can be inferred that employing a smoother surface significantly affects the movement of the frass. Notably, a smooth surface requires only a 50-degree angle to facilitate the complete release of all the frass. This suggests that smoother surfaces play a crucial role in enhancing the efficient sliding and discharge of the frass from the container.

7.5 Calculations for torque requirement

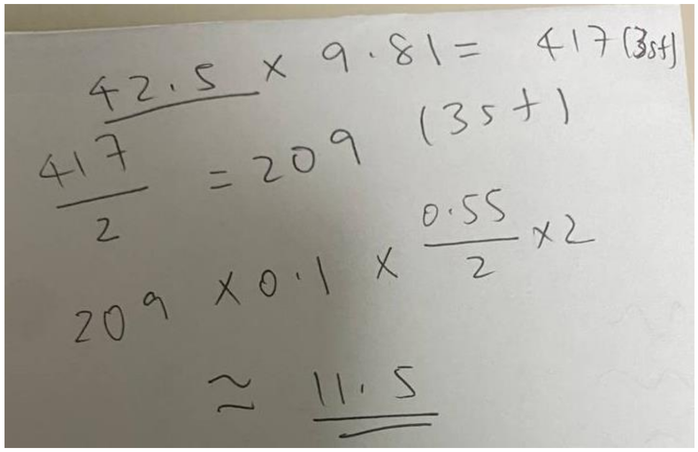


Figure 126: Calculations for torque required for design five

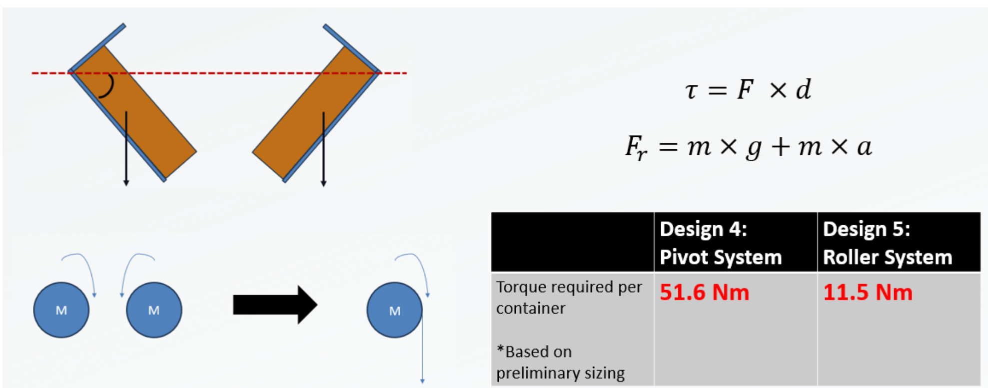


Figure 127: Comparison between pivot system and roller system.

Following calculations derived from our preliminary sizing of design five, it was determined that the required torque amounts to 11.5 Newton-meters (Nm). Despite this reduced torque requirement, the necessity for multiple motors within our chassis remains impractical. Consequently, we've opted to explore an alternative solution by considering a manual system, acknowledging its potential to better align with both our practical requirements and budget constraints.

7.6 BSFL calculations and container sizing

As a rule of thumb, we work with the following numbers: 10,000 larvae are fed with a total of 12 kg of substrate (75% water content) and harvested after a total of 12 days. Initially the 10'000 5-DOL are kept in an incubator unit (30x20x10 cm) and left to feed on a single load of 1kg for 3 days, thereafter the larvae are transferred to a larvero unit (40x60x15cm) and left to feed on a single load of 11 kg for 9 days.

Figure 128: Number of larvae to food waste ratio.

Based on the literature review indicating a ratio of 10,000 larvae per 12 kilograms of food waste, if our containers accommodate up to 40 kilograms of food waste, the estimated number of larvae per container would be approximately 33,333 (calculated as 40/12 x 10,000).

