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

MAN CHUN HANG

INNOVATION & DESIGN PROGRAMME

NATIONAL UNIVERSITY OF SINGAPORE

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MAN CHUN HANG

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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.

MAN CHUN HANG

07 March 2024

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The collective expertise, commitment, and guidance of all these professionals have been instrumental to the project's success and have inspired us to exceed the limits of our

aspirations. It has been an immense privilege to collaborate with such distinguished individuals, and we are deeply thankful for their contributions.

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Summary

The thesis titled "A Study on Smart Food Waste Recycling System Using Black Soldier Fly Larvae" (BSFL) proposes an innovative approach to mitigate the escalating food waste issue in Singapore through sustainable practices and resource efficiency. It focuses on the design and implementation of a portable reactor system employing BSFL for the conversion of food waste into high-value byproducts such as animal feed and organic fertilizer. This initiative is set against the backdrop of Singapore's critical food waste problem, characterized by limited recycling and predominant disposal methods of incineration and landfilling, which contribute to greenhouse gas emissions and strain landfill capacities.

Singapore faces a significant challenge in food waste management, with the majority of waste being incinerated or landfilled, leading to environmental concerns and inefficiencies in resource utilization. The thesis critiques these conventional disposal methods for their environmental impact, particularly in terms of greenhouse gas emissions, and their failure to recover valuable resources from waste. In contrast, the research advocates for the BSFL-based system as a superior alternative, capable of converting almost all food waste into useful products, thus supporting the principles of a circular economy. This method not only offers an environmental solution but also aligns with Singapore's "30 by 30" vision, aimed at enhancing local food production resilience.

At the heart of the thesis is the development of a BSFL reactor system, engineered for application at the sites of food waste generation, such as eateries and markets. The system is conceptualized to be user-friendly, portable, and adaptable, enabling the decentralized

processing of food waste and reducing the dependence on centralized treatment facilities. The documentation details the reactor's design process, addressing the engineering challenges, and providing solutions to achieve effective BSFL breeding and food waste conversion. The reactor's components, including the container, cage, drawer slides, chassis, and electronics, are meticulously examined, emphasizing their optimization for functionality, durability, and ease of use.

The study stresses the importance of a design that is both scalable and flexible, allowing for the system's adaptation to various operational scales and settings. This focus on adaptability and scalability underlines the project's commitment to engineering solutions that are sustainable and pragmatically applicable across different urban environments. The narrative around the design process illustrates a thoughtful approach to innovation, rooted in sustainability and practicality.

Furthermore, the thesis underscores the collaborative nature of the project, highlighting the involvement of experts and stakeholders from fields such as mechanical engineering, electronics, and waste management. This multidisciplinary approach enriches the development of the reactor system, ensuring it meets technical standards while aligning with industry needs and sustainability goals. Through this collaborative effort, the project not only addresses the technical aspects of food waste recycling but also considers the broader implications for sustainability and resource efficiency.

In conclusion, the thesis presents a compelling case for the adoption of BSFL-based food waste recycling systems as a viable and sustainable solution to Singapore's food waste dilemma. By leveraging the bioconversion capabilities of BSFL, the proposed reactor system represents a significant step forward in the pursuit of a circular economy, offering a practical and environmentally friendly alternative to traditional waste management methods. Through detailed research and collaborative design, the study contributes valuable insights into the potential for innovative technologies to address environmental challenges and support sustainable development goals.

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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 constitutes a critical portion of Singapore's waste spectrum. Data presented in Table 1 reveal that in the year 2022, a noteworthy volume of 813,000 tonnes of food waste was produced, of which only 18% underwent recycling processes [1]. To contextualize this volume, it equates to the disposal of approximately two bowls of rice per person each day [2]. The bulk of unreclaimed waste is transported to incineration plants and subsequently deposited in landfills. Moreover, as depicted in Table 2, the recycling rate of food waste has remained relatively stagnant over the previous five years, fluctuating marginally between 17% and 19% [3]. This trend underscores the persistent challenge of food waste management and the necessity for enhanced recycling efforts within the region.

1.2 Default method of processing Food Waste

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

Currently, collected food waste is transported using large vehicles to four designated incineration facilities. This default method of processing presents three primary drawbacks. The initial concern arises from the aftermath of incineration, where food waste is transformed into residual byproducts such as ashes and non-combustible materials.

Although incineration achieves a notable 90% reduction in waste volume, the resultant 10% of residue still requires disposal at landfills [3]. This residue is subsequently transported to the Pulau Semakau landfill, where it accumulates, gradually consuming valuable landfill space.

Figure 2. Pulau Semakau landfill comparison [6].

The Pulau Semakau landfill, initially anticipated to accommodate waste until 2045, is now expected to reach its full capacity by 2035, a consequence directly attributed to the current practices in food waste management [7]. Figure 2 provides a visual comparison of the landfill's occupancy over two decades: the left segment of the figure shows the status in the year 2000, and the right segment depicts the situation as of 2020. In this illustration, cells shown in blue represent areas that were vacant at the time, and those filled to capacity are highlighted in green. This visual progression underscores the rapid rate at which landfill space is being consumed, prompting urgent reconsideration of waste management strategies to mitigate the impending capacity crisis.

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 delineated in Table 3, carbon dioxide was the predominant greenhouse gas emission in Singapore for the year 2021, constituting 93.30% of the total emissions [8]. A significant portion of these emissions, specifically 15%, can be attributed to waste incineration activities, translating to 7.5 million tons of CO_2 [9]. To put this into perspective, an average individual exhales approximately one ton of CO_2 over a period of roughly 1000 days. Additionally, the logistical process of transporting food waste to incineration facilities and landfills incurs a considerable carbon footprint, equating to the emissions of 39 million passenger buses annually [10]. This highlights the environmental impact of current waste management practices, particularly concerning the contribution of waste incineration to the nation's carbon emissions.

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

Finally, the prevailing food waste management practices pose a challenge to Singapore's "30 by 30" vision, which aspires to achieve food self-resilience by producing 30% of our nutritional needs locally by the year 2030, despite allocating less than 1% of our land for farming purposes [11]. Realizing this ambitious target requires the adoption of innovative strategies that optimize output from limited resources, ensuring that our agricultural methods are not only productive but also climate-resilient and efficient in resource utilization.

However, with the nation's population estimated at 6 million in 2023 and expected to reach 6.4 million by 2050 [12], the demand for food is anticipated to surge by 50% [12]. This increase implies a corresponding rise in food waste generation in the upcoming years. The conventional approach of incinerating food waste, resulting in its disposal in landfills or incineration plants, signifies a missed opportunity to reclaim potential nutrients. These nutrients could have been recycled back into the ecosystem as compost or utilized as animal feed, thereby enhancing soil quality and promoting sustainable agricultural practices within Singapore. Such an approach would align more closely with the "30 by 30" goal, supporting the nation's efforts towards achieving greater food security and sustainability.

1.3 Alternative methods of Processing Food Waste

Given the limitations associated with the current food waste management strategy, alternative approaches are being investigated to address these challenges more effectively. Among these alternatives, anaerobic digestion emerges as a promising method.

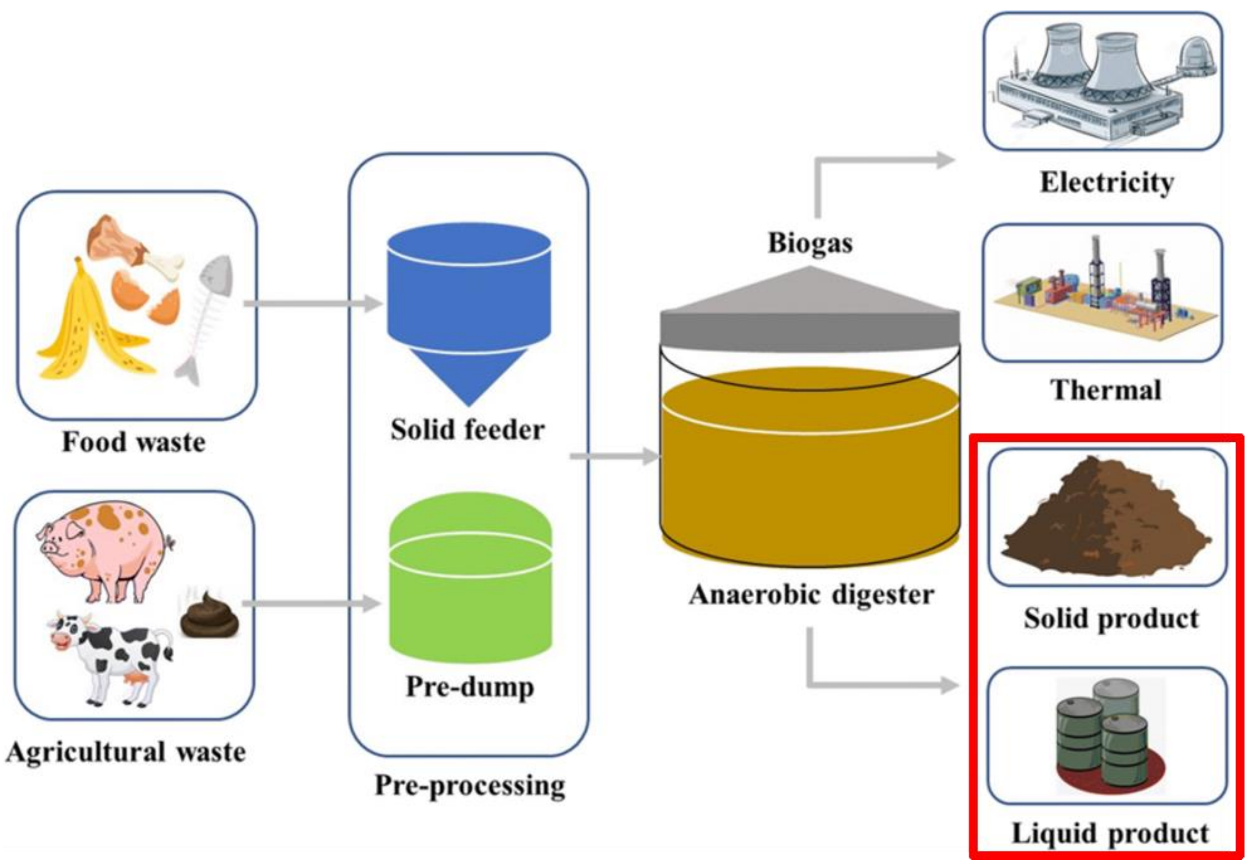


Figure 4. Anaerobic Digestion (AD) Process [13].

Anaerobic digestion is a bioconversion process that decomposes food waste enzymatically in the absence of oxygen. Illustrated in Figure 4, this microbial degradation process generates biogas, a mixture primarily of methane and carbon dioxide, along with a by-product known as digestate. The biogas produced can be effectively captured and utilized as a renewable energy source for generating electricity, providing heating, and fueling vehicles. Concurrently, digestate, following further processing, can serve as a nutrient-rich fertilizer for agriculture, enhancing soil fertility and productivity. Any residual waste not converted into biogas or digestate is then responsibly disposed of in landfill facilities [14], offering a holistic approach to managing food waste while contributing to sustainable energy and agricultural practices.

Although Anaerobic Digestion is viewed as a more environmentally friendly alternative to incineration, it is not without its drawbacks. Three primary concerns underscore its limitations:

1. Residual Waste Contribution: The process inevitably generates residual waste, which, despite the reduction in volume through digestion, still necessitates landfill disposal. This continued reliance on landfill space for disposing of residuals could hasten the rate at which disposal sites reach capacity, posing long-term sustainability challenges.

2. Carbon Dioxide Emissions: The biogas produced during Anaerobic Digestion, while a renewable energy source, contains carbon dioxide as a significant component. Consequently, the utilization of biogas as an energy source indirectly contributes to

Singapore's carbon dioxide emissions. This factor complicates efforts to achieve a substantial decrease in national greenhouse gas emissions, underscoring the need for a balanced approach to leveraging biogas as a sustainable energy solution.

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

3. Scalability and Research Challenges: The exploration of Anaerobic Digestion as a practical solution for waste management is in progress, with research to date largely confined to small-scale or laboratory settings. A notable initiative, illustrated in Figure 5, is a pilot project conducted at the East Coast Lagoon Food Village. This initiative, led by researchers from the National University of Singapore (NUS), showcases the potential of Anaerobic Digestion by transforming food waste from the venue into both biogas and bio-fertilizer [15]. By adopting this system, the project substantially diminishes the dependency on incineration and contributes to the ambitions of Singapore's Zero Waste

Masterplan. Despite the promising outcomes and insights gained from this pilot, it highlights the necessity for addressing specific challenges and making enhancements within such small-scale applications.

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

An additional innovative method under investigation for food waste management involves the utilization of insects. This strategy is gaining recognition for its sustainability and ecological benefits, presenting a viable alternative to traditional methods such as anaerobic digestion and incineration. Specifically, insects like the Black Soldier Fly Larvae (BSFL, illustrated in Figure 3, are adept at transforming food waste into valuable byproducts. These include protein-rich insect biomass and nutrient-dense frass, contributing to the reduction of greenhouse gas emissions in the process. This insect-based approach embodies the principles of a circular economy by ensuring that the generated byproducts are recycled back into the production cycle, thereby eliminating the necessity for landfill disposal and promoting resource efficiency [16].

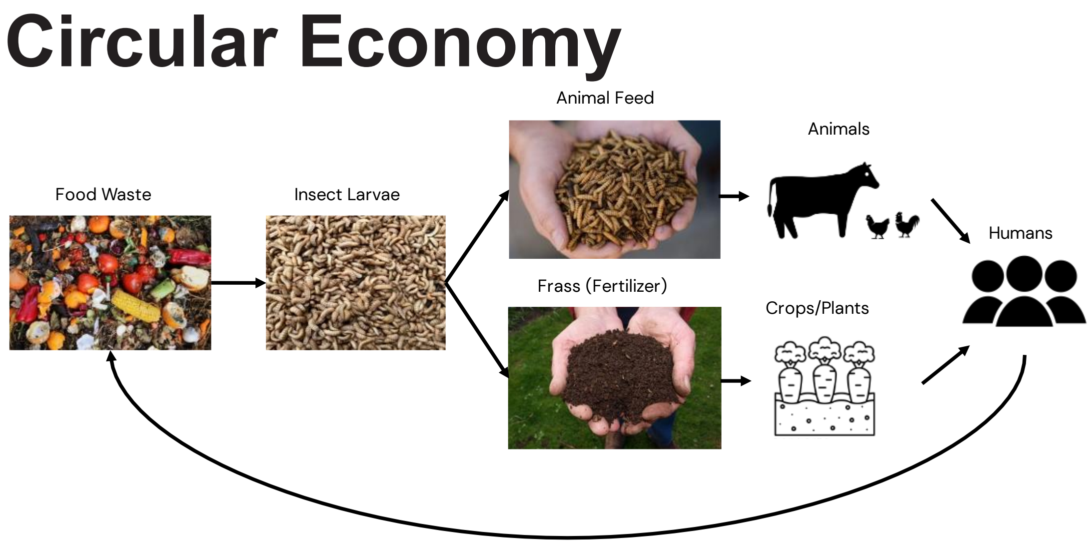


Figure 7. Circular Economy of Insects in Food Waste Management [4][16].

Insects offer a sustainable pathway by producing byproducts that serve as protein-rich feed for animals and nutrient-rich fertilizers, thereby improving livestock nutrition and supporting local crop production. These byproducts contribute to a regenerative cycle where the crops and livestock nourished by them eventually integrate into the human food chain, embodying the principles of a circular economy. This not only optimizes resource use but also closes the loop of food production, consumption, and waste management, promoting a more sustainable ecosystem.

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

In the comparative analysis provided in Table 4, three distinct methodologies for managing food waste—incineration, anaerobic digestion, and insect utilization—are evaluated with respect to their contributions to the circular economy, environmental sustainability, and the potential to bolster food security.

Circular Economy: Incineration processes, while effective in volume reduction, fall short of contributing to a circular economy due to the nature of its byproducts (ash and non-combustible materials) which necessitate disposal in landfills, thereby precluding effective recycling. In contrast, anaerobic digestion offers a more beneficial alternative by producing byproducts that can be converted into nutrient-rich fertilizers, thus supporting local agriculture and advancing the principles of a circular economy more effectively than incineration. Notably, the insect utilization approach outperforms both by transforming food waste into valuable resources such as protein-rich feed and fertilizers, thereby enhancing the sustainability of livestock nutrition and crop production. The utilization of these byproducts in agricultural practices effectively integrates them back into the human food supply, exemplifying the essence of a circular economy.

Environmental Sustainability: The environmental impact of these methods, particularly concerning carbon dioxide emissions, is critically assessed in Table 3. Incineration significantly contributes to CO_2 emissions, a concern compounded by the transportation of waste and its residuals. Although anaerobic digestion produces renewable biogas, the methane and carbon dioxide contained therein present sustainability challenges, and the need for landfill disposal of residual byproducts further complicates efforts to mitigate carbon emissions. Conversely, the insect-based approach emerges as the most environmentally sustainable option, converting food waste into biomass or frass rather than emitting greenhouse gases. This method significantly reduces the carbon footprint associated with food waste management and precludes the accumulation of waste in landfills, underscoring its considerable environmental advantages.

The comprehensive analysis provided in Tables 3 and 4 highlights the effectiveness of insect utilization in promoting a circular economy, enhancing environmental sustainability, and bolstering food security. This method stands out for its ability to alleviate the adverse environmental impacts traditionally associated with food waste management practices while facilitating the productive reuse of byproducts in agricultural activities. This represents a pivotal stride towards the realization of sustainable waste management and food production ecosystems.

The insect-based strategy is distinguished by its remarkable environmental benefits, primarily through the significant reduction of greenhouse gas emissions. It efficiently converts the bulk of nutrients present in food waste into biomass or frass, rather than releasing harmful gases into the atmosphere. This process not only circumvents the generation of environmentally detrimental byproducts but also prevents the unnecessary accumulation of waste in landfills.

Given Singapore's limited land availability and its substantial dependence on imported food, which accounts for 90% of the nation's food supply, the emphasis on enhancing local food production becomes increasingly critical [17]. The looming capacity challenges of the Pulau Semakau landfill, as depicted in Figure 2, underscore the urgency of this issue. Allocating additional land for waste management infrastructure would invariably encroach upon the space essential for agricultural endeavors, thereby undermining the '30 by 30' food security goal. Traditional methods such as incineration and anaerobic digestion exacerbate this predicament. Conversely, insect-based processing presents a viable alternative that eschews the need for landfill usage, thereby preserving valuable land for agricultural purposes and contributing to food security.

Hence, the exploration of insect-based technologies for food waste management emerges as a pressing necessity, aligning with three foundational goals:

1. Circular Economy: This approach champions the recycling of byproducts into the ecosystem, substantially minimizing waste and diminishing landfill reliance.

2. Sustainable Food Waste Management: The conversion of nutrients into biomass and frass markedly reduces the environmental footprint of waste management practices.

3. Enhanced Food Security: By minimizing the need for waste disposal infrastructure, more land can be dedicated to local food production, thus strengthening food security measures.

In summary, the adoption of insect-based food waste management holds the promise of advancing towards a more sustainable, efficient, and food-secure future, aligning with global sustainability goals and national food security objectives.

1.5 Why Black Soldier Fly Larvae (BSFL)

In evaluating various insect species for their suitability in food waste management, options such as maggots, BSFL, and mealworms were scrutinized. Based on several critical factors, BSFL emerged as the most viable candidate, distinguished by the following attributes:

1. Accelerated Decomposition of Food Waste: BSFL excel in the rapid breakdown of organic matter, showcasing unparalleled efficiency in food waste processing. Their capacity to consume up to four times their body weight daily [18] enables a significant reduction in food waste volume—between 50% to 80%—within mere days, dependent on waste composition and larvae density [19]. In contrast, mealworms consume around 34% of their body weight daily [20], and maggots ingest about twice their body weight in food waste per day [21]. This differential consumption rate positions BSFL as superior in processing speed and volume compared to mealworms and maggots.

2. Broad Diet Spectrum: BSFL exhibit a remarkable ability to digest a wide variety of organic waste, including challenging materials such as meats, dairy products, and fats [22]. This versatility enhances their utility in waste management, allowing for a broader range of food wastes to be efficiently processed. While mealworms demonstrate a capacity for decomposing plant-based materials and polystyrene foam [22], their effectiveness diminishes with meats and dairy products. Maggots, though effective in decomposing animal tissues, share similar limitations with mealworms in processing fats and dairy [23]. This capability renders BSFL uniquely adaptable and capable of handling diverse waste types.

3. Efficient Conversion into Valuable Byproducts: BSFL are exceptional in their ability to convert 100% of the food waste into biomass, achieving a complete transformation of waste and larvae into nutrient-rich feed and frass without leaving any residual waste for landfill disposal (Adrian Fuhrmann, personal communication, October 2023) [22]. Mealworms, while efficient in converting specific types of waste into valuable byproducts, are somewhat limited by the diversity of waste they can process effectively. Maggots' conversion efficiency is subject to various factors, including waste type and environmental conditions, requiring meticulous management to mitigate issues such as cannibalism and pathogen transmission [23], which may limit their practical application.

Considering these factors, BSFL stand out as a superior choice for food waste management, offering rapid decomposition rates, a versatile diet that accommodates a wide range of waste materials, and an unmatched efficiency in converting waste into valuable byproducts. This analysis underscores the potential of BSFL to significantly contribute to sustainable waste management practices, aligning with goals for a circular economy and environmental sustainability.

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)

Table 5 underscores the exceptional role of BSFL in food waste management, highlighting their unparalleled efficiency in decomposing organic materials, their capacity to digest a diverse array of food wastes—including challenging substances like meats, dairy products, and fats—and their extraordinary capability to convert nearly 100% of food waste into beneficial byproducts such as biomass and frass. This level of efficiency surpasses that of mealworms and maggots, which possess more restrictive diets and demonstrate variable effectiveness in waste conversion. The speed at which BSFL can reduce food waste volume by 50% to 80% within a span of a few days [19] further distinguishes them, alongside their ability to process a wide range of food waste types more effectively than their insect counterparts.

Nonetheless, the practical application of BSFL in waste management presents certain challenges. The requisite specific climatic and environmental conditions for their optimal development may restrict their deployment in cooler climates without the provision of controlled environments, potentially escalating operational costs. Odor management becomes a critical consideration when handling substantial volumes of food waste, necessitating measures to ensure an agreeable environment. Moreover, the need for specialized handling and processing techniques—such as timely larvae harvest to prevent maturation into flies and the efficient separation of larvae from frass—introduces additional complexity to BSFL utilization.

Despite these considerations, the advantages of integrating BSFL into waste management systems, particularly in terms of their high efficiency and significant contribution towards establishing a circular economy, render them a highly attractive option relative to mealworms and maggots. These merits invite further investigation and development to surmount the operational challenges associated with BSFL usage, reinforcing their potential as a sustainable solution in the domain of food waste management.

1.5.1 Life Cycle of Black Soldier Fly

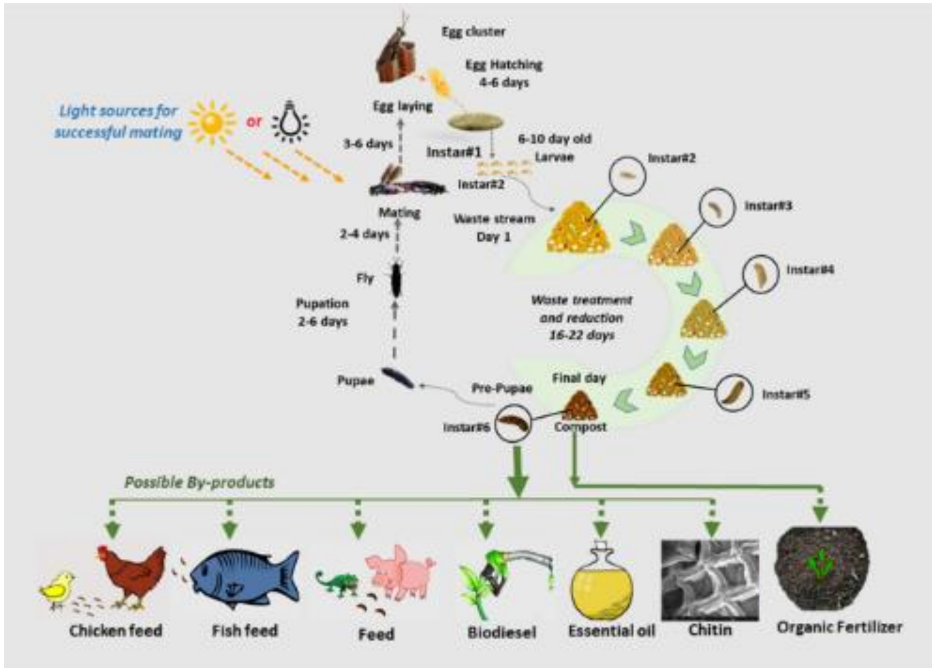


Figure 8. Black Soldier Fly Larvae (BSFL) Life Cycle [24].

Figure 8 delineates the typical life cycle of BSFL, providing crucial insights into their development phases relevant to food waste management. The diagram indicates that 5-day-old larvae (5DOL) are optimally poised for feeding initiation, marking the beginning of their utility in decomposing organic waste. The lifecycle progresses such that BSFL typically require around two weeks to advance to a stage where feeding activity ceases, identified as Instar#5 in the figure. It is at this critical point that the larvae are ideally harvested to prevent their transition into adult flies, a process that optimizes the efficiency of their use in waste management.