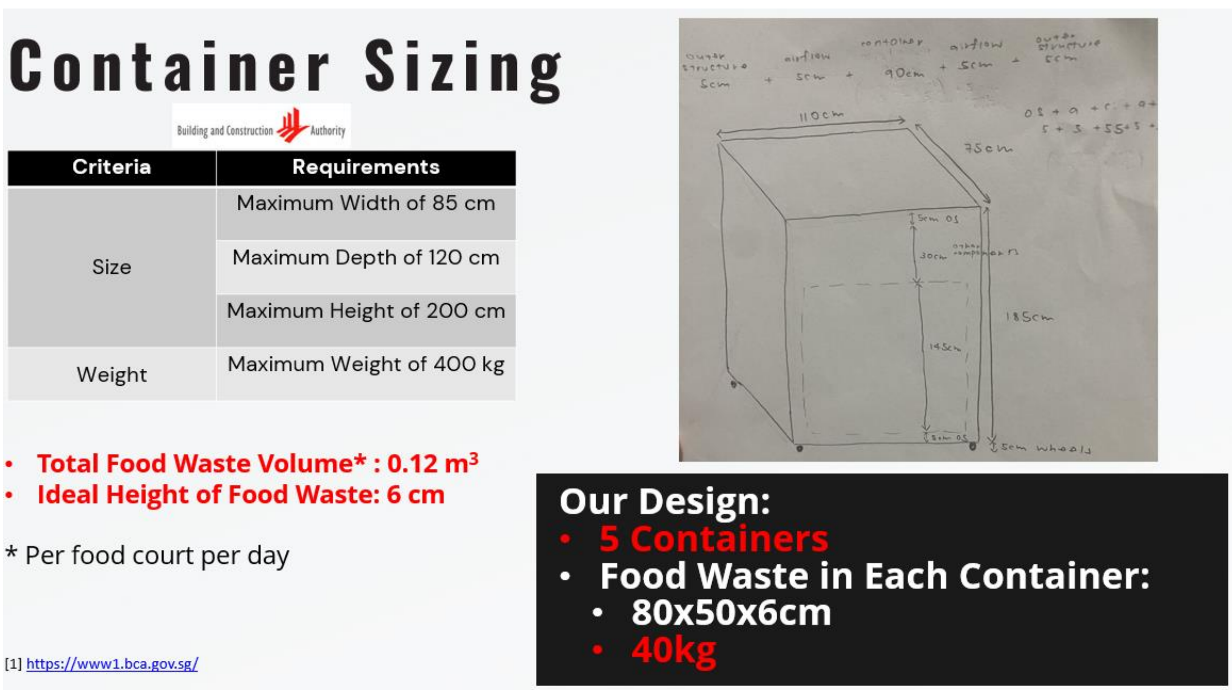
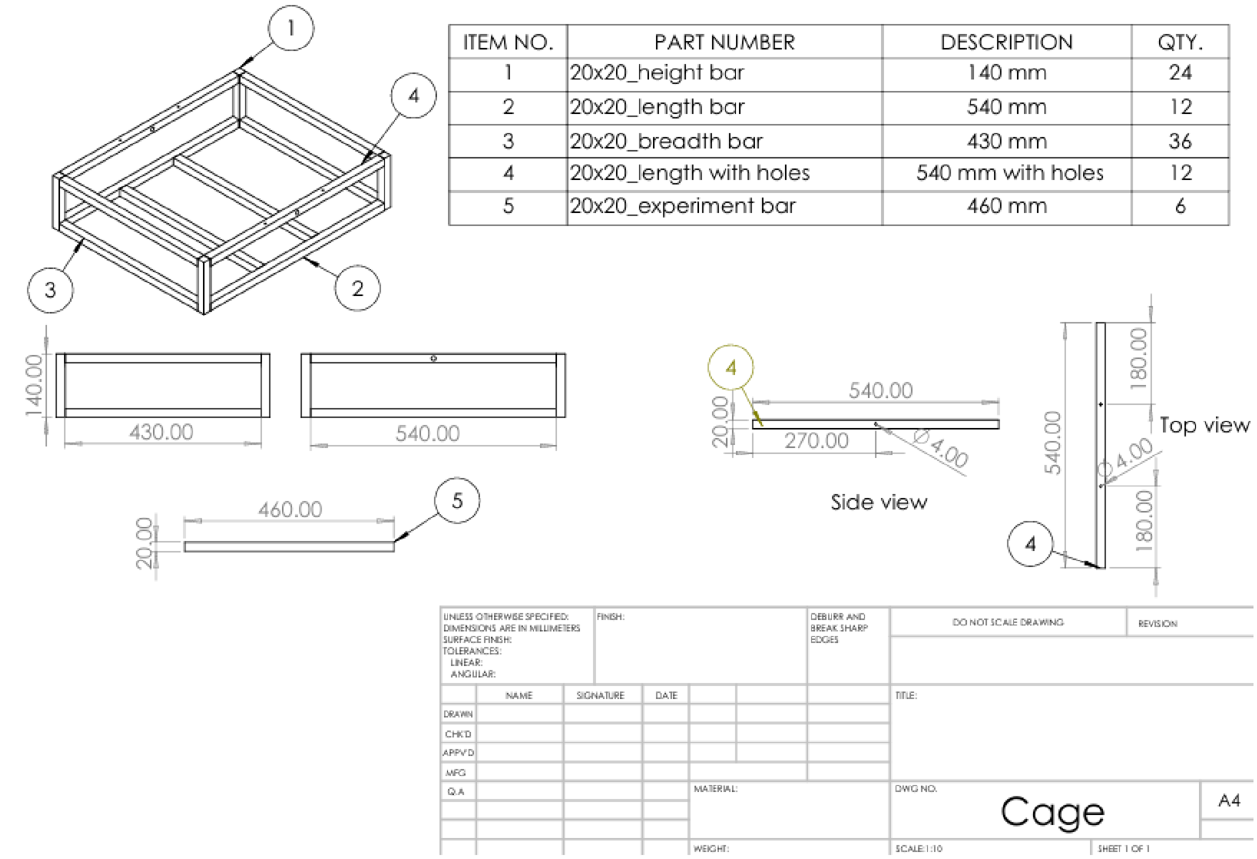


Figure 129: Container sizing calculations.

If the ideal height of the food waste is 6cm and the container's dimensions are set at a length of 80cm and a width of 50cm, the total volume available for storing food waste within the container would indeed equate to 0.12 cubic meters (calculated as length × width × height = 0.8m × 0.5m × 0.06m = 0.12m^3). Considering the estimated food density of 1.565 kilograms per litre, this volume would result in a food waste mass of approximately 40 kilograms (calculated as volume × density = 0.12m^3 × 1565 kg/m^3 = 40kg).

7.7 Detailed dimension drawings



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	20x20_height bar	140 mm	24
2	20x20_length bar	540 mm	12
3	20x20_breadth bar	430 mm	36
4	20x20_length with holes	540 mm with holes	12
5	20x20_experiment bar	460 mm	6

Figure 130: Dimensions of individual cage components.

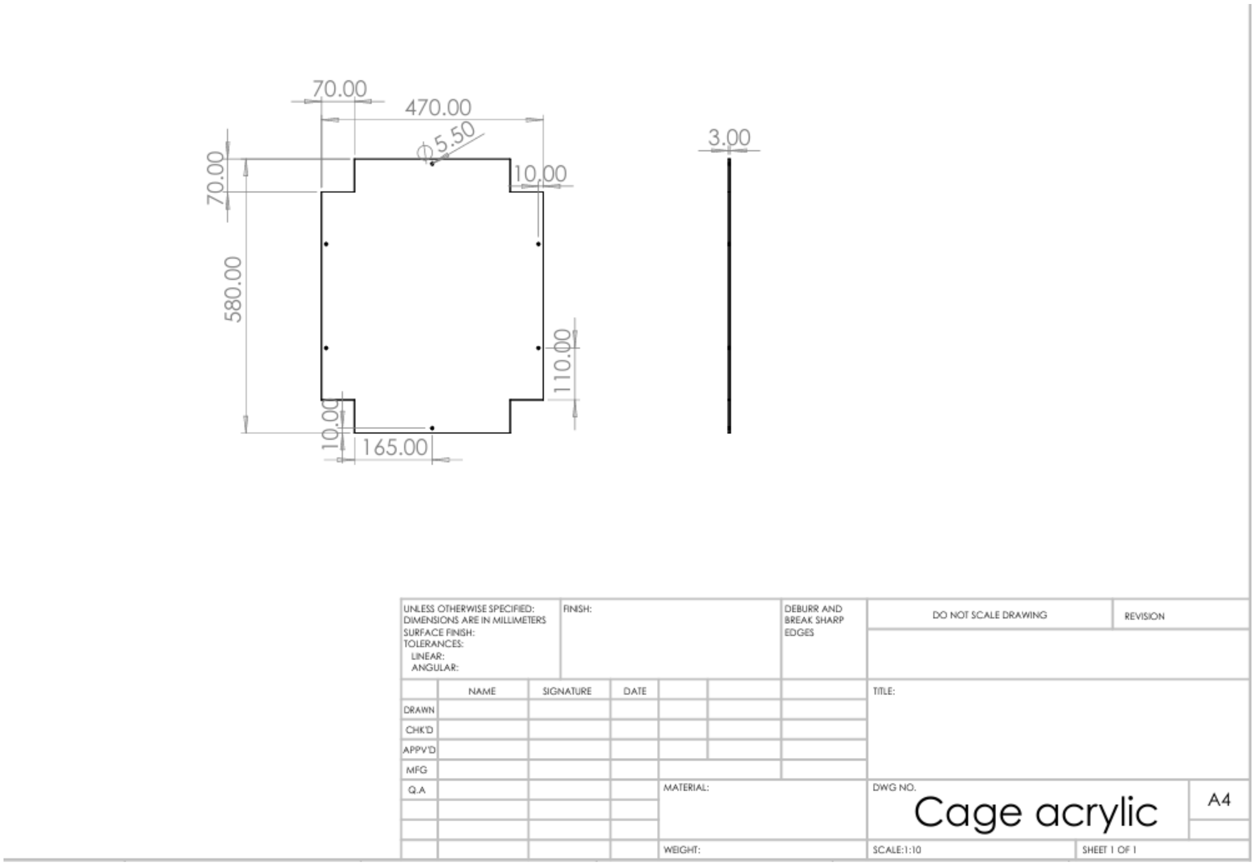


Figure 131: Dimensions of cage acrylic.