Following the collection of these mature larvae, they undergo dehydration, a process that transforms them into a valuable source of animal feed. This timing is strategic, minimizing the potential for the larvae to mature further and ensuring their optimal utility. In parallel, the byproduct of this lifecycle stage, known as frass—which consists of exoskeletons and excrement—emerges as a high-quality fertilizer. This dual-output approach, where both the larvae and frass are repurposed, underscores the efficacy and sustainability of utilizing BSFL in food waste management, reflecting a significant contribution to the circular economy by converting waste into valuable agricultural inputs.

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, there is a growing interest in adopting BSFL for food waste management. Notably, these initiatives are predominantly at the experimental or developmental stage, characterized by their small-scale nature, often conducted within centralized research facilities.

A notable example of such pioneering work involves a collaborative effort between esteemed institutions, including the Swiss Federal Institute of Technology Zurich (ETH Zurich), the National University of Singapore (NUS), and Nanyang Technological University

(NTU). This collaboration focuses on exploring the efficacy of BSFL in managing food waste and contributing to sustainable food production within urban settings. As depicted in Figure 9, the research is conducted on a laboratory scale, utilizing specialized reactors engineered to create optimal conditions for BSFL's feeding phase. These reactors are outfitted with a comprehensive suite of sensors and monitoring devices, enabling precise control and adjustment of environmental conditions within the reactors to maximize the larvae's efficiency (Adrian Fuhrmann, personal communication, October 2023).

This initiative underscores Singapore's commitment to innovative solutions for waste management and sustainable urban food production, highlighting the potential of BSFL as a viable option in the context of circular economy strategies.

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

In Singapore, Insectta stands out as a pioneering company in the realm of insect farming, particularly specializing in the utilization of BSFL technology for the conversion of food waste into valuable byproducts. This innovative approach aims to address the persistent issue of food waste by transforming it into high-value biomaterials. Among these are animal feed, organic fertilizer, and chitosan—a multifaceted compound finding applications in pharmaceuticals, cosmetics, and beyond. Insectta's methodology not only presents a solution to waste management challenges but also fosters the development of sustainable, circular economies by repurposing waste into resources [25].

As a key player in the burgeoning industry of insect farming, Insectta is at the forefront of sustainable agriculture and waste management practices. Their initiatives extend to research and development efforts focused on uncovering new uses for the byproducts of insect farming, aiming to amplify the technology's contribution to global sustainability and waste reduction.

Central to Insectta's mission is the innovative use of BSFL technology not just for food waste management but more importantly, for the transformation of waste into a spectrum of high-value products. Their strategy goes beyond simply establishing waste processing facilities; Insectta is dedicated to refining techniques that convert food waste into diverse, usable products [25]. This strategic focus is on broadening the scope of byproduct applications, exploring how these materials can be integrated across various sectors to spearhead sustainable solutions, underscoring Insectta's commitment to leveraging BSFL technology for the greater environmental good.

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

Protix, based in the Netherlands, stands as a pioneering entity in the field of BSFL cultivation, dedicated to the sustainable production of proteins. This company leads in the innovation of technologies and methodologies for transforming food waste into high-quality proteins, fats, and additional valuable byproducts through BSFL. Their initiatives are aimed at fostering sustainable food systems by offering alternative protein sources for the animal feed, aquaculture, and pet food sectors [26].

By leveraging the natural efficiency of BSFL in decomposing food waste into nutrient-dense biomass, Protix plays a crucial role in promoting a circular economy, characterized by minimal waste and the optimized use of resources [26]. Their efforts are instrumental in addressing global sustainability challenges, including the imperative for more eco-friendly food production techniques and the reduction of waste.

However, applying Protix's model in Singapore presents unique obstacles, primarily due to the nation's limited land resources. The expansive operations managed by Protix in the

Netherlands are not directly transferable to the space-constrained context of Singapore, necessitating a pivot towards smaller, decentralized facilities. These can be seamlessly integrated into Singapore's urban fabric, obviating the need for large tracts of land.

Moreover, a decentralized approach aligns with the objective to minimize the carbon footprint associated with the transport of food waste. Large, centralized facilities, while operationally efficient, often require food waste to be transported over considerable distances, thereby increasing carbon emissions. A decentralized model facilitates the processing of food waste in proximity to its generation, markedly curtailing transportation distances and the resultant emissions.

Hence, while Protix's innovative use of BSFL for sustainable waste management serves as an inspiration, the adaptation of their model to Singapore's context requires careful customization. This adaptation involves developing decentralized waste management strategies that respect Singapore's land constraints and environmental aspirations, underscoring the need for solutions that are both locally adaptable and environmentally considerate.

The advent of decentralized facilities for food waste processing introduces three primary advantages, pivotal for enhancing the efficacy and sustainability of waste management systems. Firstly, the capability for on-site waste processing inherent in decentralized facilities significantly mitigates the need for extensive food waste transportation. This proximity to waste generation points drastically reduces carbon emissions associated with the logistical aspect of waste management, presenting a substantial environmental benefit.

Secondly, decentralized facilities exhibit an inherent resilience and flexibility in the face of operational disruptions. The distributed nature of these systems allows for continued operation of unaffected units even when individual facilities encounter challenges, thereby maintaining the stability of the overall waste processing framework. This configuration also permits the exploration of varied approaches and the adaptation to site-specific environmental variables, such as fluctuating weather conditions and the diverse capacities for waste processing among facilities. Thirdly, the integration of community involvement in the operation of decentralized facilities serves as a catalyst for enhancing public engagement and awareness regarding food waste management and sustainability practices. By actively participating in these processes, community members gain a deeper understanding and appreciation of sustainable practices, fostering a collective sense of responsibility towards more environmentally friendly waste management solutions.

Decentralized facilities for food waste management offer a transformative approach with several key advantages:

1. On-Site Waste Processing: These facilities enable the processing of food waste in close proximity to its origin, significantly diminishing the necessity for its long-haul transport. This proximity greatly reduces carbon emissions associated with the transportation of food waste, aligning with environmental sustainability goals by minimizing the overall carbon footprint of waste management processes.

2. Resilience and Operational Flexibility: Decentralized systems exhibit enhanced resilience to operational disruptions. Should one facility encounter difficulties, the distributed nature

of these systems ensures that other units can maintain their operations, thus preserving the continuity and stability of the overall waste management framework. This distributed model also provides the agility to experiment with various processing methods and to adapt to local environmental variables, such as fluctuating weather patterns and the varying quantities and types of food waste produced by different locales.

3. Community Engagement and Empowerment: The implementation of decentralized facilities inherently involves local communities, both in terms of operational support and educational outreach. This engagement serves not only to elevate community awareness regarding the importance of efficient food waste management and sustainable practices but also to cultivate a collective ethic of responsibility and active participation in environmental stewardship. Through hands-on involvement and educational initiatives, community members become integral contributors to the sustainability ecosystem, fostering a culture of conservation and resourcefulness.

In essence, the deployment of decentralized food waste processing facilities represents a strategic move towards more sustainable, efficient, and community-centric waste management practices. This model not only addresses the logistical and environmental challenges associated with traditional centralized systems but also leverages local capacities and knowledge to enhance the efficacy and resilience of food waste management efforts.

Implementing a decentralized facility for BSFL processing introduces certain complexities that must be carefully managed:

1. Specialized Training and Knowledge: The operation of BSFL facilities demands specific expertise and skills. Ensuring comprehensive training for staff across all decentralized sites introduces an operational challenge, necessitating robust training programs to maintain high standards of operation.

2. Odor Management and Public Perception: Given their proximity to residential areas, decentralized facilities require diligent odor control measures and must proactively address community concerns regarding hygiene and safety. Effective communication and community engagement strategies are essential to mitigate any apprehensions and foster positive public perception.

3. Standardization and Quality Control: Maintaining uniform standards and ensuring the quality of outputs, such as larvae biomass and frass, across multiple decentralized facilities pose significant challenges. Implementing rigorous quality control protocols and standard operating procedures is critical to ensure consistency and reliability of the end products.

4. Equipment Adjustments and Adaptability: The transition to decentralized facilities necessitates a delicate equilibrium between standardization and adaptability in equipment and operational methodologies. Laboratory settings allow for precise calibration of equipment to control environmental conditions optimally for BSFL growth and facilitate experimentation. These conditions are vital for understanding BSFL's requirements and behaviors at various stages of food waste processing.

Moving to a decentralized model entails replicating these conducive conditions across diverse sites, each with its distinct environmental and operational dynamics. Unlike the homogeneity of laboratory environments, decentralized systems must be versatile, accommodating variations in climate, food waste composition, and facility capacities. This requires adaptable equipment and processes, alongside continual experimentation and refinement to ensure efficiency and efficacy.

In summary, while the advantages of utilizing BSFL for food waste management are evident, transitioning from controlled, small-scale experiments to broader, decentralized operations introduces a spectrum of new challenges. Addressing these complexities effectively is crucial for the successful expansion of BSFL-based food waste management strategies, underscoring the need for innovative solutions and strategic planning to realize a sustainable, scalable approach to food waste management in Singapore.

2. Proposed Solution

2.1 Our Vision

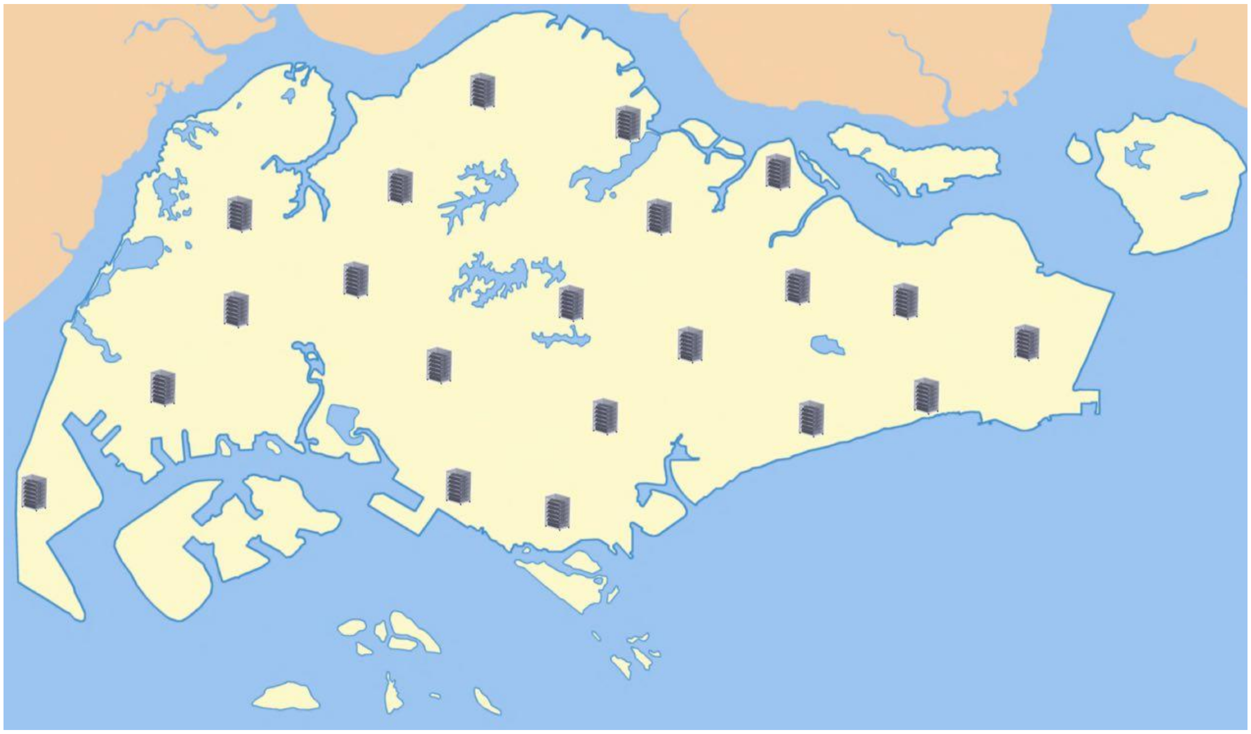


Figure 12. Our vision of our solution deployed across Singapore.

In pursuit of enhancing the integration of BSFL into the realm of food waste management, our proposed strategy advocates for a departure from the traditional centralized treatment model towards a more expansive, decentralized approach. As illustrated in Figure 7, our blueprint envisions the proliferation of independent BSFL reactors across a multitude of sites within Singapore, notably at food establishments and hawker centers. This innovative model is crafted to facilitate the on-site processing of food waste, thereby curtailing the reliance on extensive transportation networks. Given the acute challenge of land scarcity in Singapore, this decentralized model markedly diminishes the demand for large-scale treatment facilities.

At the heart of this envisioned strategy lies the principle of decentralization, aimed at augmenting the overall efficiency and sustainability of the food waste management process. By situating independent reactors directly at the sites of food waste generation—such as restaurants and food stalls—we endeavour to significantly lower the carbon footprint engendered by the transportation of waste to centralized facilities. This initiative promises not only a reduction in transportation-related expenses but also a notable decrease in carbon emissions, aligning with environmental sustainability goals.

The introduction of on-site reactors is poised to revolutionize the immediate treatment of food waste, facilitating prompt and effective management practices. This method not only embodies the essence of a circular economy but also ensures that the resultant byproducts are directly reincorporated into the local ecosystem, fostering resource conservation and environmental stewardship.

Moreover, recent regulatory developments underscore the timeliness and necessity of this approach. Legislation now requires that space for on-site food waste treatment systems be incorporated into the architectural plans of new developments, a mandate effective since January 1, 2021 [27]. Furthermore, the gradual introduction of food waste segregation and reporting protocols, specifically targeting new constructions from January 1, 2024 [27], reinforces the relevance and urgency of adopting our proposed decentralized model.

Through the strategic decentralization of food waste management and the deployment of autonomous reactors across strategic locations, we aim to forge a more efficient and environmentally harmonious system for food waste disposal in Singapore. This forward-thinking model holds the promise of transforming food waste management practices, minimizing transportation-induced emissions, and fostering a more sustainable urban ecosystem, thereby making significant strides towards a greener future.

2.2 Our Objective and Scope

The overarching goal of this initiative is to design and implement an upscaled, deployable reactor for on-site treatment of food waste, with the following key objectives:

1. Achieving Circular Economy: The primary aim is to engineer a reactor capable of not just processing food waste but also transforming it into valuable byproducts, such as nutrient-rich fertilizer and protein-rich animal feed. This strategy aligns with the ethos of a circular economy, wherein the lifecycle endpoint of one product transitions into the starting point for another, thereby converting food waste into a valuable resource.

2. Promoting Environmental Sustainability: The project seeks to significantly reduce greenhouse gas emissions by processing food waste directly at the point of generation, eliminating the need for its transportation to centralized treatment facilities. Furthermore, employing BSFL for waste processing is inherently more energy-efficient than conventional methods like incineration or anaerobic digestion, contributing to a reduction in overall energy consumption.

3. Enhancing Food Security: By advocating for the on-site processing of food waste across a variety of settings, the initiative aims to diminish reliance on traditional incineration facilities. This not only liberates valuable land for alternative uses but also facilitates the potential for these areas to be repurposed for local agricultural practices. Such a strategic pivot not only

tackles the challenge of efficient waste management but also significantly bolsters Singapore's food security by promoting local crop cultivation.

In pursuit of these objectives, we have commenced the development, design, and experimental testing of a prototype portable BSFL reactor. This reactor is intended to support the ongoing research at the NUS BSF Laboratory while being readily deployable at sites of food waste generation throughout Singapore. Serving as a crucial instrument for future inquiries and enhancements in BSFL-based food waste management strategies, this reactor is designed with careful consideration of the larvae's biological needs and the operational demands of various food-producing entities. This endeavor represents a significant step towards realizing sustainable, efficient food waste treatment solutions that align with environmental sustainability and circular economy principles.

2.3 Target Venue

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

Positioning the initial stages of development and testing within the Black Soldier Fly (BSF) Research Laboratory at the NUS, as depicted in Figure 13, represents a pivotal step in our project's progression. This deliberate choice to utilize the NUS lab as the nexus for early-phase innovation highlights our dedication to conducting thorough scientific research and fostering breakthroughs in technology. The lab's controlled setting is ideal for our team to conceptualize, design, and prototype a deployable reactor aimed at on-site management of food waste. This initiative not only capitalizes on the sophisticated research infrastructure and vast knowledge base present at NUS but also resonates with our overarching goal of making a meaningful impact in the realm of sustainable waste management.

Within the confines of the NUS lab, our endeavour focuses on the iterative enhancement of our prototype, striving to achieve optimal levels of efficiency, environmental sustainability, and adaptability. This foundational stage is indispensable, as it facilitates exhaustive evaluation, adjustment, and refinement of the reactor's design and functional parameters. Embracing this detailed-oriented methodology allows us to identify and surmount foreseeable hurdles, thereby improving the reactor's efficacy and its versatility for application in various contexts.

The primary aim of embarking on this preliminary phase at NUS is to solidify a robust basis for the reactor's subsequent application in practical settings. Following thorough validation and refinement within the laboratory environment, our strategy entails the deployment of the reactor across diverse food waste production locales throughout Singapore. This graduated deployment model ensures that, upon its introduction to operational environments, the reactor is thoroughly prepared to address the exigencies of on-site food waste treatment, thereby advancing our commitment to nurturing a circular economy, bolstering food security, and fostering a more sustainable urban landscape.

2.4 Value Proposition

The deployment of our proposed solution offers a multitude of benefits across various stakeholders, delineating a comprehensive impact on the ecosystem of waste management, agriculture, and sustainability:

1. Food Establishments: This project presents a significant opportunity for food establishments by introducing an innovative method to convert food waste into valuable byproducts. Through the adoption of our reactor technology, these entities can not only mitigate their waste management costs but also potentially generate revenue through the sale or utilization of derived byproducts, such as organic fertilizer and protein-rich animal feed. This approach not only contributes to environmental sustainability but also enhances the establishments' operational efficiency and corporate responsibility profiles.

2. Local Farms: Serving as the primary recipients of the reactor's byproducts, local farms stand to gain substantially from the nutrient-rich frass and larvae produced. The application of frass as an organic fertilizer can significantly improve soil fertility, leading to healthier crops and higher yields. Simultaneously, the larvae offer a sustainable, high-protein feed option for livestock, bolstering the overall nutrition and productivity of farm animals. This dual benefit streamlines the supply chain for organic inputs, reinforcing the sustainability and resilience of local agricultural practices.

3. Government: The introduction of our project is poised to make a tangible contribution to governmental waste management strategies. By diverting food waste from the traditional disposal routes of landfills and incineration, the project aids in prolonging the operational life of facilities like the Pulau Semakau landfill and reducing the fiscal burden associated with waste processing. Moreover, the promotion of BSFL-based waste management practices is synergistic with broader governmental objectives aimed at sustainable agriculture and food security. By decreasing reliance on imported food through enhanced local production capabilities, the initiative fosters national self-sufficiency and resilience in food supply chains.

In essence, the proposed BSFL reactor project embodies a paradigm shift in how food waste is perceived and managed, transforming it from a disposal challenge into a resource opportunity. Through its implementation, food establishments and local farms are empowered to contribute actively to a circular economy, while the government benefits from more sustainable waste management practices and strides towards agricultural self-reliance. This collaborative approach marks a stride towards realizing a more sustainable and self-sufficient future.

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 delineates the critical criteria that must be satisfied by our proposed solution, based on extensive research findings and prevailing industry norms. These benchmarks are pivotal in crafting an environment that maximizes the growth and productivity of BSFL and ensures the generation of optimal byproducts. The outlined initial values act as a compass for our experimental phase, laying the groundwork for the development of a reactor that aligns with the biological necessities of BSFL and the technical requirements of effective food waste management.

In addition to adhering to these established prerequisites, our approach encompasses the gathering of proprietary data throughout the experimentation phase. This data acquisition is aimed at refining our understanding of the specific conditions that foster the most efficient conversion of food waste into valuable byproducts within our unique operational framework. By integrating both the foundational knowledge from existing research and the insights gained from our proprietary investigations, we aim to customize and calibrate the operational parameters of our reactor to suit the specificities of our context.

This dual strategy ensures that our solution is not only grounded in proven scientific and industry practices but also tailored to address the particular challenges and opportunities presented by our deployment environment. The ultimate goal is to optimize the BSFL-based waste management process, enhancing its effectiveness, sustainability, and scalability within the context of our project.

Figure 14. Lift Dimensions in NUS Engineering Block E2.

Figure 15. Door Dimension in NUS Engineering Block EA.

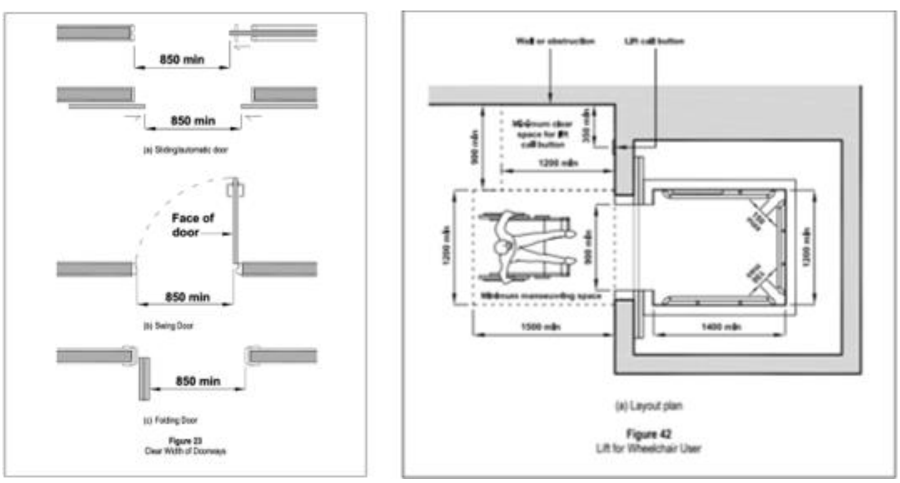


Figure 16. BCA Guidelines for Doors and Lifts [27]. (Refer to Appendix 7.1)

1. In formulating the sizing criteria for our reactor, we undertook extensive research aimed at ensuring its seamless integration within the existing infrastructure of the National University of Singapore (NUS) and, prospectively, across various

deployment sites throughout Singapore. Understanding the imperative of navigability and compatibility with the physical environment, our team conducted a thorough survey within the NUS campus. This involved measuring the dimensions of corridors, doors, lifts, and walkways—essentially, every possible pathway through which our reactor would need to be maneuvered. The dimensions and spatial constraints encountered were carefully recorded in Figures 14 and 15.

To transcend the specific architectural considerations of NUS and accommodate a wider array of potential deployment environments, we engaged with the Building and Construction Authority (BCA) Singapore's guidelines, as illustrated in Figure 16. This examination was instrumental in ensuring our design conformed to prevailing standards for corridors, doors, and lifts, as stipulated by BCA. By adhering to these benchmarks, we established a set of dimensional criteria for our reactor that not only suits the NUS setting but also is optimized for broader applicability, pre-emptively addressing logistical hurdles that may arise during the transportation and installation phases [27].

Consequently, based on our comprehensive analysis and adherence to both specific and general guidelines, we determined the optimal dimensions for our reactor to be 2 meters in length, 1.2 meters in width, and 0.85 meters in height. This specification ensures that our reactor is both functional within the constraints of urban educational institutions like NUS and adaptable enough for efficient deployment in diverse settings across Singapore, paving the way for a scalable and versatile solution in food waste management.

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

2. To define the operational capacity needed for our reactor to efficiently manage food waste, we conducted a case study focusing on the food court at the National University of Singapore's University Town (NUS UTown). Through targeted interviews with the cleaning personnel at the UTown food courts, we were able to obtain critical data regarding the daily production of food waste. The findings indicated that the food court generates approximately one full bin of food waste each day, which equates to about 120 Liters in volume.

   Given the variability in food waste density across different venues, it was crucial to establish a baseline density value to inform the design and capacity planning of our reactor. Through a review of relevant literature, we determined an average food waste density of 1.565 Kilograms per liter. Applying this density to the daily volume of food waste from the UTown food court yields an estimated total of approximately 187.8 Kilograms of food waste generated each day.

This quantification of food waste volume and density serves as a foundational parameter for our reactor design, enabling us to tailor the reactor's capacity to the specific needs and waste generation rates of the UTown food court. Furthermore, this approach provides a scalable model that can be adjusted according to the food waste characteristics of different deployment locations, ensuring that our solution is both effective and adaptable to varying operational contexts.

3. Identifying the optimal environmental conditions conducive to the thriving and efficient bioconversion activity of BSFL constitutes a vital aspect of our project. In our pursuit to delineate these essential parameters, we have anchored our methodology in a thorough examination of existing scholarly literature coupled with invaluable insights garnered from domain experts. A cornerstone of our research has been our collaboration with Adrian Fuhrmann, a committed investigator within the National University of Singapore's BSF Laboratory.

   Adrian's pioneering work, which involves the employment of reactors akin to those envisioned in our project, plays a pivotal role in elucidating the exact environmental conditions that enhance the bioconversion efficacy of BSFL. As depicted in Figure 9, these reactors function as an experimental platform to probe into the specific needs of BSFL, encompassing aspects such as optimal temperature, humidity levels, and the composition of food waste.

   Drawing from the collective insights obtained from both the literature review and Adrian’s hands-on research, we have pinpointed a spectrum of environmental conditions that are fundamental to the survival, growth, and bioconversion efficiency of BSFL [28]. These identified parameters are meticulously calibrated to not only sustain the lifecycle of the larvae within our reactor design but also to maximize their capacity for food waste processing.

This holistic approach ensures that our reactor design is scientifically informed and fine-tuned to facilitate the highest possible levels of waste bioconversion by BSFL, thereby enhancing the sustainability and efficiency of food waste management practices.