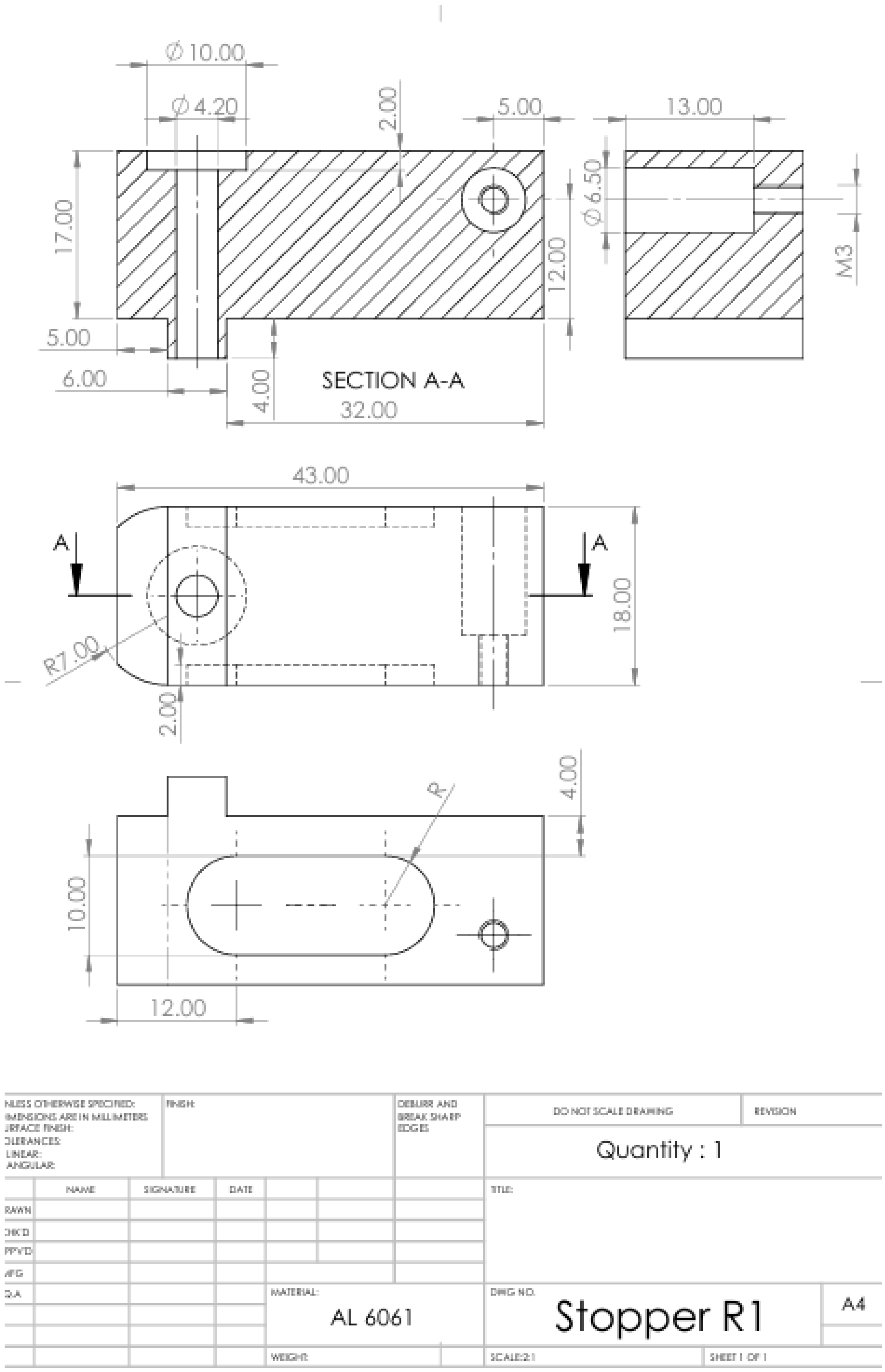
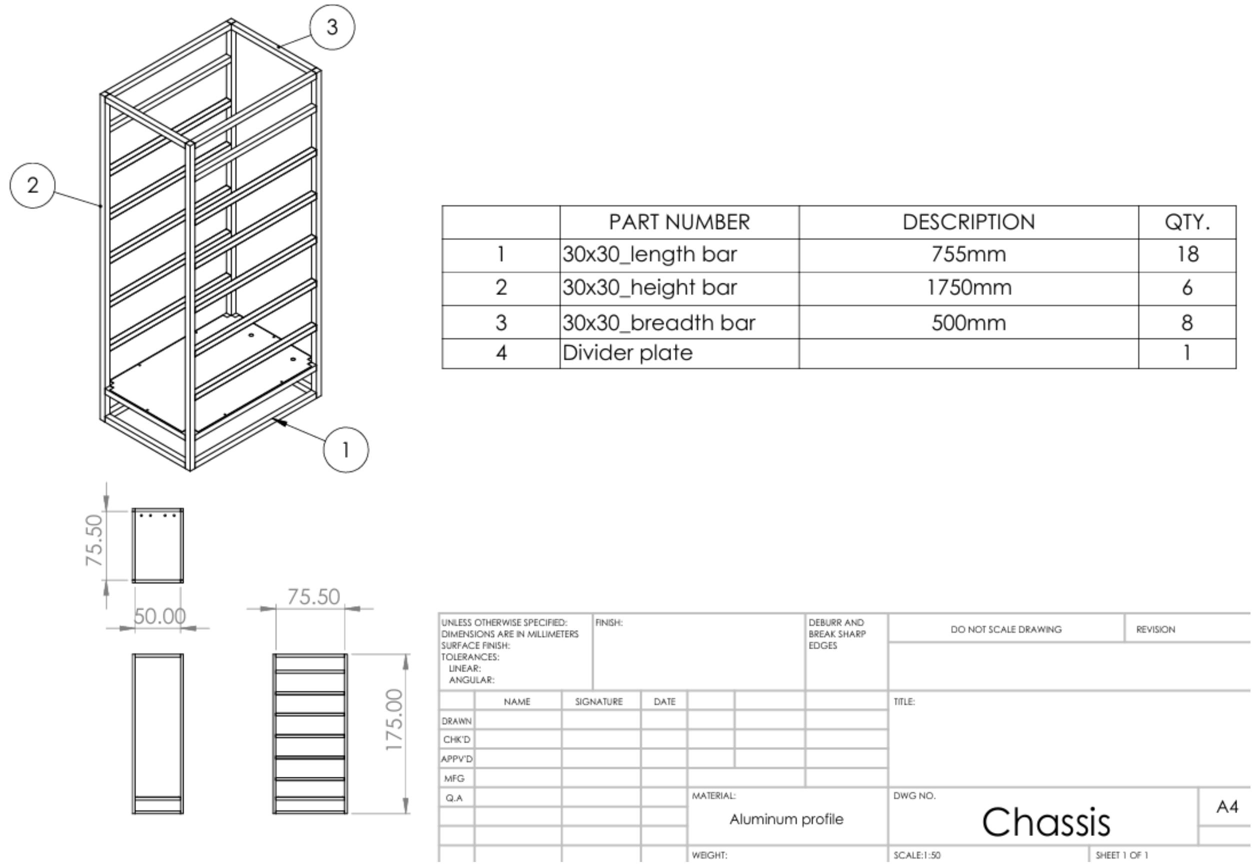


Figure 132: Dimensions of cage stopper.



	PART NUMBER	DESCRIPTION	QTY.
1	30x30_length bar	755mm	18
2	30x30_height bar	1750mm	6
3	30x30_breadth bar	500mm	8
4	Divider plate		1

Figure 133: Dimensions of individual chassis components.

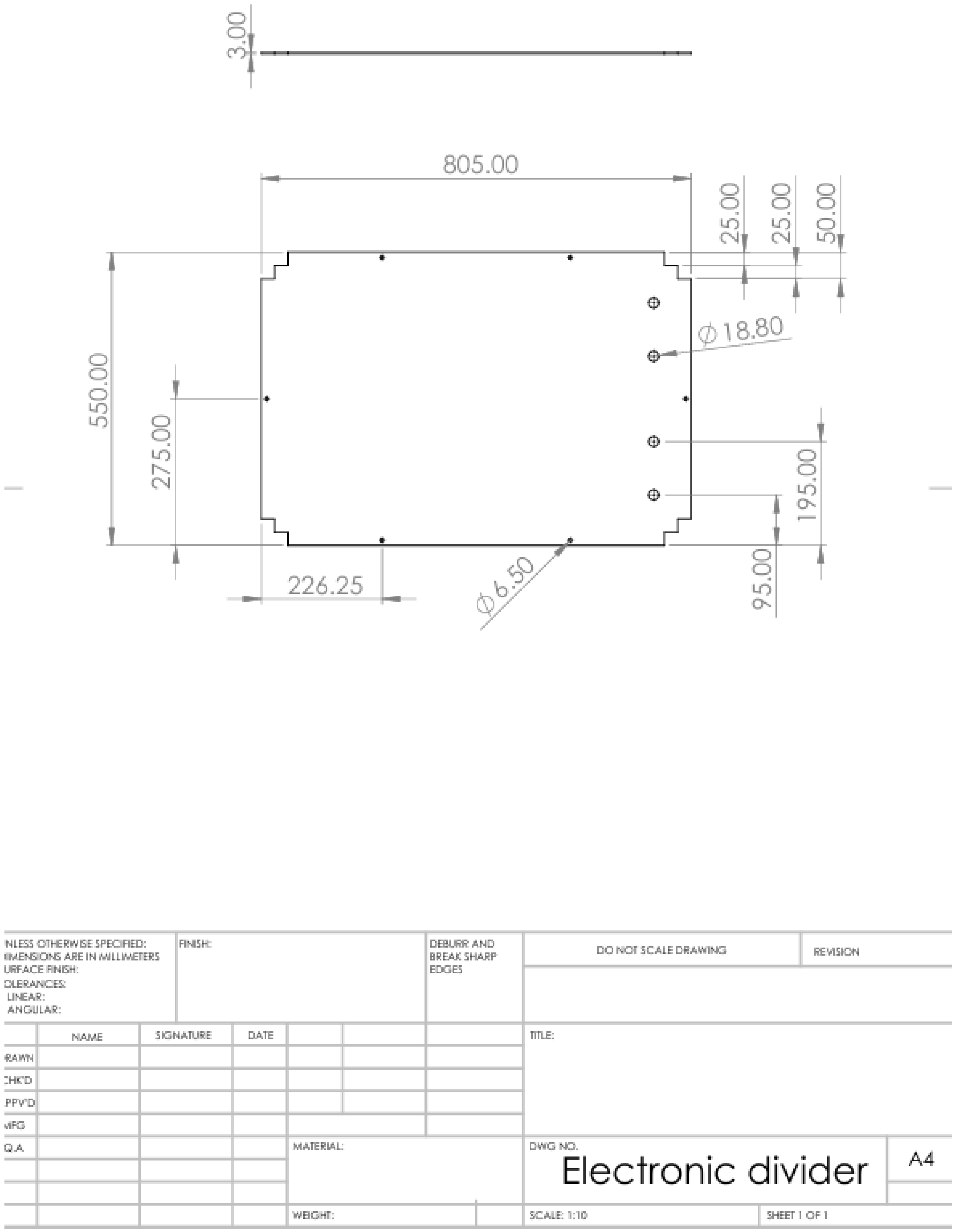


Figure 134: Dimensions of electronic divider acrylic.