4. In our exploration of the potential of BSFL for food waste reduction, we embarked on a comprehensive literature review and examined the experimental work conducted by Adrian Fuhrmann at the NUS Black Soldier Fly Laboratory. Adrian's cutting-edge research presents BSFL as an exceptionally efficient bioconversion agent, capable of transforming 100% of food waste into biomass. This finding underscores the significant potential of BSFL as a solution for food waste management. Nonetheless, a broader examination of scientific studies yields a more conservative conversion efficiency, with estimates suggesting that BSFL can achieve an 80-90% reduction in food waste mass [29].

   Confronted with this discrepancy in reported efficiencies, our team has resolved to conduct our empirical investigation to ascertain the bioconversion efficiency of BSFL within our unique operational setting. We have initially set a conservative expectation for food waste mass reduction, intending to establish a baseline for BSFL's bioconversion performance under our specific conditions. This empirical approach will enable us to accurately gauge the extent of food waste mass reduction achievable by BSFL, grounding our project's ambitions and objectives in solid experimental evidence.

By undertaking this research, we aim not only to validate the promising capabilities of BSFL but also to refine our understanding of their efficiency in reducing food waste mass in a contextually relevant manner. This foundational knowledge will be instrumental in accurately projecting the impact of our BSFL-based food waste management solution, ensuring that our objectives are both realistic and aligned with empirical data.

3. Concept Design

3.1 Overall process of Reactor

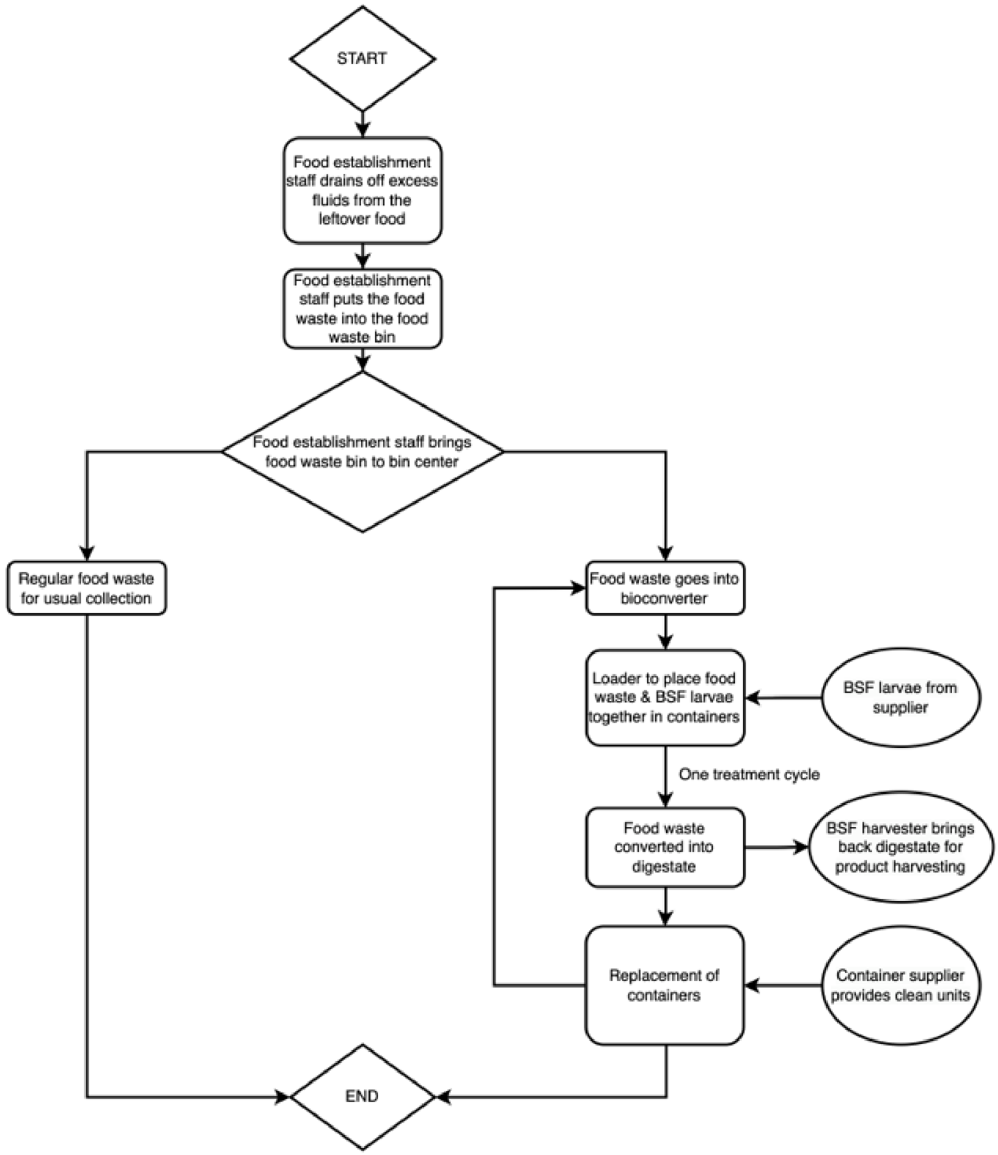


Figure 18. The overall flow of how the envisioned reactors will work.

Figure 18 graphically represents the operational paradigm of our proposed solution in comparison to traditional food waste treatment methodologies. In the innovative reactor system we propose, food waste enters the system and is transformed by BSFL into valuable byproducts. These byproducts, including nutrient-rich frass for fertilizer and protein-dense larvae biomass for animal feed, are then reintegrated into the system, creating a self-sustaining loop of resource utilization. This design paradigm embodies the principles of a closed-loop system, characterized by its zero-waste ethos and its emphasis on the sustainable and efficient use of resources.

Through this approach, our reactor not only addresses the issue of food waste management but also contributes to the broader objectives of environmental sustainability and resource conservation. By ensuring that every component of the waste is converted into usable products, the system minimizes environmental impact and maximizes the value extracted from waste materials. This contrasts sharply with conventional treatment methods, where the end products often require external disposal or processing pathways, leading to additional energy consumption and potential waste generation. Our envisioned reactor system, as depicted in Figure 18, therefore offers a forward-thinking solution to food waste challenges, aligning with global sustainability goals and promoting a more circular economy.

3.2 Overall Concept Design

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

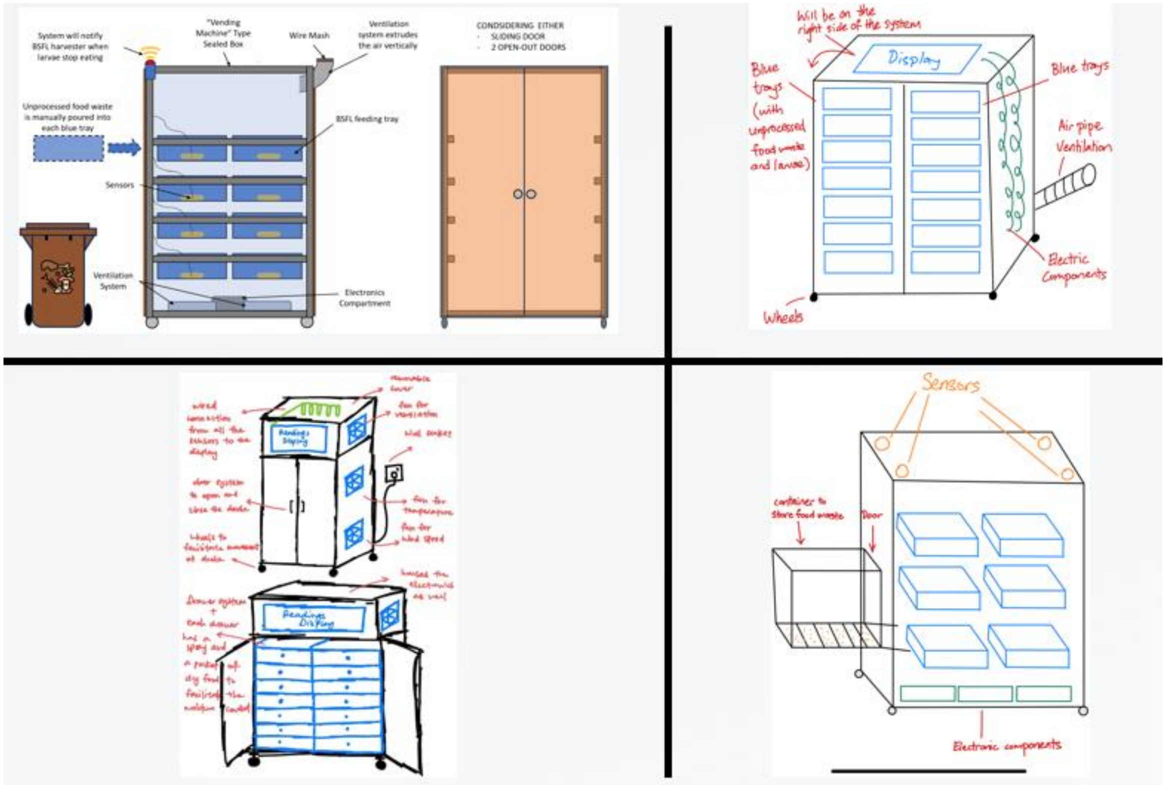


Figure 20. Concept ideas.

Drawing upon the existing reactor (illustrated in Figure 9) and the rack system (depicted in Figure 19) utilized within the laboratory framework, our research team embarked on a conceptual development phase for our proposed reactor design, as showcased in Figure 20. This design phase was rigorously guided by the dimensions and specifications outlined by the Building and Construction Authority (BCA), ensuring compliance with established architectural and safety standards.

In the process of synthesizing our design concepts, it became apparent that our proposals predominantly centered around the innovative use of multiple containers designated for the storage of food waste. Conceptualized to be arranged in a tiered fashion, these containers are designed to optimize space by being stacked at various levels within the reactor system.

This arrangement facilitates a modular approach to food waste management, allowing for the segregation and processing of waste in an organized manner.

To ensure the integrity and operational efficiency of the system, an outer shell is envisaged to encase the entire assembly of containers. This structural enclosure is intended to serve multiple functions: it provides a protective barrier against external environmental elements, maintains optimal conditions conducive to the biological processes undertaken by the BSFL, and secures the reactor's integration into its intended environment, whether it be in urban settings or specialized facilities.

This approach reflects our team's commitment to leveraging existing technological insights while innovating to meet the challenges of sustainable food waste management. The utilization of a multi-container setup within a unified structural framework epitomizes our vision for a scalable, adaptable, and efficient solution, poised to address the complexities of waste processing in varied contexts.

3.3 Sub-Systems

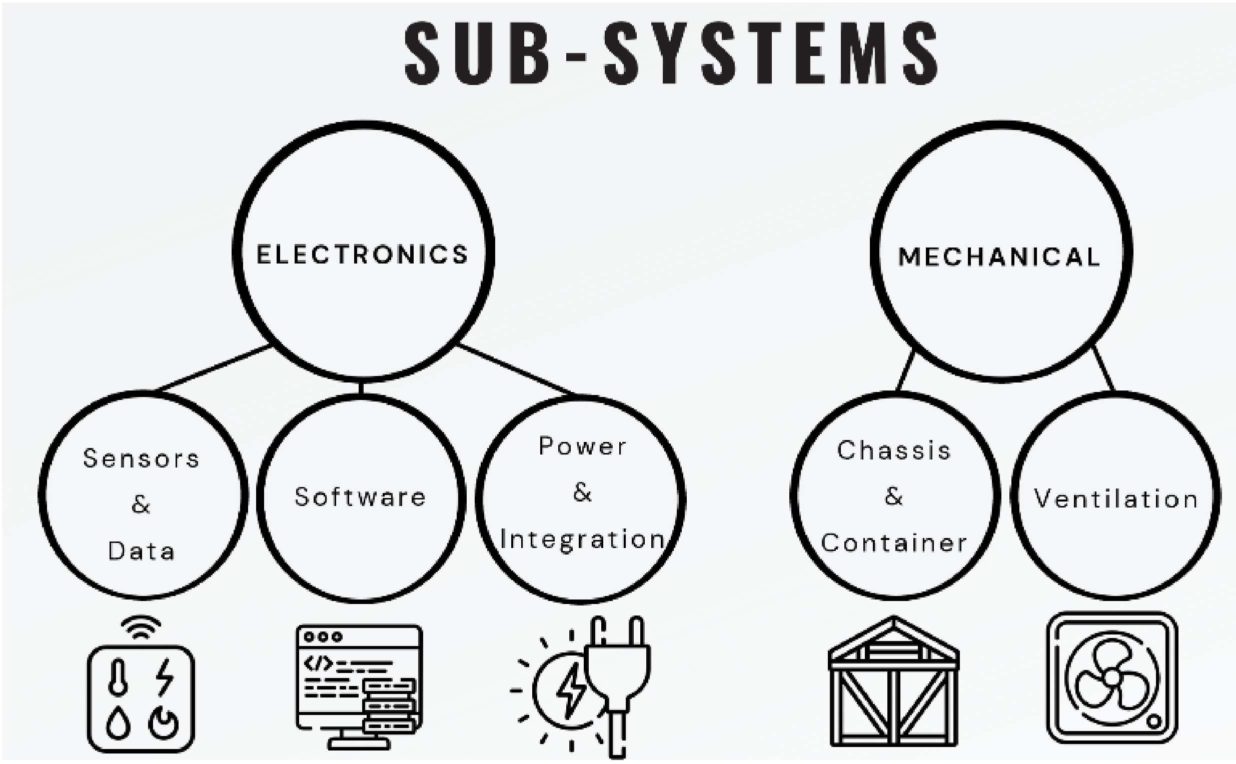


Figure 21. Sub-systems identified for our project.

In alignment with our conceptual reactor design, Figure 21 delineates the internal subsystems integral to our project's architecture. We have methodically segmented the electronics domain into three specialized sub-systems, each engineered to fulfill distinct operational needs:

1. Sensors and Data Collection: This crucial sub-system incorporates the meticulous selection, calibration, and deployment of sensors, facilitating the extraction of pivotal data. Its primary purpose is to guarantee accurate monitoring and data acquisition, ensuring the system's parameters are continuously observed and analyzed for optimal functioning.

2. Software and Automation: Central to the project's intellectual framework, the software sub-system underpins the programming and automation processes. It empowers the

system to autonomously adjust its internal conditions, enhancing the reactor's adaptability and performance through real-time computational analysis and modifications.

3. Power Supply and Electronics Integration: Tasked with managing the power supply and the harmonious integration of all electronic components, this sub-system is foundational to the seamless and efficient operation of the electronics infrastructure. It ensures that the electronic elements function cohesively, supporting the reactor's overall performance.

Parallelly, the mechanical domain is divided into two distinct sub-systems, each addressing specific structural and operational facets of the project:

1. Chassis and Container Design: Focused on the development and fabrication of the chassis and containers, this sub-system lays the physical groundwork for the project. The chassis provides the critical support structure for the reactor, encapsulating the systems within, while the containers are designated for housing the food waste and BSFL. This component is instrumental in maintaining the reactor's structural integrity and facilitating its core waste processing function.

2. Ventilation System: Dedicated to ensuring adequate ventilation within the reactor, this sub-system is paramount in sustaining the environmental conditions conducive to the BSFL's bioconversion activity. Effective ventilation is essential for regulating temperature, humidity, and air quality, thereby optimizing the internal ecosystem for the larvae's growth and waste processing efficiency.

Collectively, these subsystems—spanning both electronics and mechanical domains—form the backbone of our reactor design, each contributing uniquely to the system's overall efficacy and sustainability. Through this integrated approach, we aim to construct a reactor that not only excels in food waste bioconversion but also exemplifies cutting-edge engineering and operational excellence.

3.4 Mechanical systems goal

From the standpoint of the mechanical team, our overarching goal is to enhance the reactor's portability and ease of use. Although our immediate focus is to provide researchers with a flexible instrument for conducting laboratory experiments, we are strategically designing with an eye toward future broad-scale implementation within Singapore's varied food service environments. Our emphasis on developing a reactor that is both easily transportable and user-friendly is pivotal. This design philosophy ensures that the reactor is versatile enough to function efficiently across different scenarios, thereby supporting the research phase by enabling simple adjustments to operational parameters and internal conditions.

This foresighted approach is instrumental in not only facilitating the ongoing research activities but also in paving the way for a seamless transition to practical application in real-world settings. By prioritizing the reactor's adaptability and simplicity in operation, we aim to mitigate potential operational hurdles that could arise in a diverse array of usage contexts. Consequently, our prototype is envisioned as a straightforward, effective tool for on-site food waste management, designed to overcome the common challenges associated with deploying new technologies in varied environments. Through this meticulous design process, we are laying the foundation for a solution that promises to streamline food waste management processes, enhancing sustainability and operational efficiency in Singapore's food service industry.

3.5 Sizing of Chassis

As detailed in Section 2.5, particularly under the subsection addressing design requirements, our approach to determining the chassis dimensions was guided by two principal considerations. Firstly, we took into account the physical dimensions of walkways, lifts, and doors within the NUS, ensuring that the reactor could be easily navigated through these spaces. Secondly, we adhered to the guidelines and stipulations provided by the Building and Construction Authority (BCA) of Singapore. This adherence ensures that our design is not only suitable for the immediate context of NUS but also complies with broader standards that would facilitate its deployment across various locations in Singapore. For an in-depth exploration of how these critical factors have shaped our design approach, readers are directed to Section 2.5, specifically Point 1, where these considerations are elaborated upon. This section provides a comprehensive overview of the chassis sizing strategy, underpinning the rationale behind our design decisions and illustrating how they align with the operational and regulatory landscapes.

3.6 Current Storage used in BSF Laboratory in NUS

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

In the preliminary stage of our study, we conducted a thorough analysis of two unique containers utilized in the BSFL research laboratory. The first container, which is used alongside the racks depicted in Figure 22, is characterized by its relatively short height and a tiered structure that includes noticeable gaps between the layers.

Figure 23. Current containers used in the reactors.

In contrast, the second container, which is specifically engineered for the reactor depicted in Figure 23, features a taller design with perforations added to its increased height to enhance airflow. This design consideration is crucial for promoting a conducive environment for BSFL activity within the container.

The primary differentiation between these two container types, as showcased in Figures 22 and 23, resides in their intended operational contexts. The container associated with Figure 22 is adapted for use in non-controlled environments and is part of a more open setup, while the container featured in Figure 23 is tailored for use within the controlled environment of the reactor. The design of the latter container facilitates vertical stacking within the reactor's confines, fostering efficient spatial use and enabling precise control over environmental conditions.

However, the vertical stacking arrangement presents a logistical challenge in terms of accessibility: to reach the containers at the bottom, it becomes necessary to remove the ones positioned above. This aspect of the design limits the current reactor's capacity to three containers, underscoring the need for a redesign or adaptation of the internal rack system. The objective of this redesign would be to accommodate a greater number of containers within the reactor, thereby enhancing its operational capacity while still maintaining the essential features of the closed structure integral to the reactor's design.

This exploration into developing an alternative internal rack system seeks to expand the reactor's container capacity effectively, ensuring that the structural and environmental control offered by the reactor's enclosure is not compromised. Through such modifications, we aim to improve the reactor's functionality and adaptability, making it more suited to the demands of BSFL-based food waste processing in a variety of settings.

3.7 Current Loading and Unloading of containers

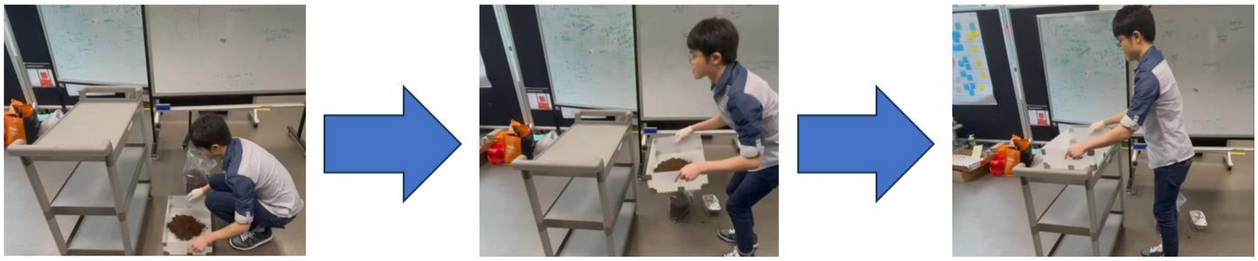


Figure 24. Current method of loading containers.

Figure 25. Current method of unloading containers.

In the course of our examination, we closely analyzed the existing methods employed by researchers for the loading and unloading of containers to and from the racks. Our observations revealed a labor-intensive and repetitive procedure, demanding considerable physical effort from the personnel involved. This current process requires the frequent handling of containers, each with an approximate weight of 8 kilograms, leading to a cycle of constant lifting and lowering activities, as depicted in both Figure 24 and Figure 25.

Based on these findings, we recognized the imperative need to devise more ergonomic and user-friendly strategies for the loading and unloading operations within our reactor system. The primary objective of this development is to significantly reduce the physical burden placed on users during these essential tasks. By innovating in this direction, we aim to enhance the overall usability and efficiency of our reactor system, ensuring that it not only meets the operational demands of BSFL-based food waste processing but also addresses the well-being and operational ease of the research staff and future users.

3.8 Loading and Unloading Concept designs

3.8.1 Loading Concept designs

In the initial stages of conceptualizing the loading mechanism for our reactor design, our team investigated the possibility of incorporating a top opening to simplify the process of introducing food waste into the system. The aim behind this design choice was to enable a more efficient and uniform distribution of food waste into the designated containers housed within the reactor. This approach, however, encountered significant obstacles, primarily stemming from the complexity of the mechanisms involved.

The incorporation of a top opening mechanism necessitated the development of intricate, potentially cumbersome operational features that could lead to an overcomplicated and impractical solution for our intended use. Such complexities might not only hamper the ease of use but also affect the reliability and maintenance requirements of the reactor, factors that are critical for the long-term sustainability and user-friendliness of the system.

Given these considerations, our team acknowledged the need to reassess our approach to the reactor's loading mechanism, with a focus on striking a balance between operational efficiency and simplicity. This realization underscored the importance of designing with practicality in mind, ensuring that our reactor remains accessible and manageable within the dynamic environments it is envisioned to serve.

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

Subsequently, our focus shifted towards exploring an alternative method that involves the use of pumps integrated within the food waste bin. This concept envisioned the pumping of food waste directly into the reactor's designated containers, guided by an operator controlling the nozzle. This method promised a streamlined and efficient mechanism for waste distribution, as conceptualized in Figure 26.

Despite its initial appeal, the idea of implementing a food pump system was ultimately deemed unsuitable for our project due to several critical drawbacks:

1. Substantial Cost Implications: The initial investment required for the acquisition, installation, and integration of a food pump system poses significant financial challenges. Beyond the purchase price of the pumps themselves, the costs associated with setting up, integrating into the existing infrastructure, and the requisite ongoing maintenance would substantially increase the project's budget.

2. Reduced Flexibility in Waste Handling: Fixed pump systems may lack the versatility needed to manage varying quantities of waste or to process waste of different types and consistencies effectively. This limitation could hinder the system's ability to adapt to the diverse range of food waste typically generated in a food service environment.

3. Sanitation Concerns: Mechanical systems, particularly those involved in food waste management, necessitate rigorous cleaning and sanitation protocols to prevent bacterial contamination. Ensuring the cleanliness of a food pump system would require regular, possibly intensive, sanitation efforts, posing additional operational challenges, especially within food handling areas.

4. Mechanical Complexity: The operational and maintenance demands of a food pump system require skilled personnel, trained in its use and upkeep. The need for such specialized staff may not be practical or feasible for all establishments, particularly those with limited resources or access to technical expertise.

Given these considerations, our team concluded that the incorporation of a food pump system, despite its potential advantages in waste distribution efficiency, does not align with our project's goals of simplicity, cost-effectiveness, and operational flexibility. This decision underscores our commitment to developing a reactor design that is practical, user-friendly, and adaptable to the needs of diverse food service settings.

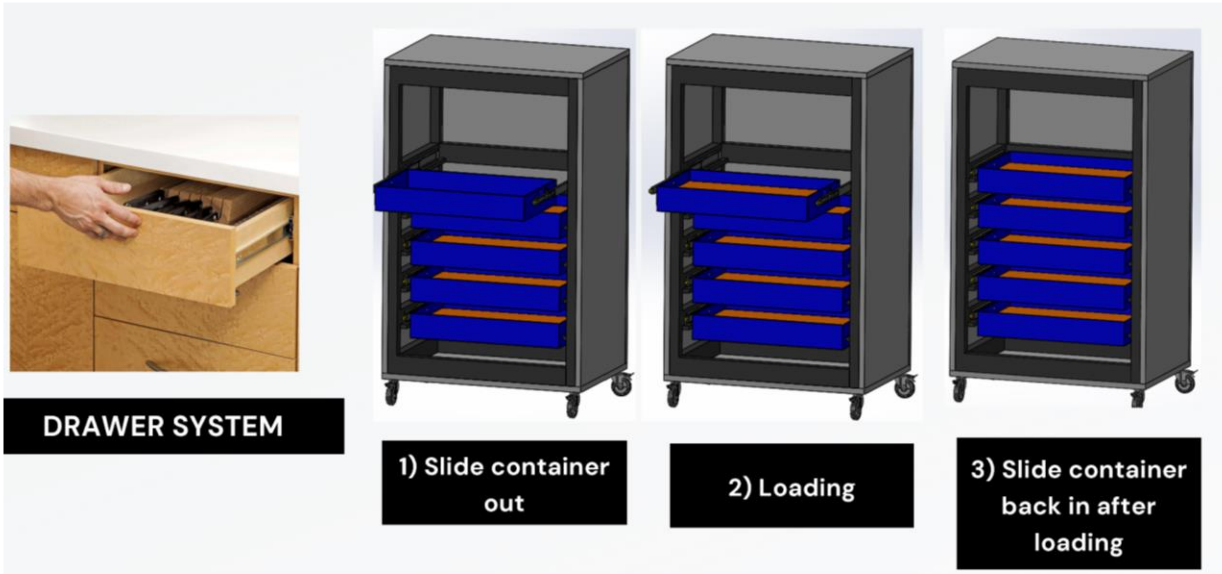


Figure 27. Drawer system loading concept.