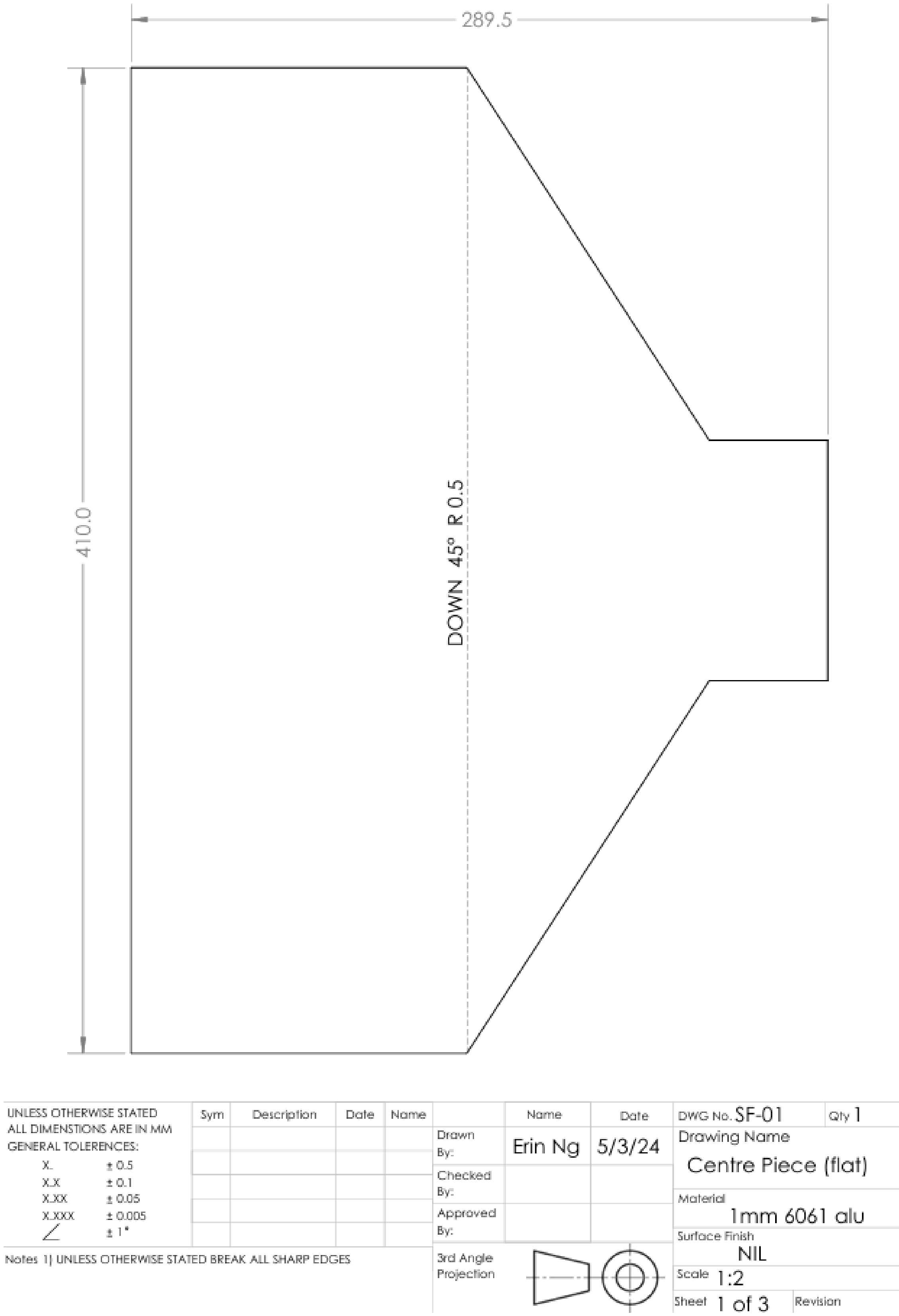


Figure 135: Centre piece of guider.

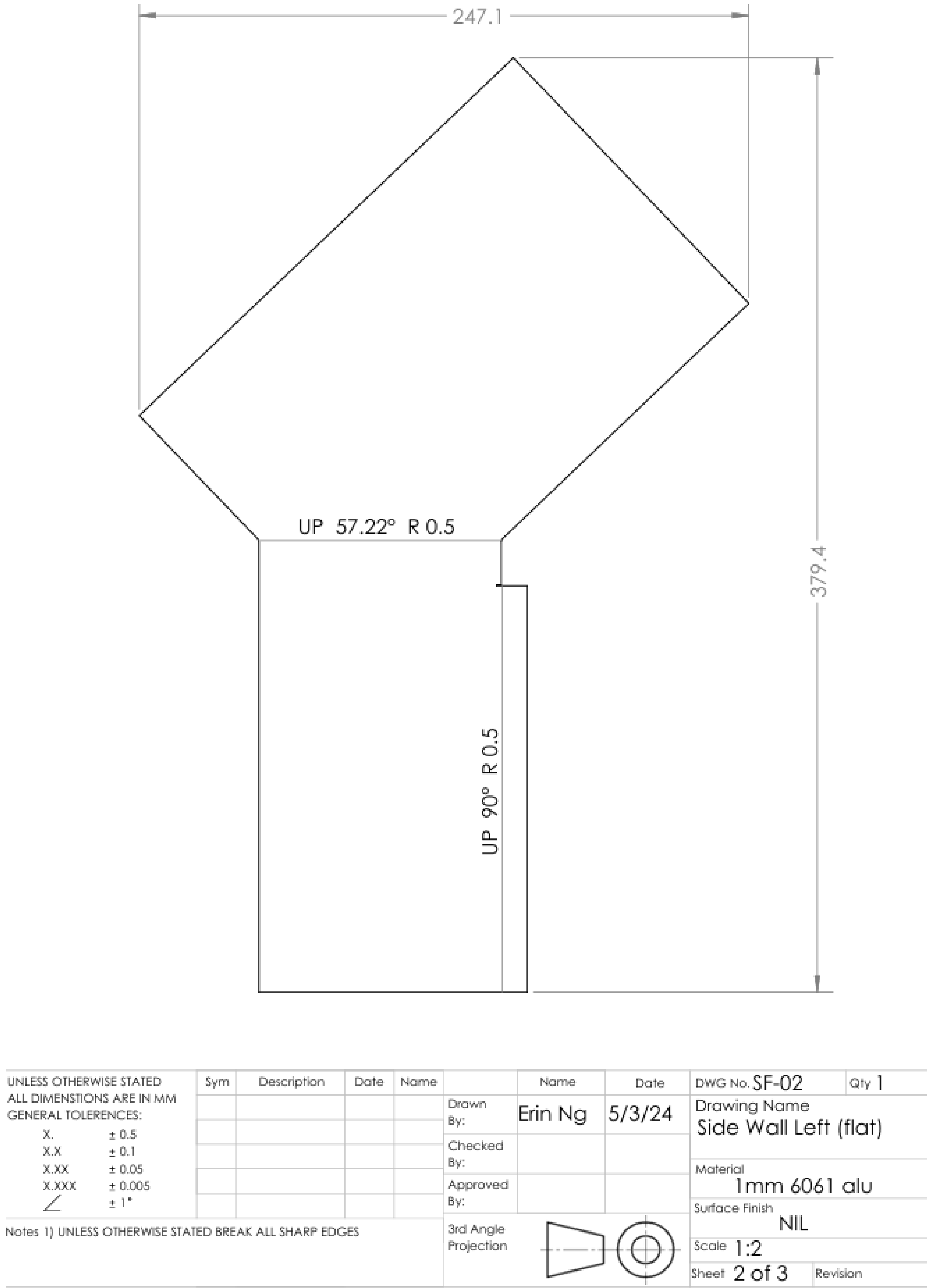


Figure 136: Side left wall of guider.

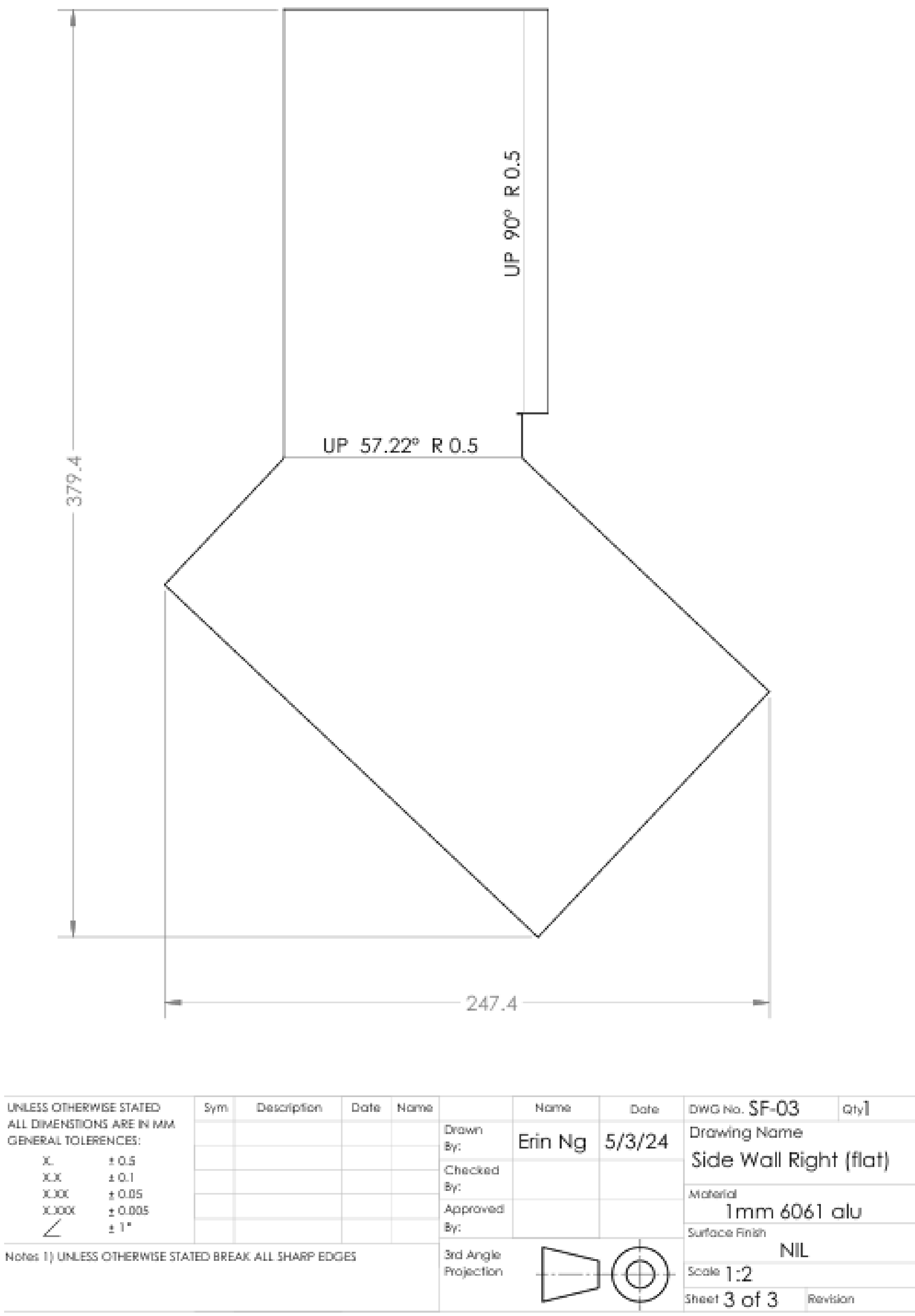
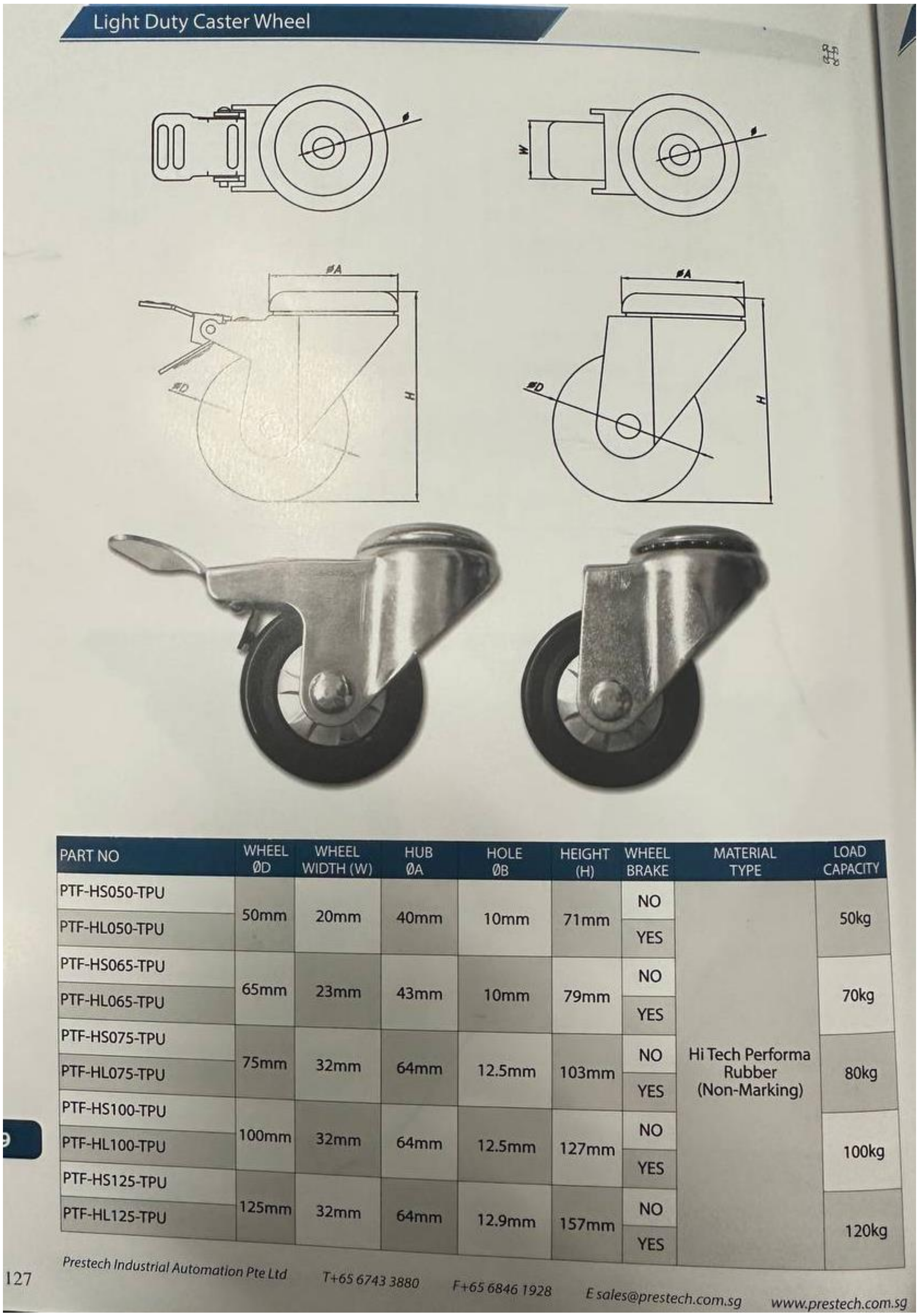