Consequently, our exploration led us to conceive a drawer-style system, wherein containers can be directly attached to the reactors. This innovative design enables staff to deposit food waste straight into the containers, eliminating the need for the separate handling and transportation of the containers to the reactor, as illustrated in Figure 27.

The adoption of a drawer system is primarily favored for two significant reasons:

1. Control over Weight and Distribution: With this system, the personnel tasked with loading the food waste into containers are afforded precise control over the weight and even distribution of the waste. This meticulous approach to waste management ensures that the containers are optimally filled, maintaining balance and maximizing the use of available space. Such precision in loading practices not only improves the efficiency of the bioconversion process but also contributes to the overall performance of the reactor system.

2. Ergonomic Efficiency: The design of the drawer system prioritizes ergonomic considerations, positioning the containers at waist height to facilitate ease of access. This

strategic placement markedly reduces the necessity for loaders to engage in repetitive bending or lifting motions to handle the waste containers. As a result, the physical strain associated with the loading process is significantly minimized, thereby enhancing operational comfort and reducing the risk of strain injuries among staff.

By integrating these principles into the reactor design, we aim to create a system that not only streamlines the food waste management process but also prioritizes the well-being and efficiency of the operational staff. The drawer-style system embodies our commitment to combining practical functionality with ergonomic design, ensuring that our solution is both effective in its waste processing capabilities and considerate of the user experience.

3.8.2 Unloading Concept Designs

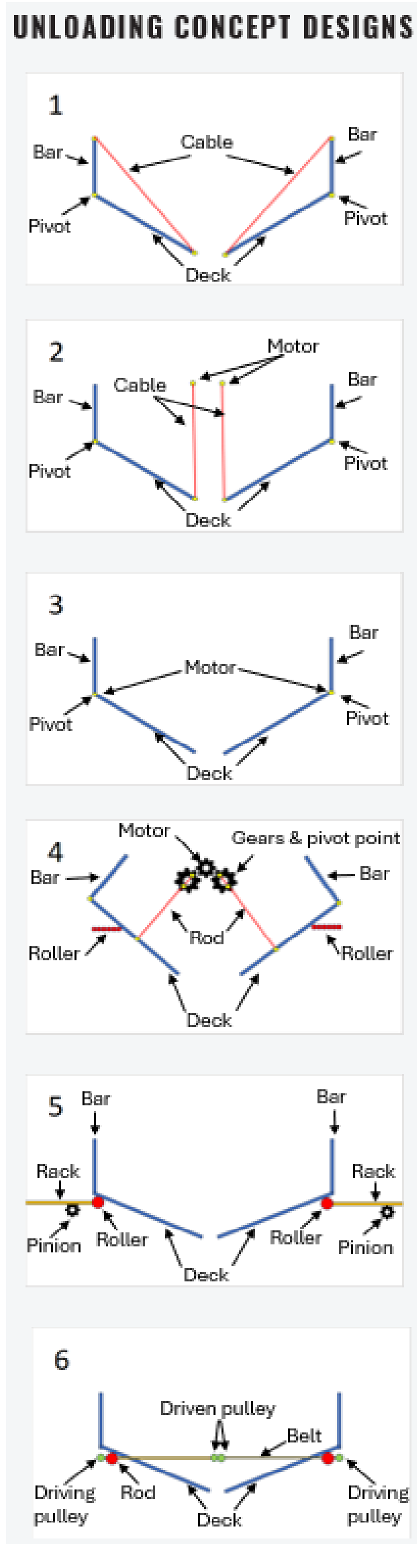


Figure 28. Unloading concept designs.

During the formative stages of developing our unloading mechanism, our team brainstormed a variety of conceptual designs, with ideas coalescing around two main strategies. The first method proposes the modification of the container's structure by elevating its sides, creating a gap at the base that would allow for the efficient discharge of frass and larvae. This concept is visually represented in Figure 28, specifically in design 4. The alternative approach suggests implementing a division within the lower segments of the container, a feature depicted across the other designs showcased.

Following a thorough evaluation of these initial concepts, a selection of designs deemed most appropriate for our operational context was chosen for rapid prototyping. This step is pivotal in enhancing the tangible understanding of each concept and identifying the most viable option for further development and refinement. Through rapid prototyping, we aim to bring our ideas into the physical realm, thereby facilitating a more informed assessment of each design's functionality and effectiveness in meeting our project's requirements.

This iterative process is crucial for narrowing down the options to those with the greatest potential, enabling us to focus our efforts on optimizing the unloading mechanism. By adopting this methodical approach to design exploration, we are better positioned to evolve our concepts into a practical, efficient solution tailored to the unique demands of our reactor system.

3.8.3 Unloading Concepts Prototyping

In the prototype development phase, we utilized cardboard to construct scale models of the containers, incorporating holes for string attachment to simulate operational functionality. Blue bottle caps served as stand-ins for frass and larvae, offering a realistic approximation of the system's internal dynamics. These prototypes were created on a one-to-three scale, ensuring proportionate accuracy for evaluating design elements and operational mechanisms. This scaled approach facilitates the detailed examination and refinement of the reactor's design before advancing to the full-size version, allowing us to identify and address potential issues effectively. Through this process, we aim to optimize the design and operational workflow, laying a robust foundation for the successful scaling up and implementation of the reactor system.

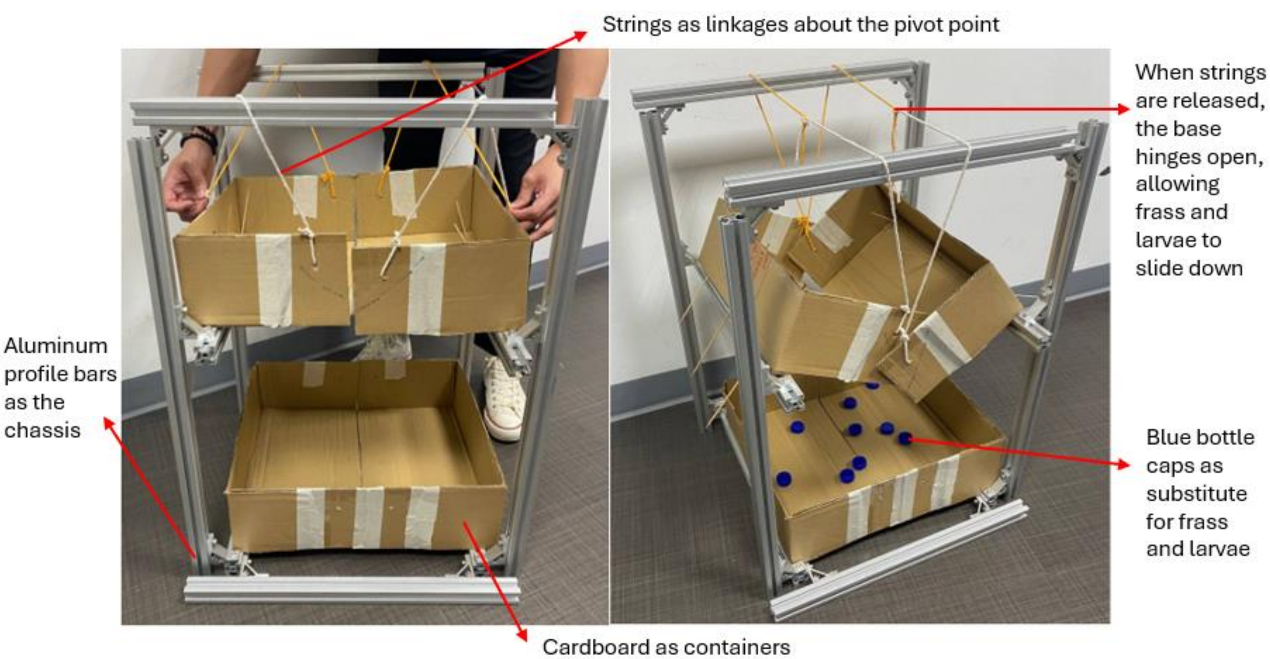


Figure 29. Prototyping of design one.

In implementing design one, we adopted a configuration that utilized strings and wooden sticks to attach both containers securely to the aluminum profile frame. Through manual operation—specifically, pulling the strings—we managed to close the containers effectively. By then relaxing the string tension, the containers were made to collapse inward, deliberately creating a gap at their base. This strategically designed opening allowed for the controlled release of frass and larvae, simulated by blue bottle caps, enabling their smooth transition into a lower container placed beneath. This method demonstrated a practical approach to facilitating the movement of contents between containers within the reactor system.

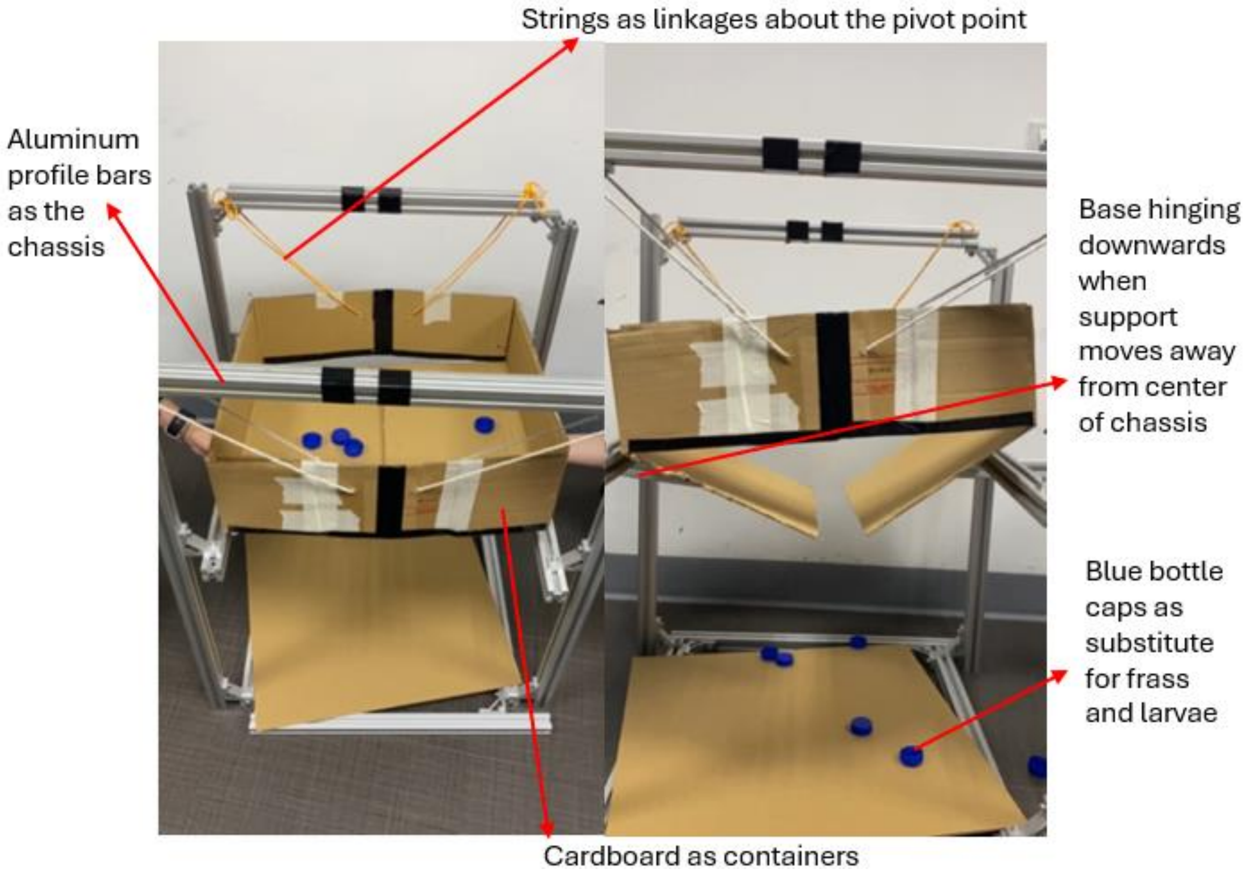


Figure 30. Prototyping of design three.

For the prototyping of the third design, we created a model where the container's base is designed to pivot downward from both sides, utilizing hinges installed at the container's outer edges. This design allows the base to open up, thereby facilitating a controlled release of frass and larvae—represented in this case by blue bottle caps—ensuring their directed flow into the container positioned directly beneath. This innovative approach demonstrates an effective mechanism for transferring contents between containers within the system, emphasizing ease of operation and precision in the unloading process.

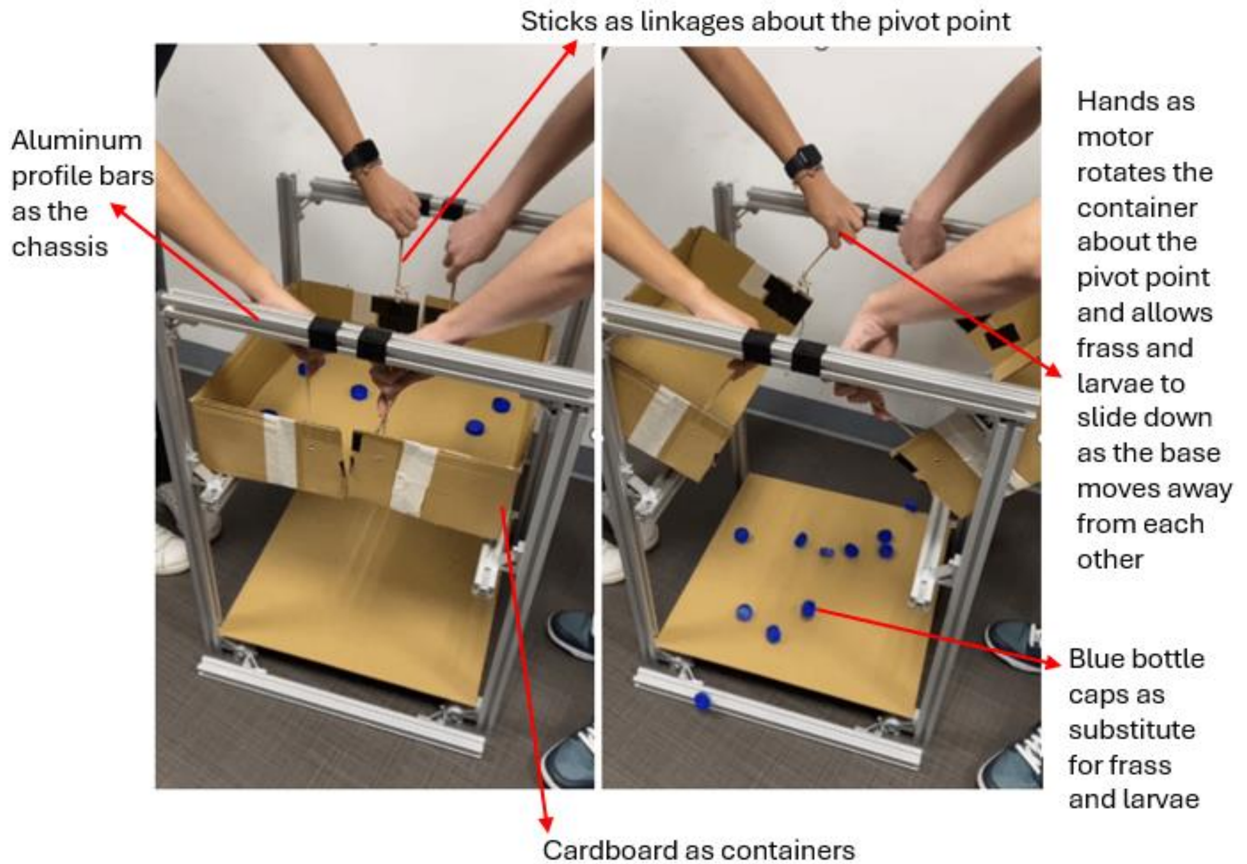


Figure 31. Prototyping of design four.

In design four, we applied manual manipulation to operate the containers, specifically by pivoting them apart to create an opening at the base. This intentional gap enabled the controlled release and descent of frass and larvae, which were symbolized by blue bottle caps, effectively guiding their transfer into the next container placed beneath. This method showcased a straightforward yet effective technique for managing the contents' movement within the reactor system, emphasizing manual control and precision in the unloading process.

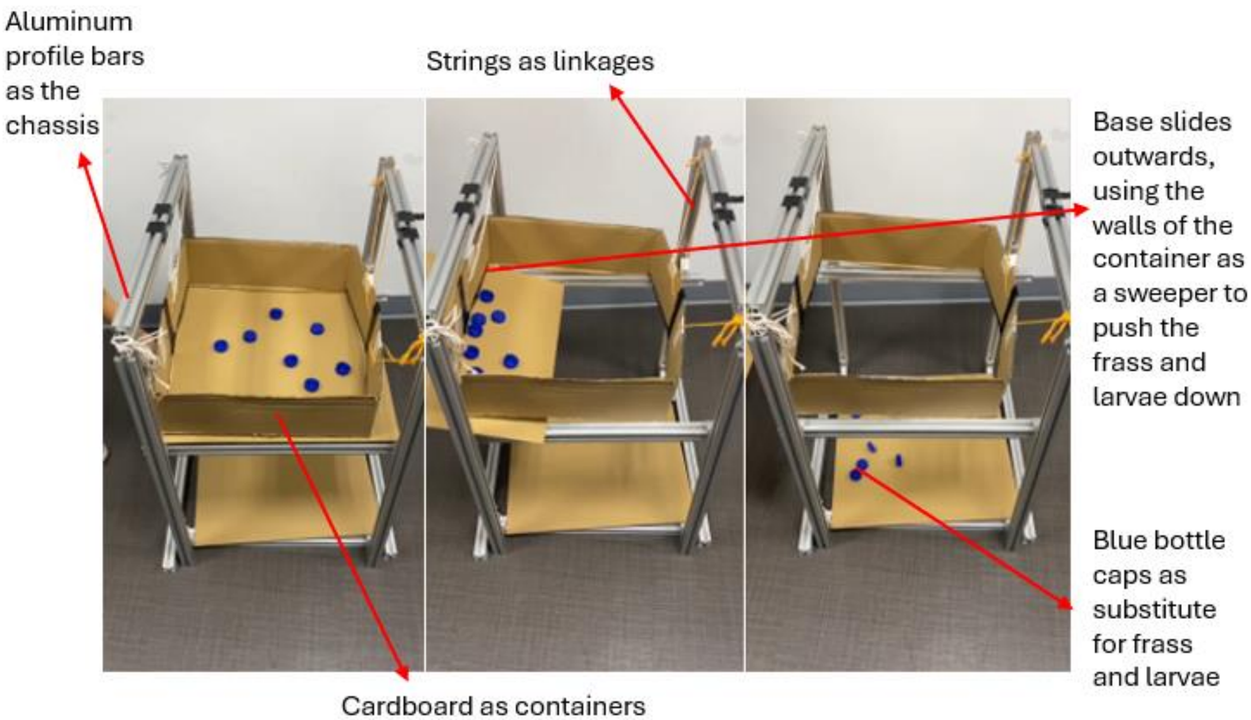


Figure 32. Prototyping of design six.

For prototyping design six, we introduced a novel feature: a fully detachable bottom section within the container. This design innovation comes into play during the unloading process, whereby the bottom section is manually removed from the container's side. Such a mechanism facilitates a controlled release of frass and larvae, depicted by blue bottle caps in this scenario, allowing for their methodical transfer to the container below. This approach provides a distinctive solution for efficiently managing the contents' movement within the system, highlighting ease of operation and effectiveness in the unloading sequence.

3.8.4 Unloading Concept Design Evaluation

As detailed in Section 3.8.2 of our report, our exploration of unloading design concepts identified two main strategies: the elevation of the container's sides and the segmentation of the container's base. To better visualize and refine these ideas, we turned to computer-aided design (CAD) software. This technology allowed us to delve deeply into each concept, enabling precise examination and enhancement of the mechanisms involved. By utilizing CAD software, we ensured a thorough understanding of how these design elements could be effectively incorporated into our reactor system, thereby facilitating informed decision-making in the finalization of our design. This approach underscores our commitment to leveraging advanced tools for optimal design accuracy and innovation.

3.8.4.1 Elevating Container's sides (Pivot system)

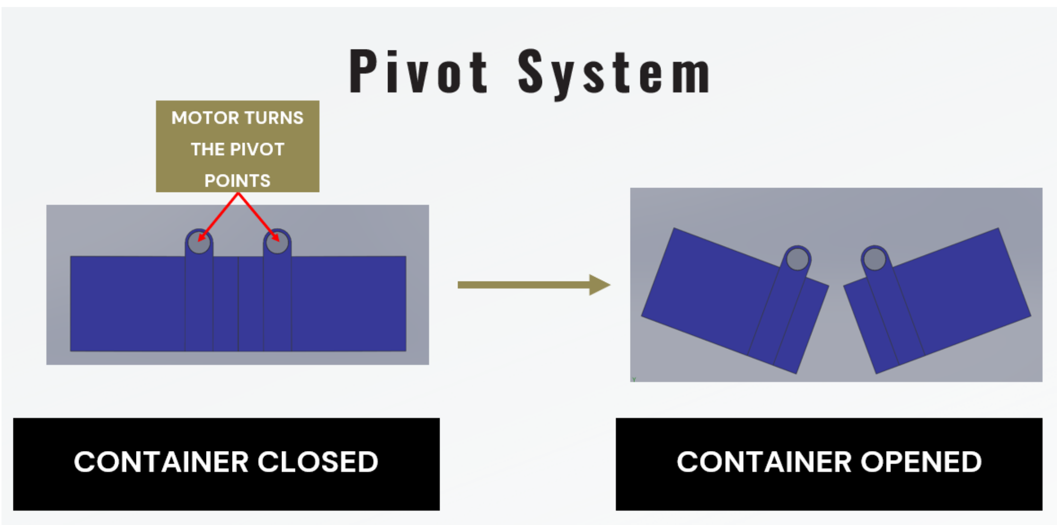


Figure 33. Elevating container's sides for opening and closing.

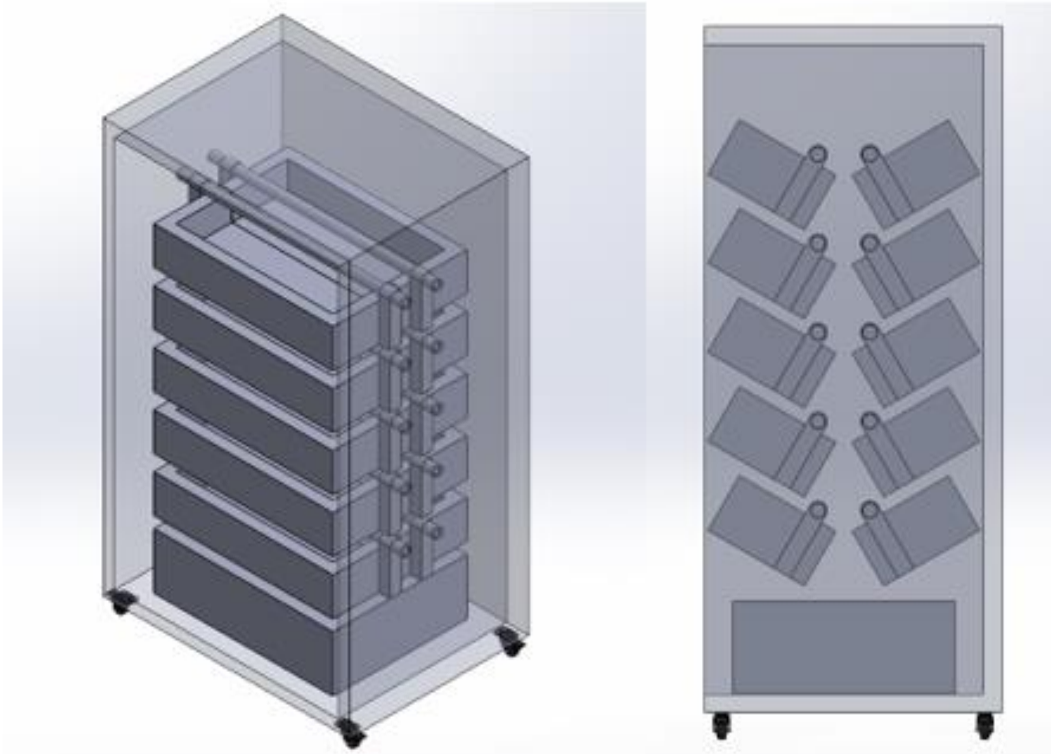


Figure 34. CAD design for pivoting system.

In the rapid prototyping phase, we constructed multiple cardboard prototypes to assess the viability of different design options. Our attention was particularly drawn to design four, which incorporates a pivot mechanism allowing for the controlled opening and closing of the containers, as depicted in Figure 32. Additionally, to provide a detailed visualization of the reactor's complete structure and enhance our understanding of how design four integrates within the overall system, a Computer-Aided Design (CAD) model was specifically developed for this design. This CAD model facilitated a deeper exploration of the design's functional aspects, enabling us to meticulously evaluate its effectiveness and potential for practical application in the reactor system.

3.8.4.2 Separation of Container base (Roller system)

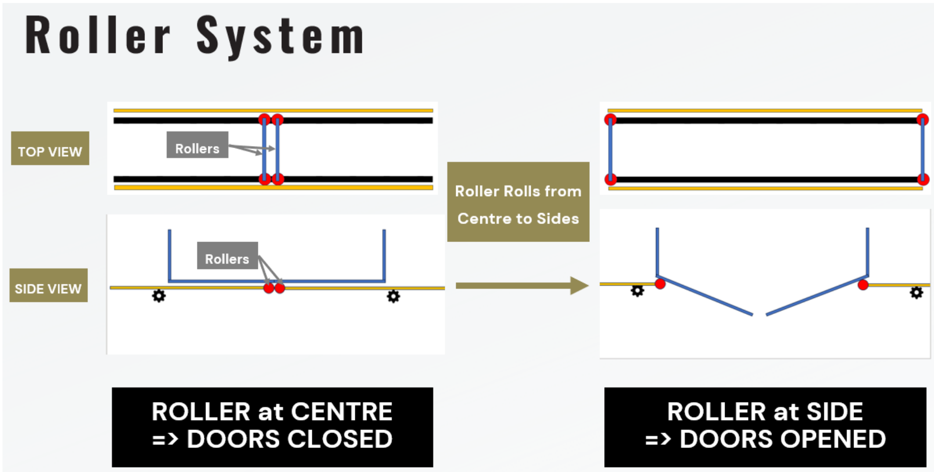


Figure 35. Roller system opening and closing.

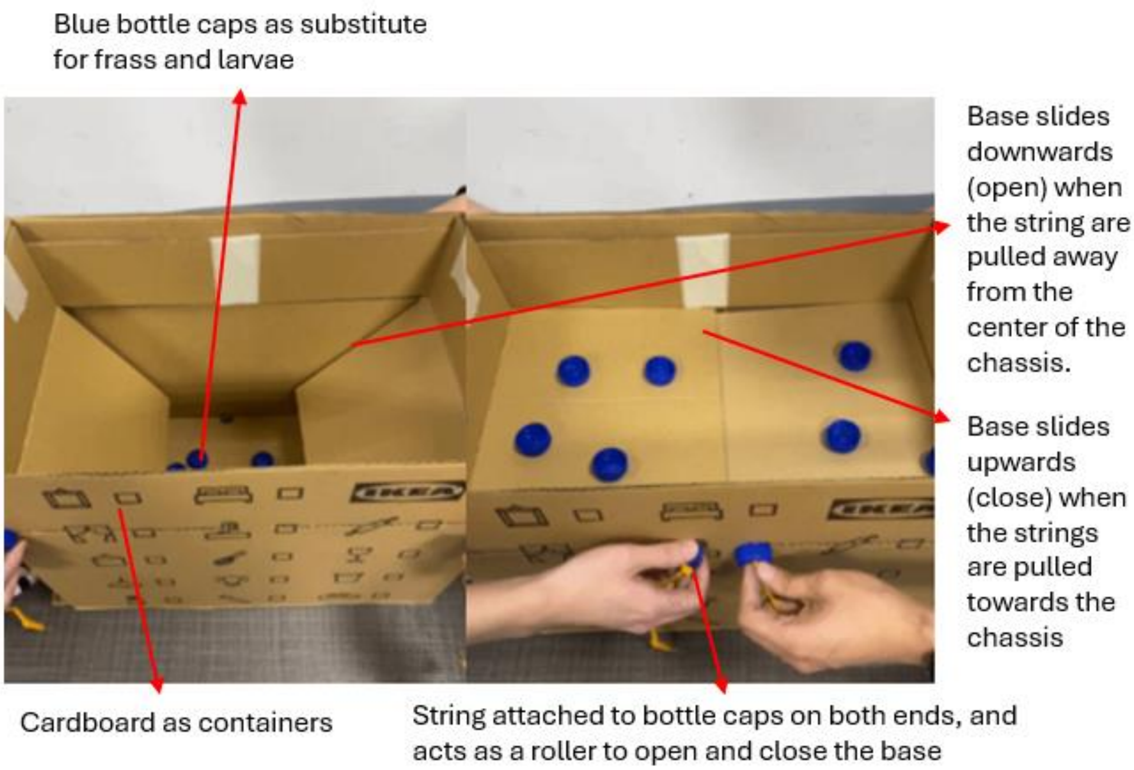


Figure 36. Roller system prototyping.

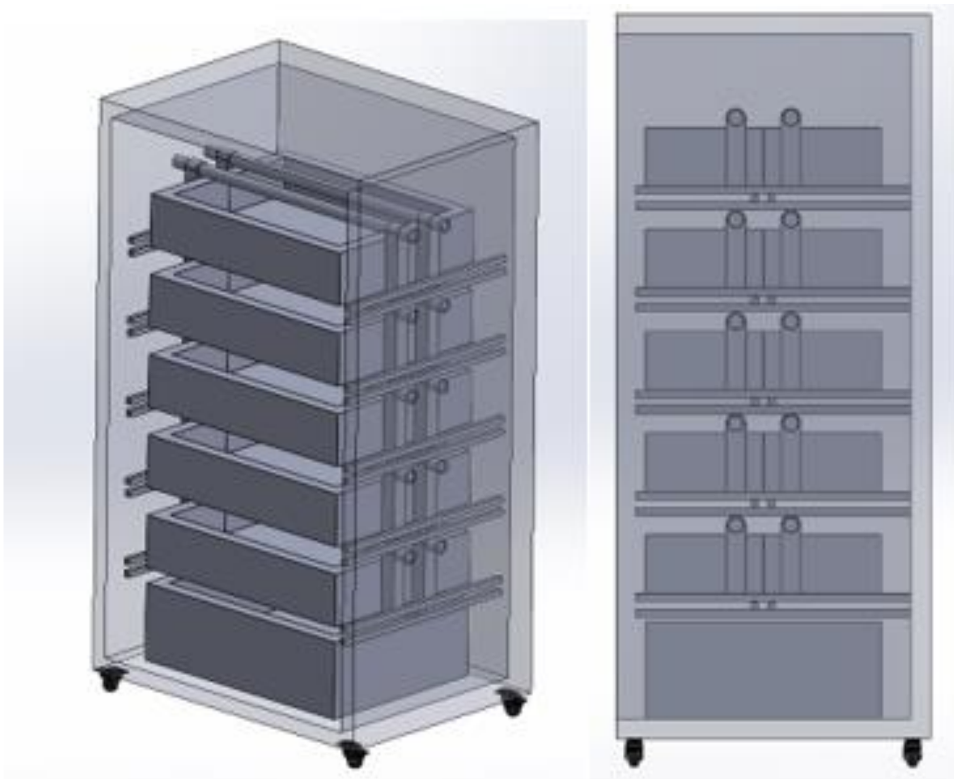


Figure 37. CAD design for Roller system.

Upon performing detailed calculations (as outlined in Appendix 7.3), it was determined that the implementation of the pivot system in our design posed significant challenges, primarily due to the high torque required from the motor to maneuver the container. This requirement proved to be a limiting factor, especially considering the constraints of our project budget. As a result, we redirected our focus towards an alternative design that necessitates lower torque, thereby enabling the integration of a more cost-effective motor solution.

This pivot in our design strategy led us to the exploration of a roller system. By employing a roller-type mechanism, we aim to facilitate the movement of the container's bottom, effectively creating the necessary gap for the controlled descent of contents. This innovative approach not only addresses the torque and budgetary challenges but also promises to maintain the operational efficiency required for the reactor system. Through this adjustment, we continue to seek viable solutions that align with our project's technical and financial parameters, ensuring the feasibility and success of the overall design.

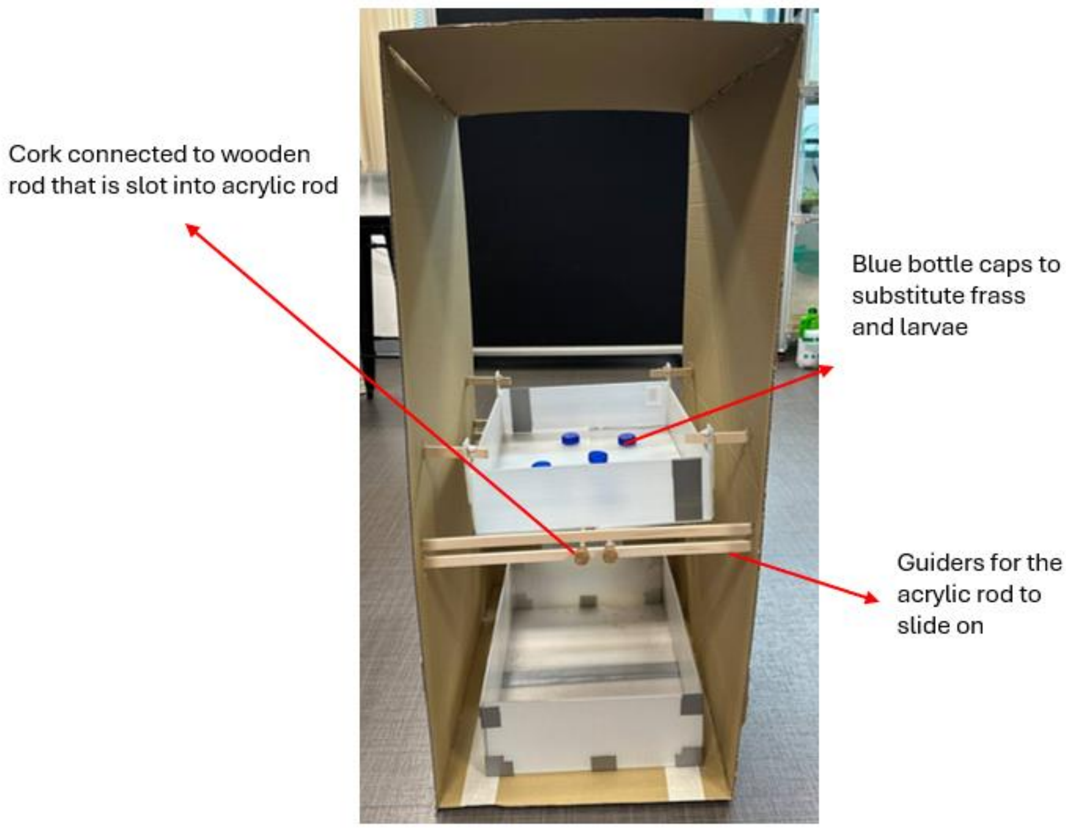


Figure 38. 1:2 scale prototype of Roller system.

In our efforts to refine our design, we constructed a 1:2 scale prototype, enabling a detailed and hands-on examination of the design's performance and the identification of any potential challenges. For the construction of the containers, corrugated board was chosen due to its combination of strength, durability, water resistance, and a smooth surface that facilitates the easy movement of frass and larvae. To simulate the roller system with greater accuracy, we utilized a wooden solid rod passed through an acrylic rod, with cork stoppers at both ends to permit limited movement. This setup closely mimics the functionality of a rolling pin, effectively reducing friction between the rollers and the container's base. By adopting such a mechanism, we aimed to lessen the effort needed to activate the rollers, favoring a turning motion over dragging. This innovation contributes to the overall system's efficiency, making the roller system more effective and user-friendly in practice.

3.9 Angle of Tilt Experiment

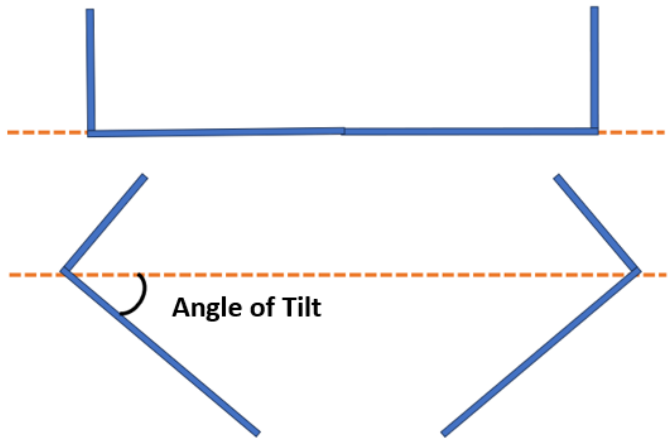


Figure 39. Angle of tilt of container.

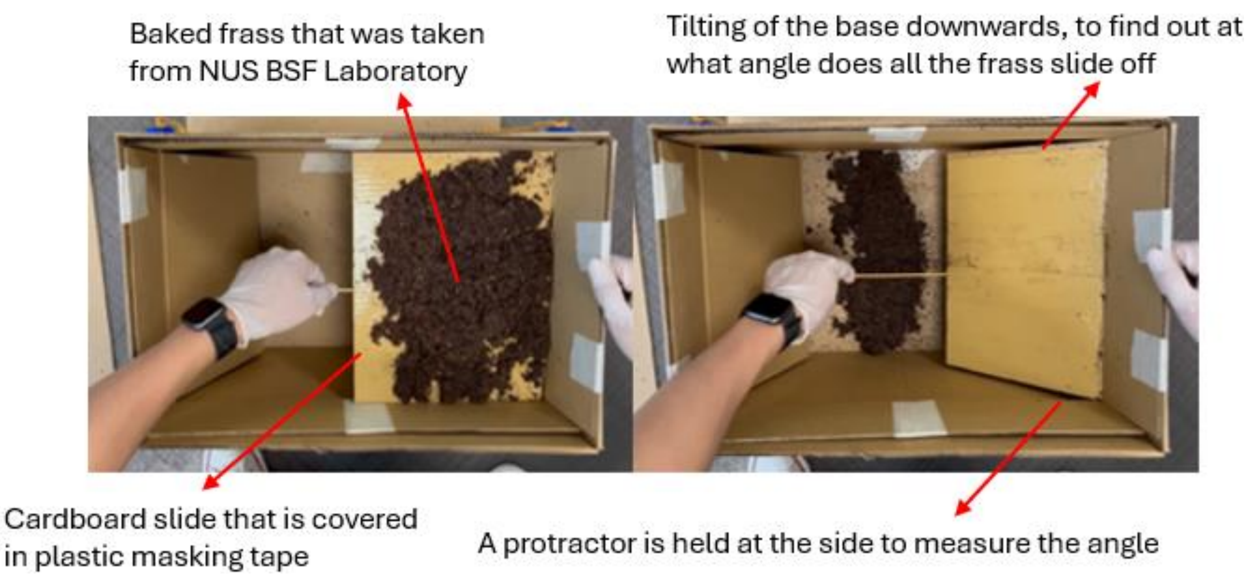


Figure 40. Angle of tilt experiment.

Understanding the optimal tilting angle for the containers emerged as a critical factor in our design process, given its influence on the efficient expulsion of frass and larvae, the spatial arrangement between containers, and the torque requirements for manipulating the container's base. To elucidate this aspect, we undertook an experiment with our cardboard prototype, aiming to determine the exact tilt angle necessary for the successful discharge of frass and larvae. This experiment was instrumental in gaining valuable data to refine our design for practical use. Our findings indicated that on a smooth surface, akin to plastic, a tilt angle of 50 degrees is required to achieve a 99% successful slide of frass to the container's bottom. These insights, detailed in Appendix 7.4, are pivotal for optimizing the reactor design, ensuring its efficiency and operational feasibility in real-world scenarios.

3.10 First Iteration of Final Design

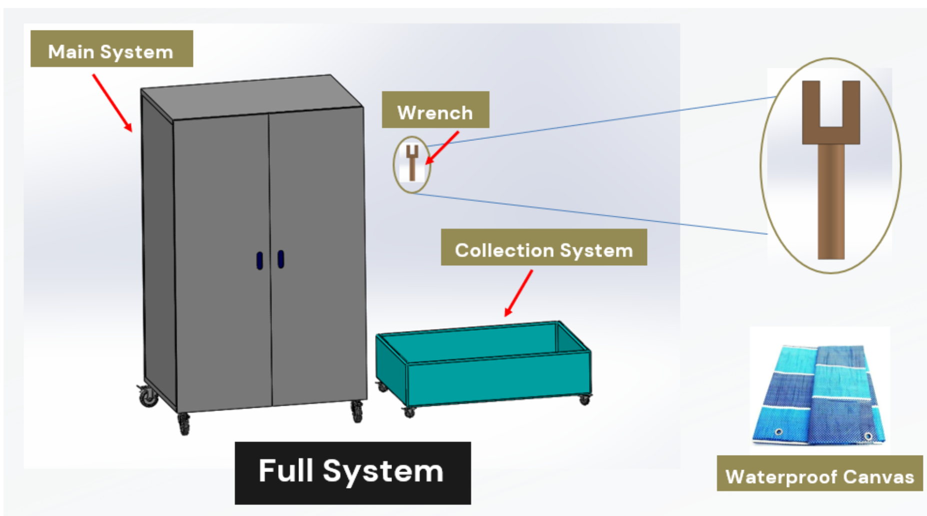


Figure 41. First Iteration of Final Design.

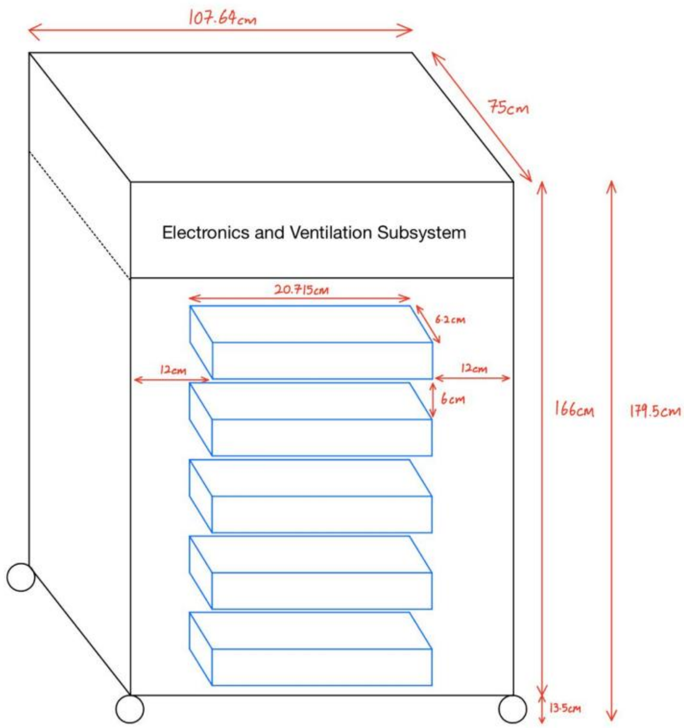


Figure 42. Dimensions for First Iteration.

In our endeavor to refine the design and reduce the torque requirements to just a fifth of what was initially proposed, we encountered persistent budgetary limitations that rendered the cost of implementing a motorized system unfeasible. In light of these financial constraints, we decided to pivot our approach away from relying on motorized mechanisms, instead focusing on strategies that would lessen the physical strain on operators. This strategic shift led to the development of a new schematic, representing our initial design iteration for a comprehensive reactor system.

This design is structured around two main subsystems: the primary system, which includes the chassis and containers for food waste, and the collection system, designed to streamline the unloading of frass and larvae after processing. A key feature of our proposed solution is the incorporation of a waterproofing canvas during the unloading phase. This canvas is strategically wrapped around the unloading container to efficiently direct the frass and larvae into the collection system, thereby minimizing manual effort and enhancing the system's overall ergonomics.

Our alternative approach, detailed further in Appendix 7.5, underscores our commitment to developing a practical, user-friendly system that respects budgetary realities while prioritizing the well-being of the workers involved. By reimagining our design to circumvent the challenges posed by high costs and mechanical complexity, we aim to offer an effective solution that balances operational efficiency with ease of use.

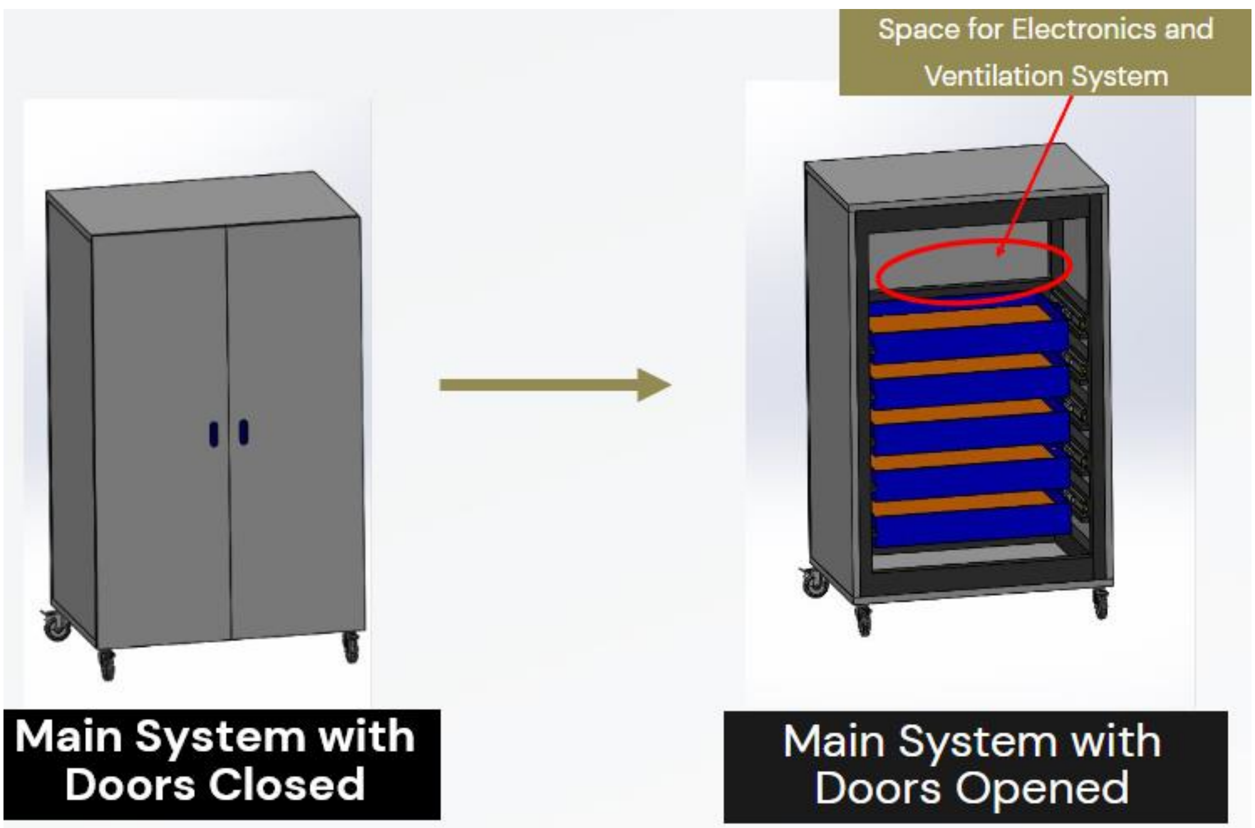


Figure 43. Opening and closing of first iteration.

Within our primary system, the closure of the doors seals the internal environment, creating an enclosed space reserved for electronic and ventilation systems crucial for maintaining an optimal environment for BSFL. These electronic systems are integral, monitoring and adjusting internal conditions to foster a habitat that accelerates the BSFL's feeding process, thereby significantly shortening the food waste treatment time.

The dimensions of the containers are tailored to meet the specific needs for food waste accommodation, with a height limitation set at 6 cm based on optimal requirements (Adrian Fuhrmann, personal communication, October 2023). This constraint necessitates adjustments in length and width to suit our design specifications. Consequently, our prototype design includes five containers within the system's chassis, each measuring 80x50x6 cm. Individually, these containers are designed to hold up to 40kg of waste, necessitating approximately 33,500 larvae per container to effectively process the waste [30], culminating in a total system capacity of 200kg. Further details and the underlying calculations supporting this configuration can be found in Appendix 7.6. This design approach aims to optimize both the biological process and the system's physical structure to enhance efficiency and efficacy in waste treatment within the reactor's operational framework.

Figure 44. First Iteration design of loading system.

The methodology for loading the reactor system with food waste and BSFL encompasses a series of methodical steps designed to ensure efficiency and safety. This process commences with the opening of the reactor doors, which precedes the unlocking and subsequent sliding out of the drawers from the chassis, facilitating access to the containers. Once the drawers are securely positioned outside the reactor, they are locked to prevent unintended movement. Following this, the containers are meticulously loaded with food waste and inoculated with BSFL for the bioconversion process. The next phase involves unlocking the drawers to slide them back into the reactor, where they are then re-locked to secure their position within the system. The procedure is finalized by closing the reactor doors, marking the commencement of the bioconversion process. This sequential operation is critical for maintaining the integrity of the system and ensuring the effective initiation of the waste processing cycle.