Figure 137: Side right wall of guider.

The figures depicted above represent detailed dimensional drawings created using SolidWorks by our team, specifically intended for the fabrication process undertaken in the central workshop. The actual fabrication of these parts was expertly carried out by Mr. Hamilton and his dedicated team. These drawings play a crucial role in ensuring the accuracy and precision of the fabrication process, reflecting our project's emphasis on meticulous planning and collaboration with skilled professionals to achieve the highest standards of quality and functionality in our components.

7.8 Details on light duty caster wheel



Light Duty Caster Wheel

PART NO	WHEEL ØD	WHEEL WIDTH (W)	HUB ØA	HOLE ØB	HEIGHT (H)	WHEEL BRAKE	MATERIAL TYPE	LOAD CAPACITY
PTF-HS050-TPU	50mm	20mm	40mm	10mm	71mm	NO	Hi Tech Performa Rubber (Non-Marking)	50kg
PTF-HL050-TPU						YES		
PTF-HS065-TPU	65mm	23mm	43mm	10mm	79mm	NO		70kg
PTF-HL065-TPU						YES		
PTF-HS075-TPU	75mm	32mm	64mm	12.5mm	103mm	NO		80kg
PTF-HL075-TPU						YES		
PTF-HS100-TPU	100mm	32mm	64mm	12.5mm	127mm	NO		100kg
PTF-HL100-TPU						YES		
PTF-HS125-TPU	125mm	32mm	64mm	12.9mm	157mm	NO		120kg
PTF-HL125-TPU						YES		

127 Prestech Industrial Automation Pte Ltd T+65 6743 3880 F+65 6846 1928 E sales@prestech.com.sg www.prestech.com.sg

Figure 138: Different light duty caster wheels from prestech.

The figure presented above showcases a variety of light-duty caster wheels sourced from Prestech, accompanied by comprehensive details ranging from wheel diameter and mounting hole specifications to overall wheel height. Of particular importance, the figure also includes information on the load capacity of each wheel, a critical factor in determining the suitability of each caster for specific applications within our project. This detailed overview aids in the informed selection process, ensuring that the chosen casters meet the precise requirements for mobility and load-bearing capacity essential for the optimal functionality and efficiency of our design.