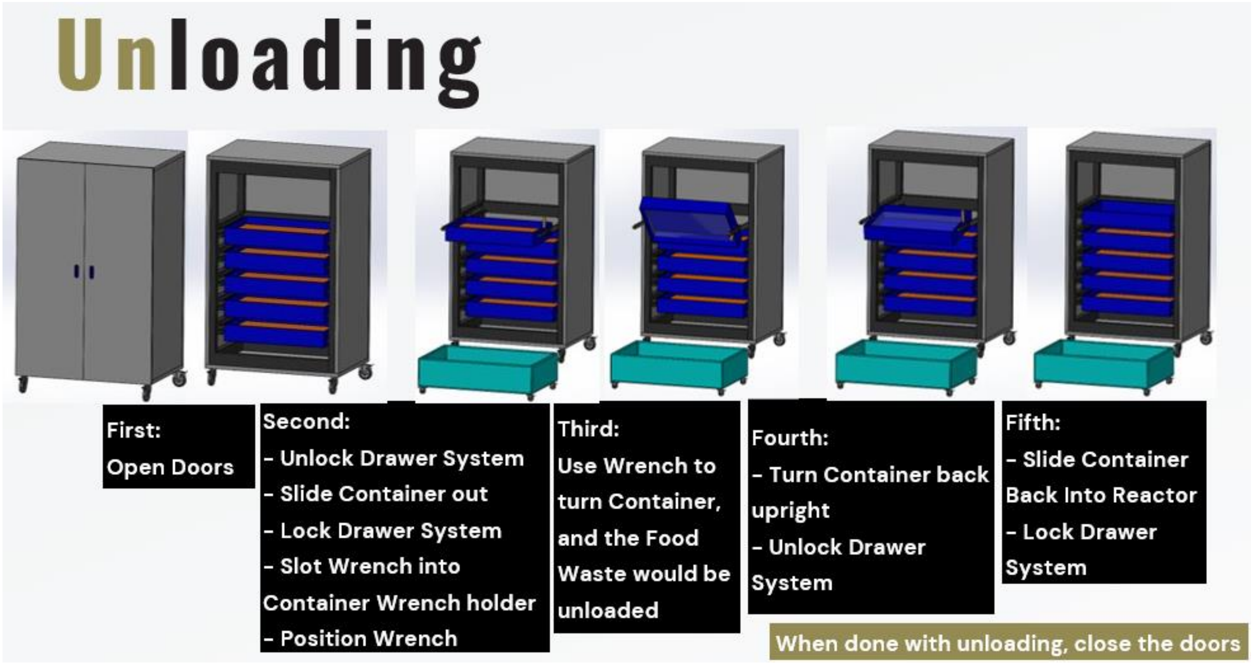


Figure 45. First Iteration design of unloading system.

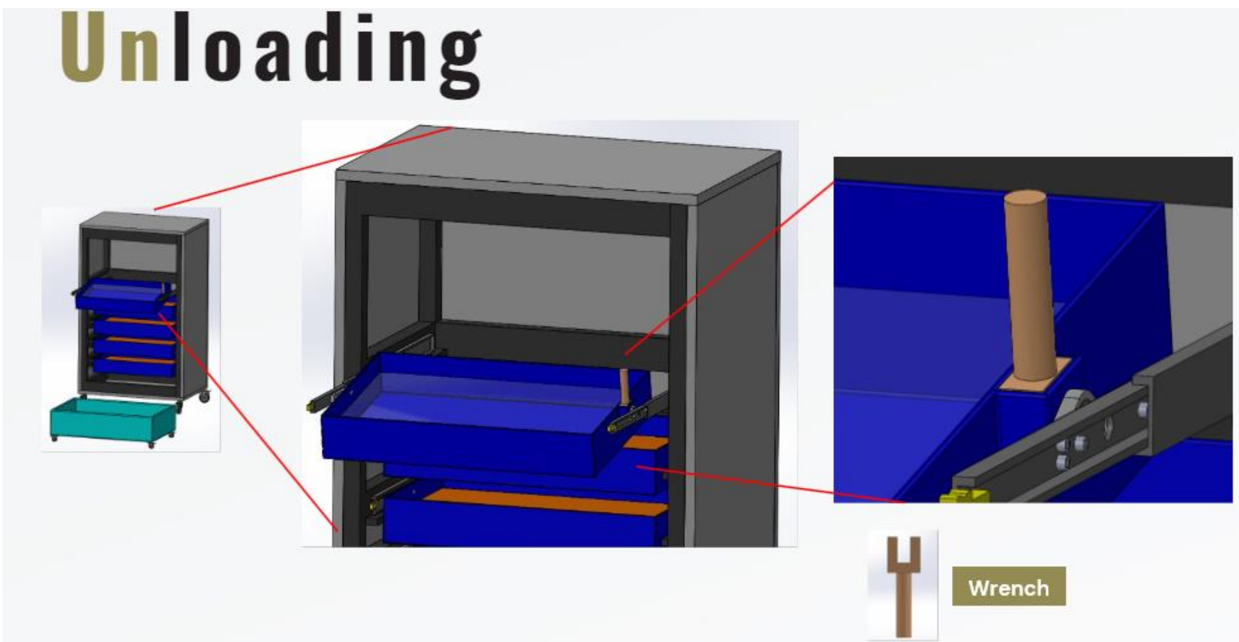


Figure 46. Close up view of wrench system

The unloading mechanism of our system, while mirroring the initial phases of the loading protocol—characterized by the opening of the reactor doors and the unlocking and sliding of the drawers to extricate the containers—introduces distinct operational modifications at a crucial point. Commencing with the affixation of a waterproof canvas around the container, the process then incorporates the insertion of a wrench into a bespoke holder affixed to the container. This holder acts as a fulcrum for the container's rotation, a maneuver designed to enable the precise and controlled evacuation of its contents. The contents are channeled by the waterproof canvas directly into the collection system below. Following the content discharge, the removal of the canvas and the reorientation of the container to its original stance precede the reversal of the initial steps. The container is reinserted into the reactor, secured, and the system is sealed by closing the reactor doors, thereby concluding the unloading sequence. This methodical approach ensures the efficiency and cleanliness of the unloading process, aligning with the system's overall operational objectives.

4. Final Design

4.1 Final Design in CAD

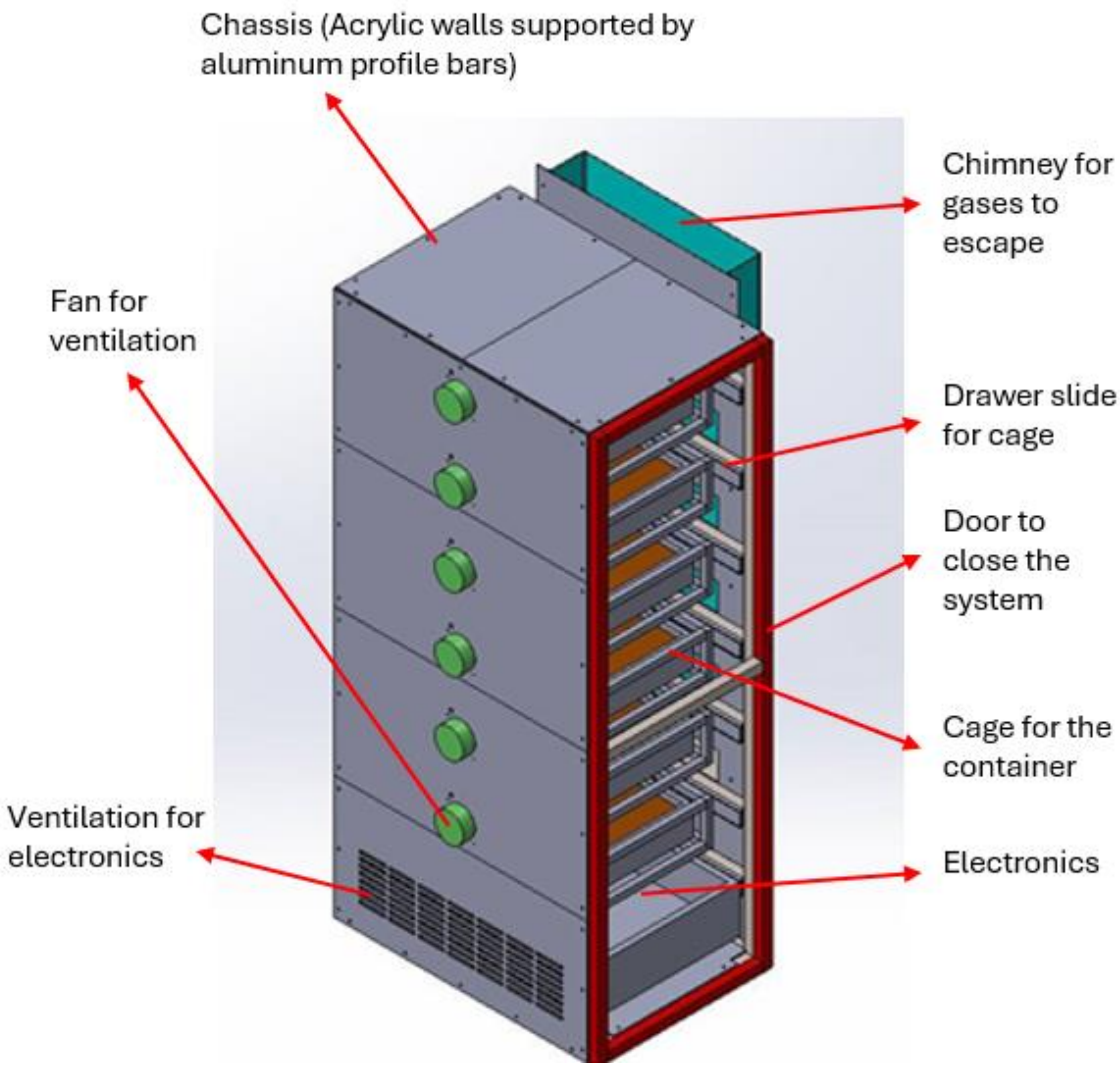


Figure 47. Final Design done in CAD.

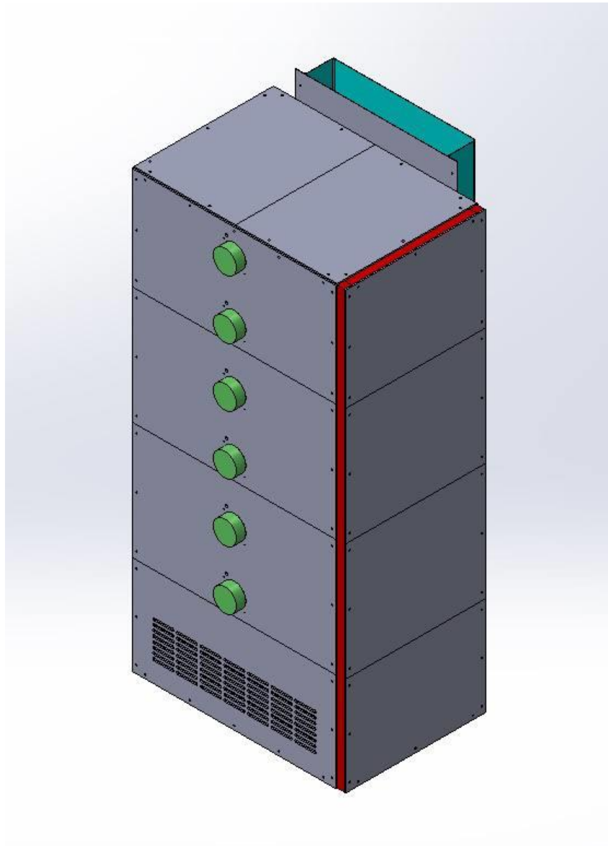


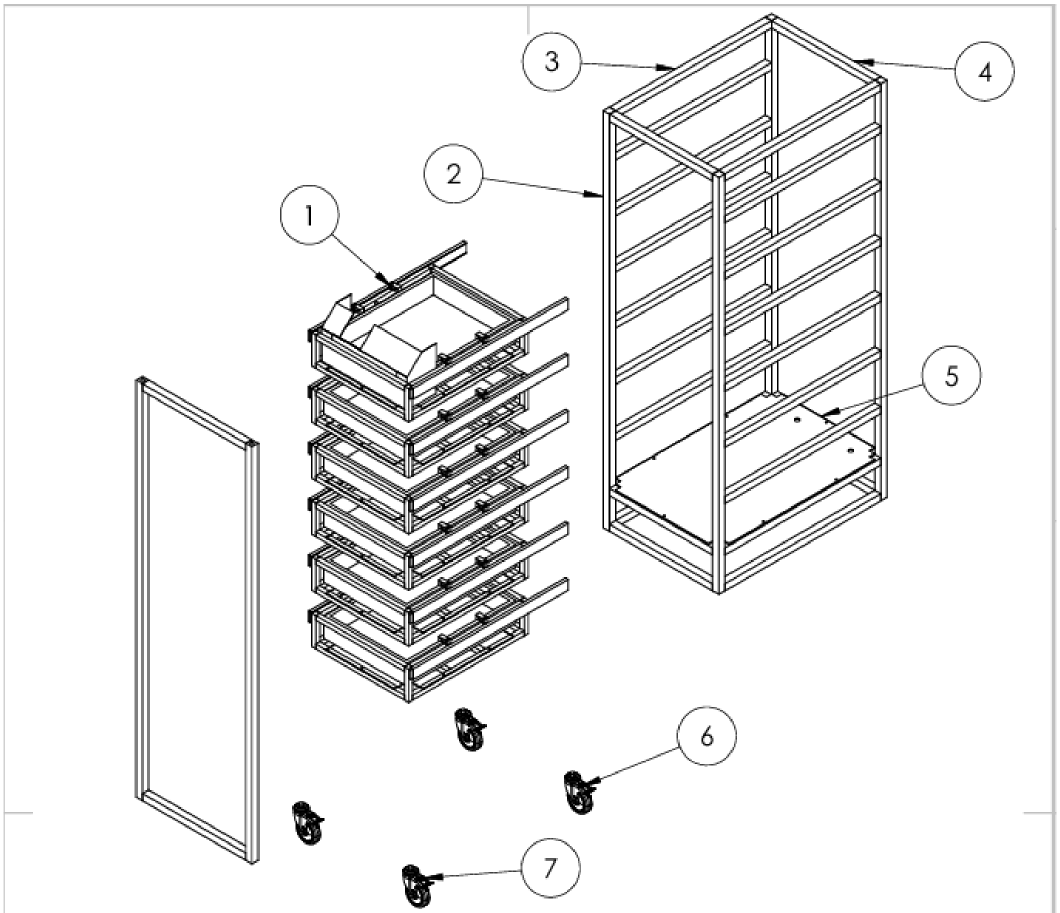
Figure 48. Final Design in CAD (Closed system).

In the process of refining the design of our reactor system from its initial concept to its final iteration, a series of critical adjustments were necessitated to better accommodate the specific constraints and objectives of our project. A significant modification was the resizing of the chassis, coupled with a decision to employ laboratory containers and to revise the quantity of these containers utilized within the system. This culminated in a downscaled final design, reducing the reactor's size to a third of its initial dimensions and incorporating a total of six containers. Additionally, to address potential risks associated with corrosion or malfunction triggered by the accumulation of internal gases such as methane, the placement of electronics was meticulously planned to be at the base of the setup.

These design alterations were primarily dictated by the limited resources at our disposal. The constraint was notably evident in the restricted availability of larvae, which was a critical component of our project. The larvae, being sourced from a laboratory environment, had to suffice both the requirements of our project and the ongoing research needs of the laboratory, highlighting the challenge posed by the larvae's production scale, which is optimized for research rather than large-scale farming. Furthermore, the fabrication laboratory we relied on for materials and components also faced its own set of limitations. The lab's need to manage time efficiently while accommodating material orders and addressing the demands of numerous concurrent projects added another layer of complexity to our project's development.

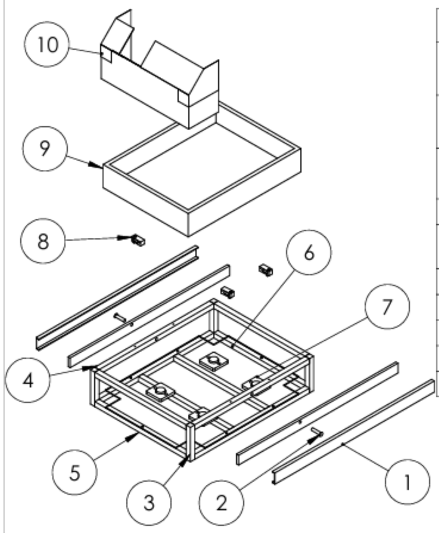
In light of these constraints, the strategic decision to scale down the reactor's design to a third of its original size was a calculated move. This decision was influenced not merely by the limitations posed by larvae availability and fabrication resources but also by our ambition to devise a reactor that would serve the research community effectively. By adopting this approach, we aimed to ensure that the reactor would emerge as an indispensable tool for laboratory researchers, enabling them to conduct experiments and gather data critical for enhancing the reactor's performance. This thoughtful, strategic resizing and redesigning of the reactor system reflect our commitment to contributing significantly to the field of sustainable waste management, navigating the challenges and limitations inherent in our project's context.

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 illustrations included within this document offer intricate exploded views of the project's chassis and the individual components of the cage, meticulously delineating the placement and specifying the quantities of each part, thereby providing a crucial visual reference for the ensuing segments of this report. In the sections that follow, an in-depth exploration into the rationale behind the selection of each component will be conducted, scrutinizing their individual roles and contributions towards the holistic design of the system. This analysis is designed to shed light on the decision-making process, underscoring the significance of each part's functionality and attributes in guiding our selections. Such a detailed examination ensures that the system's design is not only effective but also efficient for its intended applications. (For comprehensive dimensions, refer to Appendix 7.7).

4.2.1 Container

Figure 51. Containers from NUS BSF Research Laboratory.

During the initial phases of our project, the team aspired to enhance our containers with the addition of a custom wrench holder, an endeavor that quickly introduced us to the intricacies and financial implications of bespoke designs. The necessity for specialized molds, whose costs exponentially increase with the complexity of the design, rendered the prospect of small-scale customization economically untenable due to prohibitive upfront expenses. Furthermore, the journey from conceptualization to production in custom design is not only lengthy but also riddled with potential for delays, stemming from the iterative process of revisions. Efforts to identify manufacturers willing to engage in low-volume customizations faced substantial challenges, with most declining and the few in agreement proposing exorbitant fees.

In light of these considerations and with an eye towards the long-term viability and scalability of our reactor, the decision was made to utilize pre-existing lab-standard container boxes. This strategy markedly improves the practicality of material procurement for larger scale endeavors, ensuring the availability and accessibility of these components when required. By adopting the use of these universally available containers, we effectively safeguarded the project's sustainability and practicality, leveraging their proven reliability and efficiency. This pivotal strategic decision was instrumental in keeping the project within budget and on schedule, adeptly navigating the hurdles associated with custom component fabrication. Consequently, this choice not only meets the immediate logistical requirements of the project but also positions it for seamless future growth and adaptation, demonstrating a keen understanding of project management and scalability within the constraints of design and resource availability.

4.2.2 Cage

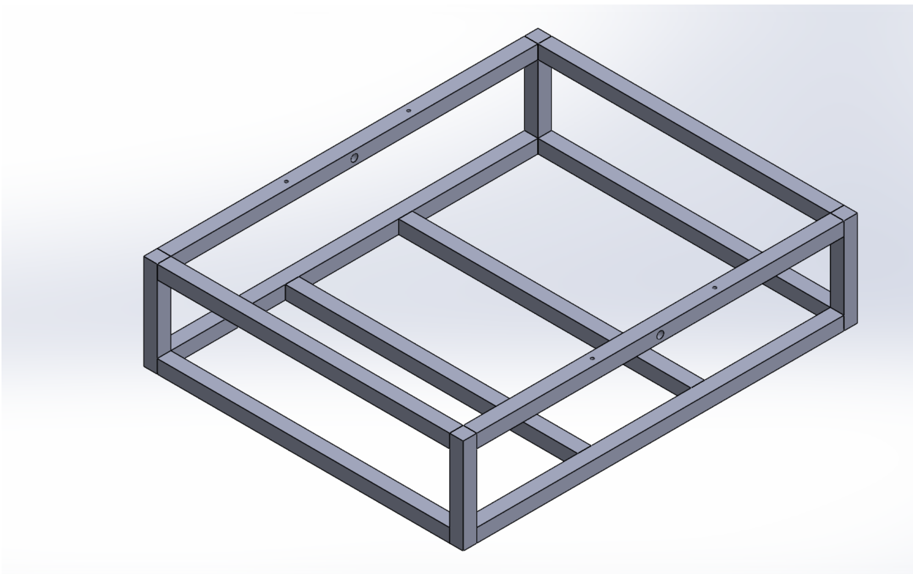


Figure 52. Cage design in CAD.

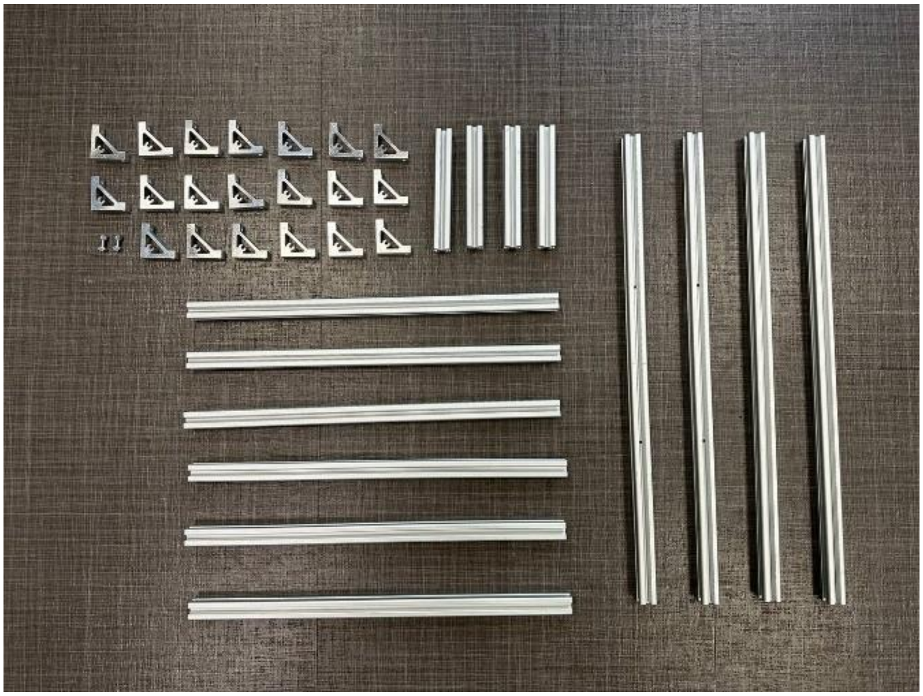


Figure 53. Fabricated parts for the cage.

Figure 54. Side view of assembled cage.

Figure 55. Top view of assembled cage.

In advancing our project, we prioritized the development of a mechanism that would ensure the container's secure attachment to the drawer system while also allowing for easy detachment, thereby streamlining the cleaning process post-utilization. Initially considering a direct mounting approach, our team pivoted towards the creation of a supportive cage structure. This innovative design not only maintained the container's stability and levelness throughout its operation but also facilitated its easy rotation, enabling efficient unloading. This feature significantly simplified the containers' removal for subsequent cleaning, markedly improving the system's operational usability and maintenance efficiency.

The material selection for the cage's construction was meticulously decided upon, with 20 by 20 aluminum profile bars emerging as the chosen material due to their lightweight nature compared to alternatives like steel. This lightness is advantageous, enhancing the ease of handling and assembly of the cage. The aluminum's favorable strength-to-weight ratio assured us of its durability for our application's needs without the burden of unnecessary weight. Furthermore, aluminum's compatibility with various machining processes, such as cutting, drilling, and precision shaping, played a pivotal role in its selection. This characteristic is particularly crucial for our project, as it permits the execution of quick and precise modifications when needed, thereby enhancing the design process's efficiency and flexibility.

For the cage's assembly, a total of eight aluminum profile bars were employed, supplemented by an additional two bars positioned centrally to ensure the even distribution of the container's weight across the structure. The laboratory-provided container dimensions are specified as 53 cm in length, 40 cm in width, and 9.5 cm in height. Conversely, the cage's constructed dimensions were slightly larger, measuring 58 cm in length, 47 cm in width, and 14 cm in height, to accommodate the pivot screws necessary for the cage's functionality. The deliberate design choice in the discrepancy of width between the container and the cage, primarily to house the pivot screws, and their operational significance within the cage's design, will be further discussed in subsequent sections of our analysis.

4.2.2.1 Load Cell and Acrylic mounting plate

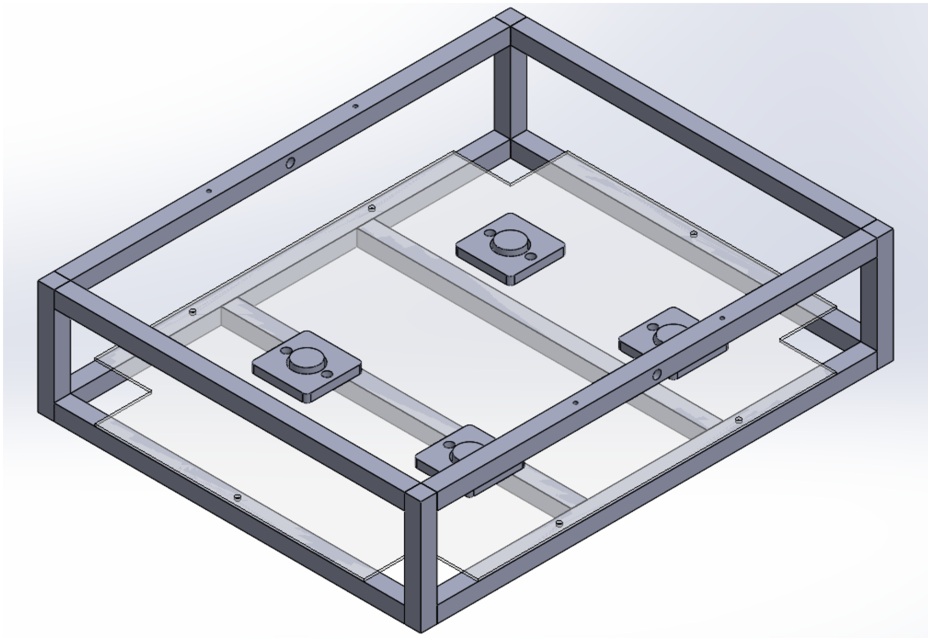


Figure 56. Load Cell with Acrylic Mounting plate with cage design in CAD.

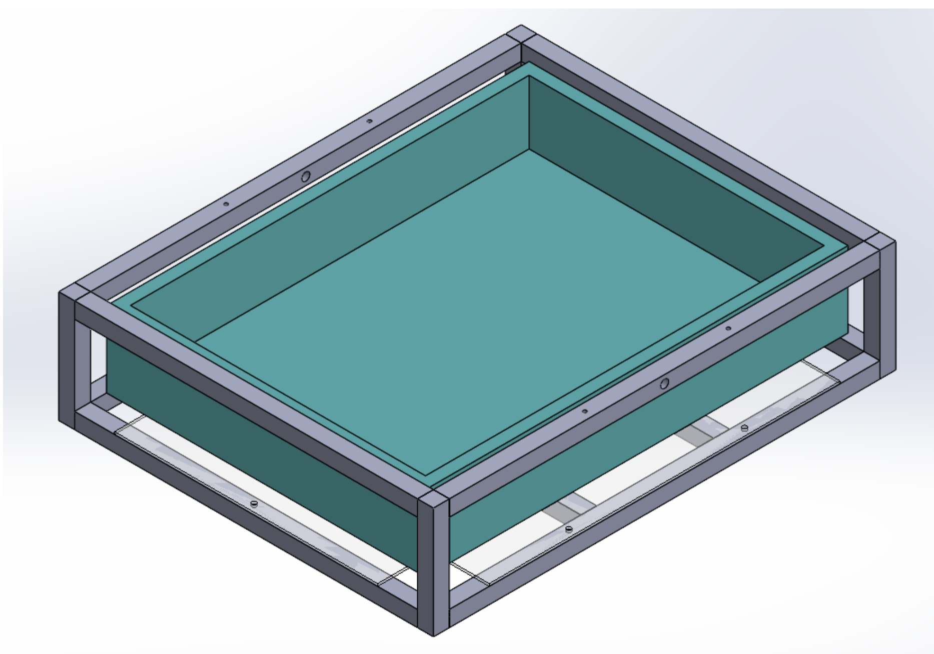


Figure 57. CAD of container in the cage with Load Cell.

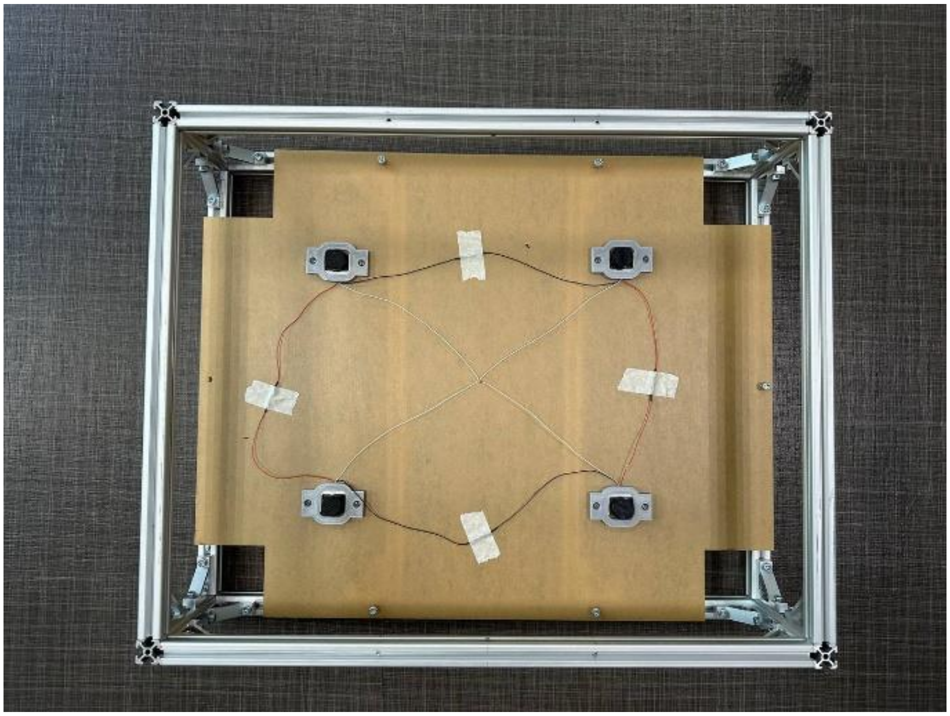


Figure 58. Assembled cage with load cell and acrylic mounting plate.

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

In our endeavor to meticulously assess the efficiency of our reactor, a collaborative initiative with the electronics department was undertaken to determine the most effective approach for continuous monitoring of the container's weight during the bioconversion process. The consensus favored the integration of load cells, thereby ingeniously enabling the system to function concurrently as a precise weighing apparatus. This innovative solution necessitated a structural redesign of the cage, notably an elevation in height, to facilitate the inclusion of an additional acrylic plate designed to host four load cells and their holders. This configuration is not merely structural; it is strategically designed to ensure the uniform distribution of the container's weight across the cage, thereby securing the assembly within and enhancing the precision of weight measurements. This pivotal enhancement aligns with our project's objectives, significantly bolstering the reactor's operational efficiency and accuracy in real-time monitoring.

4.2.3 Drawer Slide

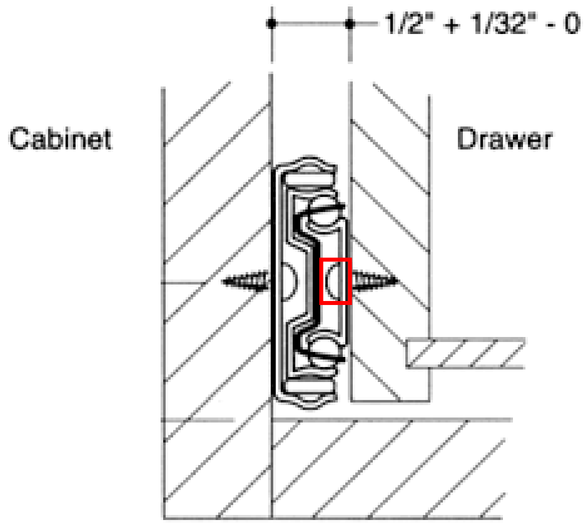


Figure 60. Cross section view of how drawer slide is connected.

In the process of refining the mechanism for pivoting the cage within our system, it became clear that our initial strategy of using a stainless-steel pivoting bar presented significant practical challenges, particularly concerning its attachment to the drawer slide. The main complication arose from the limited space available for this integration, as highlighted by the constrained gap delineated in the red box in an earlier schematic representation of a standard drawer slide [31]. This restricted area posed a substantial barrier to securely affixing the pivoting bar without impinging on the drawer slide's operational integrity. Specifically, any effort to utilize space beyond this designated area risked obstructing the slide mechanism, thereby precluding the drawer's ability to extend fully. This critical insight necessitated a thorough reevaluation of our design approach to reconcile the need for a functional pivot mechanism with the imperative to preserve the drawer slide's functionality.

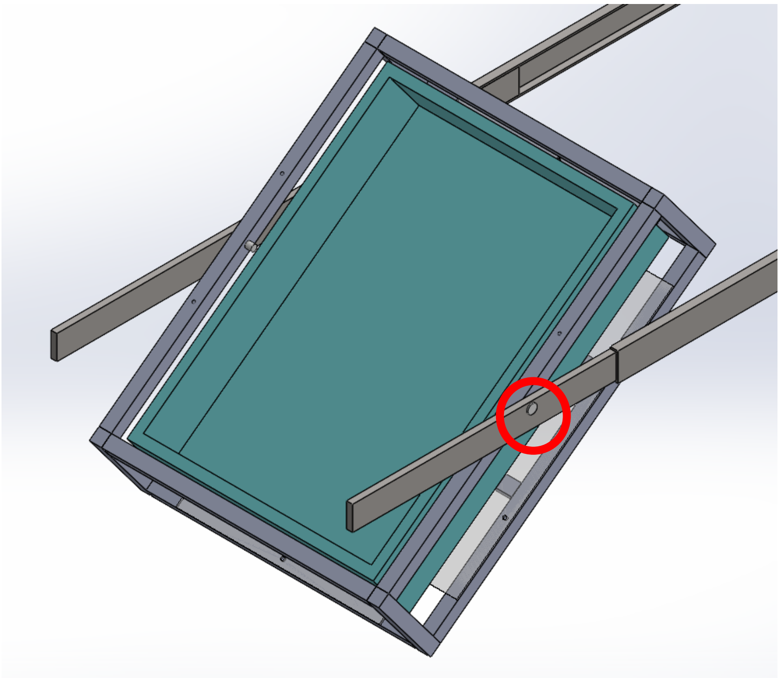


Figure 61. Drawer Slide connected to cage in CAD.

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

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

As a resolution to the challenges encountered with the initial pivot design, our team devised an innovative pivot mechanism that employs two screws to enable the cage's rotation on the drawer slide, as illustrated in the accompanying photo. This refined approach, which substitutes screws for the initially considered rods, offers the advantage of allowing the screw heads to be strategically placed on the side of the drawer slide. The fixation is achieved by securing the opposite end of each screw with two nuts, a solution that not only simplifies the assembly process but also capitalizes on the load-bearing capabilities of the screws. Specifically, an M4 screw has been identified to support up to 214.7 kg, which, when using two screws, escalates the total support capacity to 429.4 kg [32]. When considering the combined weight of the cage (approximately 2.332 kg), the acrylic plate (approximately 0.91 kg with a thickness of 3mm), the container (approximately 0.5 kg), and the contents therein (approximately 8 kg), the aggregate weight amounts to roughly 11.742 kg. This cumulative load is comfortably within the structural support threshold of the dual-screw pivot mechanism. (Refer to Appendix 7.8 for calculations)

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

Figure 65. Mounting of drawer slide on aluminum profile.

In the selection process for a drawer slide suitable for our reactor system, our team focused on two critical attributes. The first consideration was the necessity for the drawer slide to extend beyond the cage's length, ensuring that rotation could occur without interference or collision with adjacent cages, thus facilitating a more efficient spatial arrangement. The second requirement was the structural capacity of the slide to support the aggregate weight of the cage and container, which totals approximately 11.742 kg. To account for any potential unforeseen stresses and ensure a margin of safety, we applied a Factor of Safety (FOS) of 2, elevating the requisite weight capacity to approximately 23.5 kg [33]. Consequently, the criteria for our drawer slide selection stipulated a maximum weight capacity of at least 23.5 kg to guarantee the system's robustness and reliability under operational loads.

During the procurement stage, we assessed two variants of drawer slides: a 76cm model fabricated from cold rolled steel and a 66cm version made from polyester [34] [35]. Although the steel drawer slide offered benefits in terms of length and was more economically viable—being significantly cheaper than the polyester model—its load capacity of 10-15kg did not meet our project's safety and functionality thresholds. On the other hand, the polyester drawer slide, despite its higher cost, presented a considerable load capacity advantage, supporting up to 45kg. This feature made it the preferable choice, aligning with the project's stringent requirements for safety and operational efficacy, thereby justifying its selection despite the higher expense.

4.2.4 Chassis

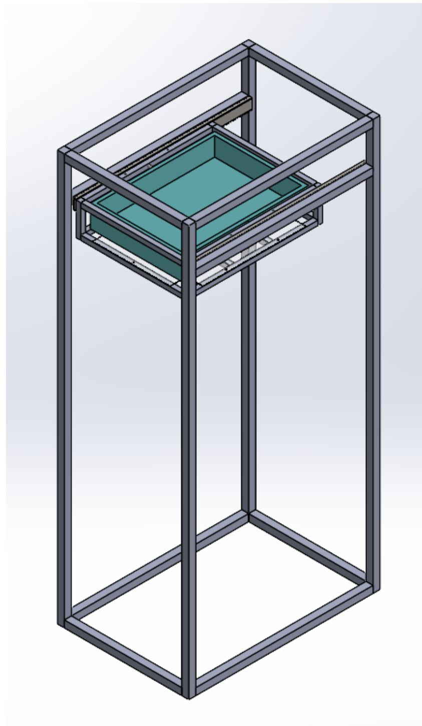


Figure 66. Structure of Chassis with one attached drawer slide, cage and container in CAD.

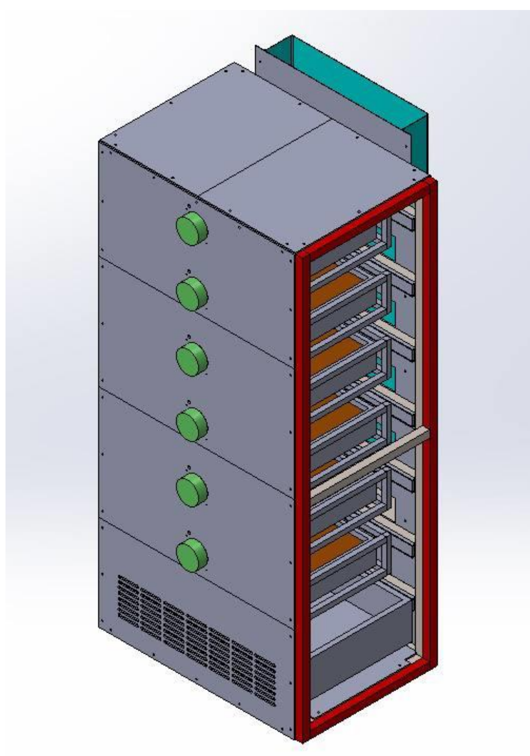


Figure 67. Configuration 1 (larger distance between cages).

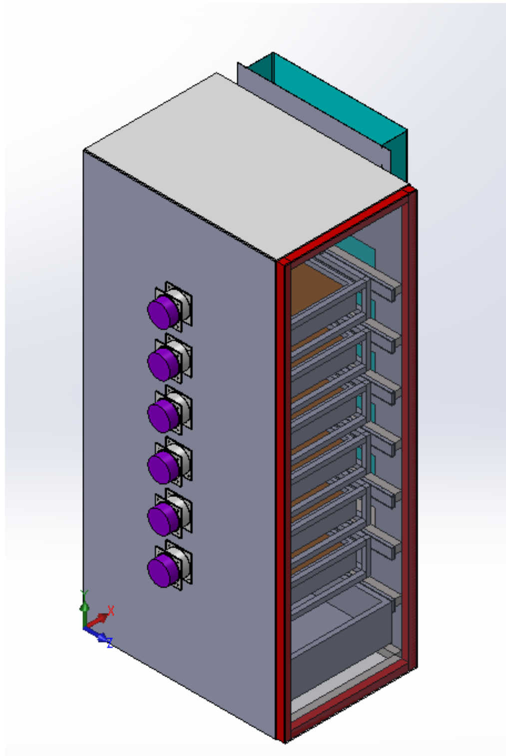


Figure 68.Configuration 2 (smaller distance between cages).

In the architectural conception of the chassis, we decisively opted for 30 by 30 aluminum profile bars, a choice motivated by similar considerations that led to the selection of 20 by 20 aluminum bars for the cage's framework. The augmented dimensions of these profile bars not only imbue the chassis with superior structural integrity but also markedly augment the design's versatility. This versatility is critically beneficial in the positioning of drawer slides, which, owing to the aluminum bars' modifiable nature, can be adjusted in height to meet specific needs, thus not restricting the design to a predetermined elevation. Additionally, the intrinsic capacity of aluminum to develop a protective oxide layer bestows upon it a significant resistance to corrosion, a characteristic of vital importance for our reactors. Given the likelihood of encountering corrosive gases generated by the BSFL during prolonged usage, the corrosion-resistant properties of aluminum are instrumental in ensuring the chassis's longevity and robustness, making it eminently suitable for the project's distinct requirements.

Furthering the refinement of our reactor's design, a strategic decision was enacted to position the cages along their lengthier dimension within the chassis, aiming for a more streamlined profile. This design revision is instrumental in facilitating the compact organization of multiple reactors when aligned adjacently, a critical factor for efficient spatial management. This consideration was driven by the imperative to conform to the spatial limitations typically present in elevators and corridors, culminating in the establishment of precise chassis dimensions: 81.50 cm in length, 56 cm in width, and 175 cm in height. These specifications were diligently derived to house six cages, permitting the exploration of two distinct cage configurations within the chassis. This innovative approach was supported by initial simulations performed by our team, which indicated that the inter-cage spacing exerts a minimal effect on airflow distribution within the system. Prompted by these insights, our investigation extended into optimizing the chassis design to accommodate an increased cage count without detracting from the critical environmental conditions necessary for optimal reactor functionality, thus deepening our comprehension of how spatial design influences reactor efficacy.

4.2.5 Cage Locking Mechanism

4.2.5.1 Iteration 1

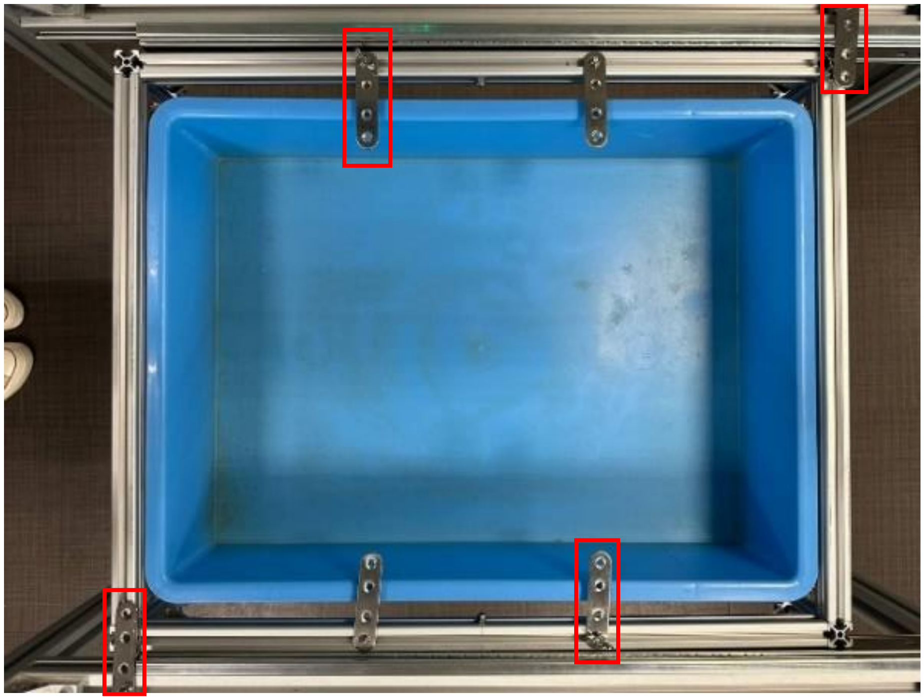


Figure 69. Top view of container locked in cage and cage locked on drawer slide (Iteration 1).

In the development of our cage locking mechanisms, our focus was directed towards achieving two fundamental goals. The primary goal was to guarantee the secure retention of the container within the cage throughout the rotation process essential for unloading, thereby averting any risk of the container inadvertently dislodging. The secondary objective was to preserve the stability of the cages subsequent to loading, ensuring that they remained horizontally aligned and did not tilt within the chassis framework. The initial version of our design, as illustrated in the accompanying photograph, incorporated the use of six steel straight brackets to fulfill these requirements. Of these, four brackets were judiciously placed to firmly anchor the container in position during the unloading phase, while the two additional brackets were dedicated to maintaining the cage's equilibrium within the chassis, effectively mitigating any potential for undesired tilting movements.

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

Figure 71. Locking the cage in place.

To effectuate the rotation of the steel straight brackets, the initial step involves loosening the wingnut. This adjustment permits the bracket to pivot, allowing for its reorientation to a desired alignment. Subsequent to this realignment, it is imperative to securely retighten the wingnut, thereby ensuring the bracket is steadfastly anchored in its adjusted position, maintaining stability and preventing misalignment.

Regarding the configuration of the two outer brackets, it is practical to maintain the bracket situated furthest from the door in a permanent horizontal placement. Conversely, the bracket proximate to the door necessitates a design that permits adjustability. This adjustability is crucial to facilitate the unencumbered withdrawal of the cage; specifically, the bracket must be capable of being repositioned to prevent any interference with the wingnut on the cages, thus guaranteeing a smooth extraction of the cage without the risk of obstruction.

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 project's second iteration, a substantial enhancement was achieved through the introduction of a bespoke stopper mechanism, meticulously crafted using a Computer Numerical Control (CNC) machine housed in the central workshop. This innovation represents a leap forward in terms of user-friendliness and security of operation, effectively rendering the previous necessity to loosen a wingnut for adjustment obsolete. In its stead, the mechanism allows users to effortlessly lift the stopper and rotate it to the preferred orientation. A key feature of this upgraded design is the integration of a spring that ensures the stopper remains firmly in its adjusted position. Additionally, the mechanism is equipped with an extrusion that is specifically tailored to engage with the crevices of the profile bar, guaranteeing a secure relocking. This refinement, vividly depicted in the provided photograph, significantly simplifies the adjustment process, rendering it more efficient and safer, thereby markedly improving the overall user interaction with the system.

4.2.5.3 Final Iteration

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

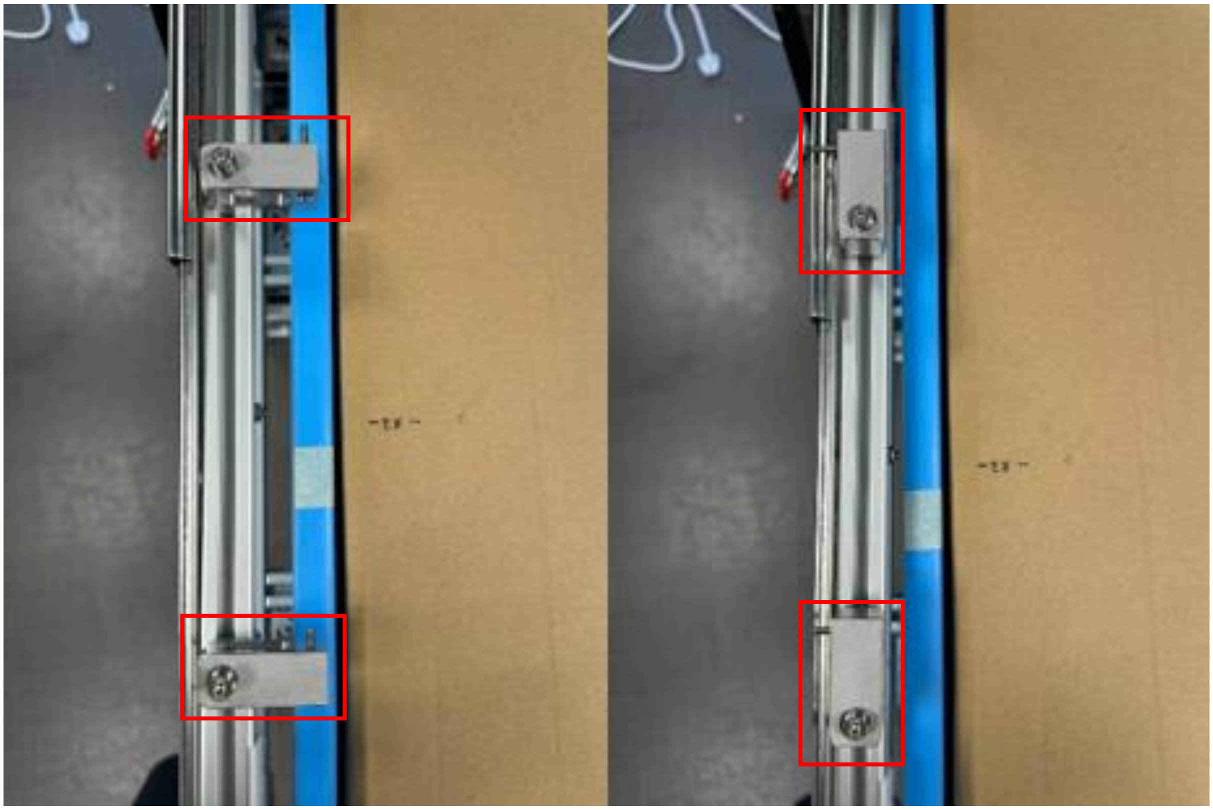


Figure 76. Assembled spring-loaded stopper on the cage (left is to lock the container, right is to lock the cage).

In the ultimate refinement of our stopper mechanism design, we targeted a more cohesive functionality that would singularly address our twin objectives, thereby obviating the necessity for separate outer brackets. Diverging from the previous iteration where the stopper's utility was confined to securing the container in a horizontal orientation, this final design iteration introduces a pivotal enhancement. The integration of a M3 x 20 Internal Hex screw into the stopper ingeniously expands its utility, enabling the device to fulfill a dual role. Specifically, when positioned vertically, the stopper now additionally acts to inhibit any tilting of the cage within the chassis. This strategic alteration significantly streamlines the assembly process, transitioning from a setup that initially required four stoppers and two straight brackets to a more simplified arrangement consisting solely of four stoppers.

To further enhance the user experience, an indentation has been ingeniously incorporated into the stopper's design. This ergonomic modification affords users a more secure grip, thereby simplifying the act of manipulating the stopper. Such design improvements not only amplify the system's usability and operational efficiency but also substantially reduce the complexity and the overall component count of the assembly. Consequently, this refined stopper mechanism stands as a testament to the project's continuous design optimization efforts, delivering a solution that is both significantly more user-friendly and streamlined.

4.2.5.4 Loading and Unloading comparison

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

<table>
<tr><th colspan="3">Loading</th></tr>
<tr><th>1st Iteration</th><th>2nd Iteration</th><th>Final Iteration</th></tr>
<tr><td>1. Extract the Cage: Begin by pulling the cage out from the chassis to facilitate access.</td><td rowspan="5">As with the initial iteration</td><td rowspan="4">As with the initial iteration</td></tr>
<tr><td>2. Insert New Container: Place a new container within the cage, preparing it for loading.</td></tr>
<tr><td>3. Load the Container: Fill the container with food waste and larvae, initiating the treatment process.</td></tr>
<tr><td>4. Reposition the Cage: Gently push the cage back into the chassis, ensuring it is correctly aligned.</td></tr>
<tr><td>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.</td><td>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.</td></tr>
</table>

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

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

The comparative tables showcased delineate the progressive evolution of our cage locking mechanisms through three distinct iterations, meticulously charting the development journey. These tables serve a dual purpose: they highlight the nuanced differences between each iteration and furnish a comprehensive, step-by-step manual for the operation of engaging and disengaging the stoppers throughout the loading and unloading processes. With each iteration, targeted enhancements were introduced, focusing on refining either or both of these essential operations. This process of iterative refinement reached its zenith in the third and final iteration, encapsulating the series of improvements and embodying the project's continuous advancement. This final version stands as a testament to the systematic and thoughtful evolution of our design, reflecting the project's overarching commitment to optimization and user-centric innovation.

4.2.6 Wheels

Figure 77. Wheels without stopper.

Figure 78. Wheels with stopper.

In our reactor's design process, the emphasis on portability necessitated the selection of light duty caster wheels, chosen specifically for their synergy with the reactor's height constraints and required load-bearing capabilities. The chosen PTF-HS050-TPU model, with its modest height of 71 mm, is capable of supporting up to 50kg per wheel, facilitating a cumulative maximum load capacity of 200kg when employing a quartet of these wheels. To augment stability and afford greater control, the integration of PTF-HL050-TPU wheels was undertaken. These wheels mirror the HS050 model in dimensions and capacity but are distinguished by the inclusion of a wheel brake, a feature designed to immobilize the chassis when desired. The deliberate diagonal arrangement of these braked wheels across the chassis allows for the reactor to be securely stationed as necessary, seamlessly blending mobility with stationary stability. (See Appendix 7.9 for more details)

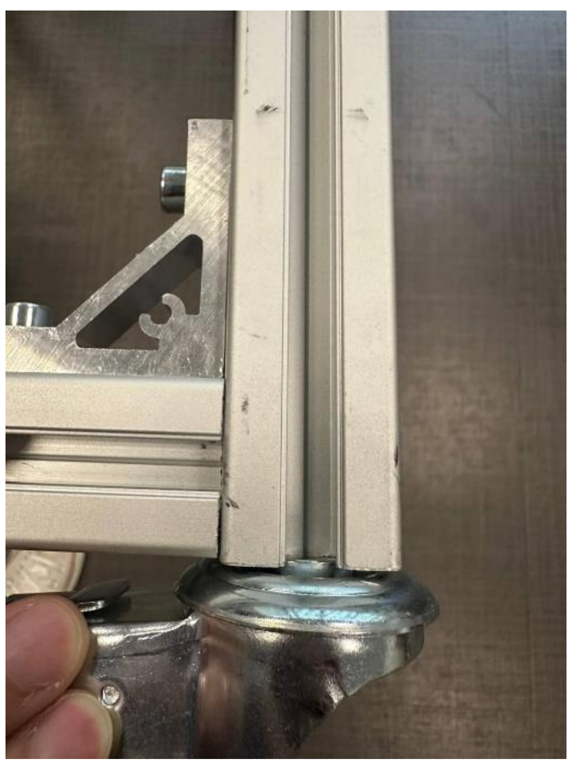


Figure 79. Side view of wheels mounted to chassis.

Figure 80. Bottom view of wheel mounted to chassis.

For the installation of the wheels onto our reactor, we capitalized on the existing central hole in the 30 by 30 profile bars, opting for an M10 x 25 mm countersunk screw as the attachment mechanism. This installation technique guarantees a robust and stable linkage between the wheels and the profile bar, thereby supporting the reactor's mobility while also preserving the structural integrity of the wheel assembly. This methodical approach to wheel attachment is instrumental in ensuring that the reactor remains both maneuverable and structurally sound, reflecting a meticulous attention to detail in the design process to optimize functionality and durability.

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).

Beyond structural enhancements, our design thoughtfully integrates a divider plate, serving as a crucial barrier to segregate electronic components from the potential gases produced during the BSFL treatment process. This preventive strategy is key to shielding the electronic systems from corrosive or potentially hazardous environments that could compromise their functionality. Additionally, the deliberate incorporation of four holes at the back of the divider plate is designed to accommodate cable glands. These glands play a vital role in ensuring the secure passage of wires, effectively guarding against environmental hazards such as moisture, contamination, corrosion, and exposure to flammable gases. Such considerations are paramount in bolstering the safety and extending the operational lifespan of the electronic systems that are fundamental to the reactor's performance, illustrating a meticulous approach to design that prioritizes both efficiency and safety.

4.2.8 Experiment Profile Bar

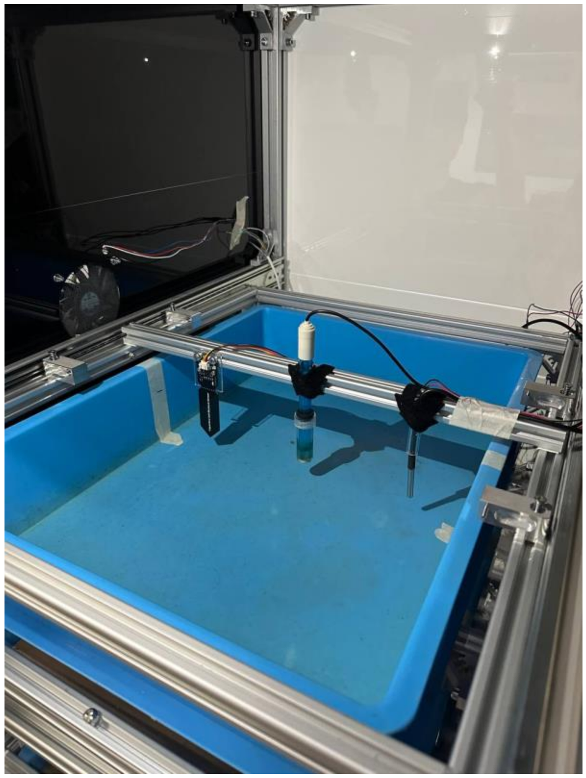


Figure 83. Experiment bar for sensors to be mounted on.

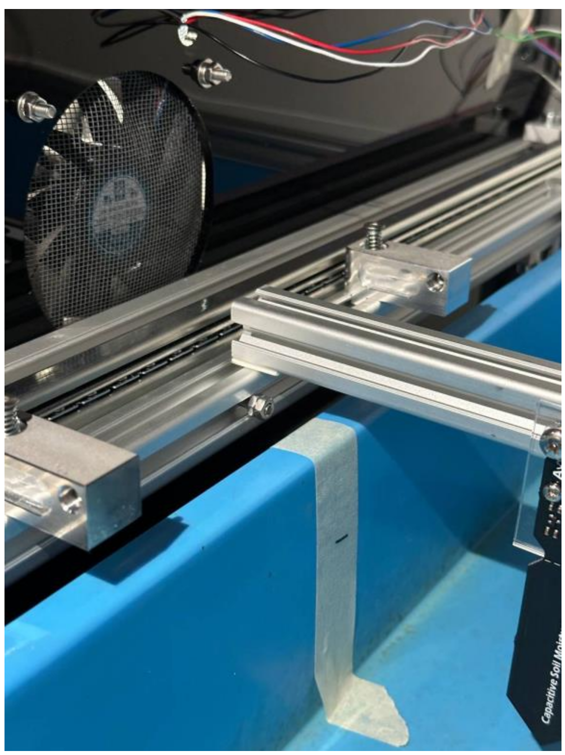


Figure 84. Close up photo of how to experiment bar sits on the cage.

In our design, we have judiciously incorporated a 20 by 20 aluminum profile bar, positioned along the two horizontal edges of the cage. This strategic addition is tailored specifically to aid the electronics team in the mounting of sensors, thereby greatly broadening the system's adaptability. The configuration of the profile bar is such that it permits versatile positioning across the horizontal edges of the cage, thus accommodating a variety of sensor setups. Moreover, the capacity to mount sensors at any juncture along the profile bar provides the electronics team with the latitude to tailor sensor placement to the specific demands of individual experiments. This integration highlights our dedication to ensuring that the reactor's design is not only adaptable but also precise, facilitating the efficient execution of a diverse array of experimental configurations. This aspect of the design vividly illustrates our commitment to enhancing the system's versatility and operational efficacy.

4.2.9 Guider

Figure 85. Prototype guider to test effectiveness.

The incorporation of a guider into our design emerged as a pivotal enhancement for improving both the efficiency and cleanliness of the unloading process. This need became apparent following preliminary experiments, which revealed that, in the absence of a guider, the dispersion of remains was haphazard, leading to considerable mess. An initial attempt using a simple cardboard piece as a provisional guider indicated that although a substantial portion of the material was directed into the intended container below, a significant quantity failed to reach its destination, scattering around the vicinity instead. This observation highlighted the necessity for a more refined solution capable of guiding the contents accurately during the cage's rotation. In response, we decided to conceive and construct a custom guider tailored to our specific requirements. This bespoke solution was designed with the goal of optimizing the unloading process by ensuring a precise and neat channeling of remains into the collection box below, thereby significantly reducing spillage and upholding 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.

Drawing inspiration from the functional design of a French fry sorter, we engineered a guider that boasts side walls meticulously contoured to fit snugly within the container, as depicted in the accompanying photograph. A critical innovation in our design was the integration of an air conditioner duct vent and its connector, enabling the creation of a pathway that deftly channels frass along the guider's side walls and directly into the duct. A standout feature of this arrangement is the duct vent's collapsible design, greatly enhancing the guider's compatibility with various cage sizes. This adaptability allows for the duct vent's length to be modified to accommodate cages of different heights, efficiently directing frass to the intended unloading container and significantly reducing spillage.

An additional layer of ingenuity is introduced through the use of Velcro for securing the guider to the cage, streamlining the process of attachment and detachment while maintaining the guider's stability throughout the unloading process. This thoughtful design choice not only simplifies the unloading operation but also substantially diminishes the necessity for clean-up efforts by confining the frass to a predetermined path. Consequently, this innovative approach to guider design enhances the efficiency of the unloading process and presents an effective solution for managing waste during these activities, embodying a significant leap forward in operational efficiency and cleanliness.

4.2.10 Door

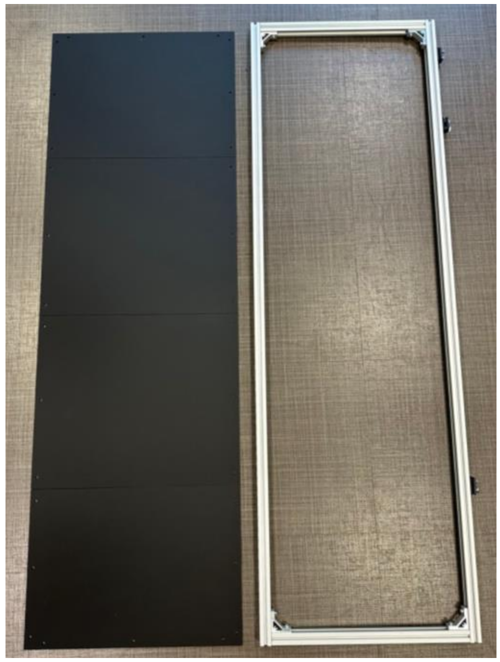


Figure 89. Unassembled acrylic door walls and door frame.

Figure 90. Assembled door with hinges.

Figure 91. Side profile of door hinge.

Figure 92. Top profile of door hinge.

For the door's construction, our approach involved creating a frame using four 30 by 30 aluminum profile bars, onto which acrylic panels were mounted to achieve effective enclosure of the chassis. The hinge mechanism employed for attaching the door to the chassis was part PTA-H3030-8, a Plastic Hinge tailored for seamless integration with 30 by 30 aluminum profile bars [36]. Utilizing this hinge in conjunction with four M6 countersunk 16 mm screws and four M6 Rhombus Nuts facilitated the creation of a flush mount, ensuring that the door aligns perfectly with the chassis, leaving no gaps when in the closed position. To support the door's weight adequately and preserve its alignment, three such hinges were judiciously spaced along the length of the door, ensuring equal distribution of the load. This careful consideration in the design and assembly of the door not only guarantees a smooth and secure closure but also significantly contributes to the chassis's overall functionality and visual appeal, embodying a thoughtful fusion of practical design and aesthetic considerations.

Figure 93. weather foam strip around door frame.

Figure 94. weather foam strip around door hinge.

Additionally, to augment the door's sealing capability and enhance the system's containment efficiency, we integrated a weather foam strip along the door's perimeter. This strategic inclusion guarantees a snug seal, thwarting the possibility of gas leakage through the door's edges. By ensuring that gases are directed exclusively through the chimney for exit, this improvement effectively eliminates the risk of unintended leakage. This measure not only reinforces the containment strategy of the system but also underscores our commitment to maintaining environmental safety and operational integrity within the reactor's design.

4.2.11 Door Lock

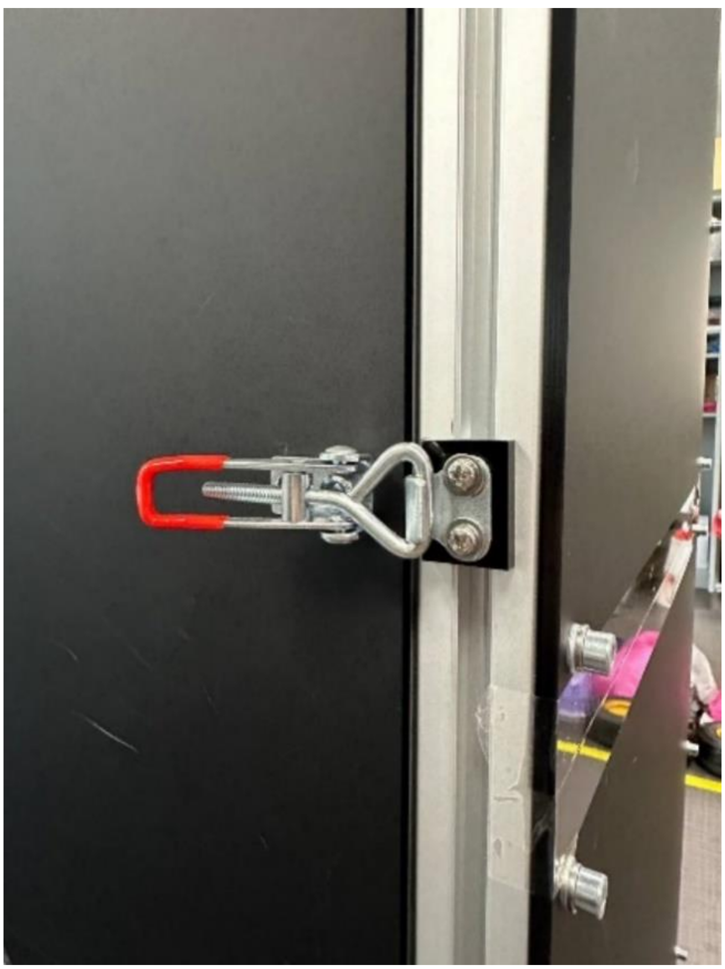


Figure 95. Close up view of attached door lock.

Figure 96. Zoomed out view of door lock.

In the architectural conception of the door lock mechanism for our system, identifying a method that ensured a secure closure against the foam strip, thus establishing a reliable seal, was paramount. After careful consideration, our choice fell on an adjustable pull toggle latch clamp. This particular clamp was selected due to its proficiency in pulling the door firmly against the chassis, effectively securing it in a stationary, locked position. Such an arrangement is crucial for sustaining the integrity of the system's internal environment by ensuring a robust seal. To enhance user convenience and ensure swift access, reopening the door has been simplified to an act of lifting the red handle upwards. This action disengages the latch, enabling the door to be effortlessly opened, thereby eliminating any obstacles to access. This design choice reflects our dedication to balancing security and accessibility within our system, ensuring that it remains both sealed and readily accessible as required.

Figure 97. Final iteration of door lock.

After deploying our initial locking mechanism, we observed that utilizing a solitary lock positioned at the center of the door was insufficient to achieve a comprehensive seal along its full length. While this arrangement succeeded in securing the door's central section, it inadequately applied pressure at the door's extremities, resulting in an ineffective seal at both the top and bottom edges. To rectify this issue, we augmented our design by incorporating two additional locks, strategically placing one at the top and the other at the bottom of the door. This adjustment significantly improved the door's sealing capability, guaranteeing a uniform and complete seal across its entire length. This evolution in our locking mechanism design underscores our commitment to ensuring the integrity and effectiveness of the system's containment, by addressing and rectifying identified deficiencies.

Here's a comparison to highlight the improvements made to the door's sealing mechanism:

Table 9. Before and After comparison of the door locking mechanism

Aspect	Before Modification	After Modification
Lock Configuration	A single lock placed at the center, leading to an incomplete seal due to lack of pressure on the door's extremities.	Two additional locks introduced, one at the top and one at the bottom, providing comprehensive sealing pressure.
Sealing Capability	Inadequate, with the seal effectively limited to the central portion of the door.	Significantly improved, ensuring a uniform and complete seal across the door's entire length.
Issue Addressed	Insufficient sealing force resulting in potential security and environmental control concerns.	Enhanced sealing force ensuring complete security and environmental control across the entire door.

The strategic placement of additional locks has resolved the initial inadequacies, offering a robust solution that ensures a complete and uniform seal, addressing both security and environmental control requirements efficiently.

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.

To evaluate the portability of our fully assembled reactor, we undertook a series of practical tests to examine its mobility across various settings. The tests, illustrated through photographs, confirmed that the reactor could be easily moved by a single person. Its ability to navigate through common infrastructural elements such as corridors, alleyways, doorways, and elevators further affirmed its design's effectiveness in achieving high portability and accessibility across diverse environments. These tests were pivotal in validating the reactor's adaptability and its capacity for straightforward integration into its intended use scenarios.

Here's a comparative analysis highlighting the reactor's portability assessment:

Table 10. Reactor portability assessment

Evaluation Criteria	Findings from Portability Tests
Mobility	The reactor can be effortlessly maneuvered by a single individual, demonstrating ease of movement.
Compatibility	Successfully navigated through corridors, alleyways, doorways, and elevators, proving its adaptability to various environments.
Practicality	The testing phase underscored the reactor's functional adaptability and potential for easy integration into operational contexts.

The reactor has achieved our objectives for portability and adaptability, showing its capability to be transported and used in diverse environments, specifically within the NUS. This feature is crucial, facilitating the reactor's easy transfer to the research laboratory for further testing and experimentation.

4.3.2 Loading Test

Figure 102. Loading baked frass into the container.

The adoption of the drawer system has brought about considerable improvements in the process of preparing containers for BSFL treatment, streamlining operations and reducing manual labor. Here's a comparative analysis of the process before and after the implementation of the drawer system, highlighting the procedural enhancements and operational efficiencies gained.

Table 11. Comparison between the before and after the implementation of drawer slides (loading)

Process Step	Before Drawer System Implementation	After Drawer System Implementation
Food Waste Distribution	Even distribution of food waste into each container initiated the process.	Directly add food waste into the container within the cage, achieving desired weight with built-in load cell accuracy.
Weighing	Each container weighed individually to ensure desired weight, adjusting as necessary.	The cage's built-in load cell facilitates accurate measurement during filling, simplifying the process.
Repetition	The process of distribution and weighing repeated for uniformity across containers.	Streamlined repetition of adding food waste and BSFL, utilizing the drawer system for each container as needed.
BSFL Introduction	After reaching target weights, BSFL added to each container.	BSFL are introduced directly into the container in the cage, then the cage is returned to the chassis.
Placement	Manual carrying and positioning of each container in its designated rack location.	The drawer system allows for the easy insertion and retraction of cages, significantly reducing manual effort.

Findings from test: The evaluation highlighted a transformation in the container preparation process for BSFL treatment with the drawer system's introduction. Previously characterized by its laborious nature—especially the frequent lifting and moving of trays for weighing—the new system has mitigated these challenges. It has minimized the manual labor and time required for precise measurement and placement of containers, marking a significant advancement in operational efficiency and ease.

4.3.3 Unloading Test

Figure 103. Unloading frass into container.

The transition from a manual retrieval system to an advanced drawer system for unloading containers in our operations marked a significant improvement in both efficiency and ease of use. Below is a comparative analysis of the procedures and outcomes associated with each system, highlighting the enhancements brought about by the implementation of the drawer system.

Table 12. Comparison between the before and after the implementation of drawer slides (unloading)

Aspect	Before the Drawer System	After Implementing the Drawer System
Retrieval Method	Containers manually carried down from each rack.	Cages easily pulled out; guiders attached to facilitate directed flow.
Unloading Preparation	Repetitive and physically demanding manual process for each container.	Unloading container positioned below the cage; guiders adjusted for targeted flow. Activation of stoppers unlocks the container within the cage.
Efficiency	Time-consuming and labor-intensive.	Efficient unloading through rotation of the cage, directing contents into the unloading container via a specially designed guider.
Manual Intervention	Not applicable.	Required to tap on the guider to dislodge frass and ensure its descent.
Additional Observations	None.	Some frass escaped, collecting on the acrylic plate. Significant reduction in physical labor by eliminating the need to manually remove containers.

Findings from Test: The evaluation of the unloading phase under the new system revealed both strengths and areas for improvement. While the drawer system significantly reduces the physical effort previously required to unload containers, observations indicated that a small amount of frass escaped the guider, necessitating manual intervention to ensure complete unloading. Despite these minor issues, the drawer system's introduction has greatly facilitated the unloading process, notably eliminating the need for manual removal of fully loaded containers from the chassis and simplifying the redirection of contents into the designated container through strategic cage manipulation.

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.

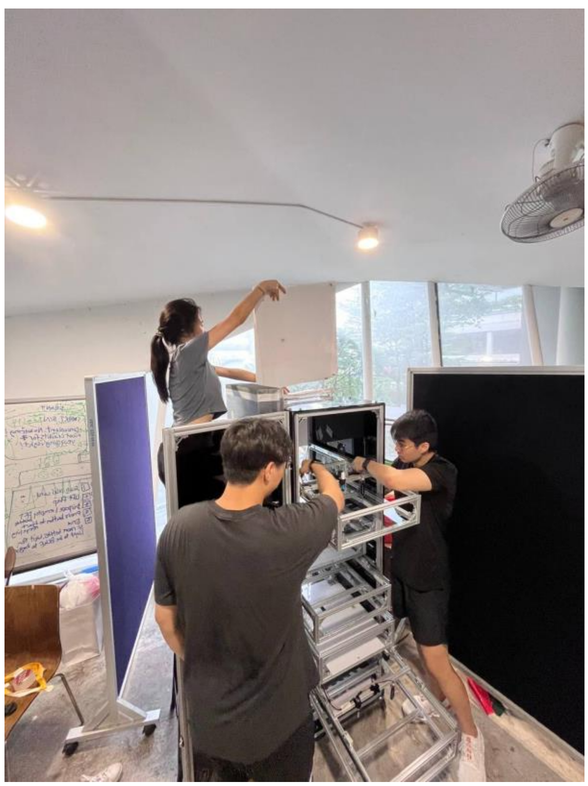


Figure 109. Final touch ups to the reactor.

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

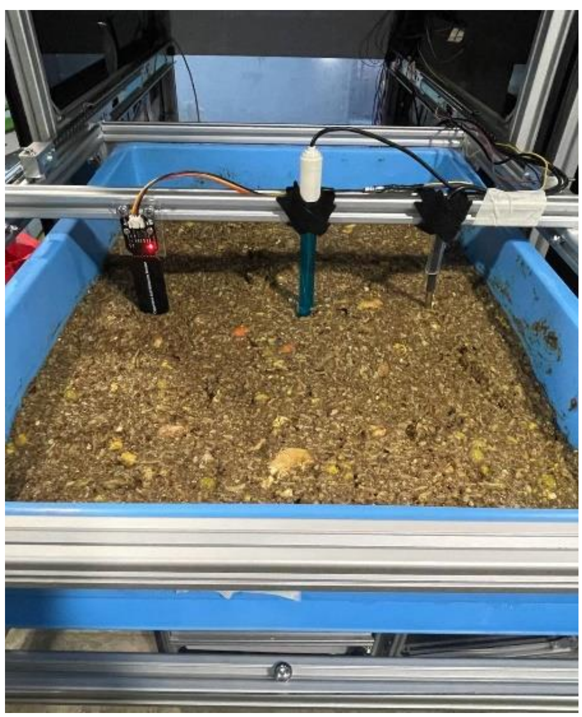


Figure 111. Putting in the sensors before pushing the cages into the reactor.

Figure 112. All containers loaded and all cages secured.

In the final stages of our study, we undertook an extensive experiment in our reactor, requiring a visit to the lab for the collection of essential food waste and larvae. The experiment began by preparing 39 kg of food waste combined with 1.17 kg of cocopeat to reduce moisture in the substrate. This mix was then evenly blended to create a consistent substrate mixture. For precise measurements, we filled each tray by hand, totaling 6.695 kg per tray, including 6.5 kg of food waste and 0.195 kg of cocopeat.

The next step involved moving the filled containers to our experiment site, where the reactor was ready for operation. After making the necessary tweaks to the reactor, we loaded the containers. Before placing the containers back into the reactor, we introduced around 10,000 larvae into the mix and set up sensors for data recording.

At this preliminary phase, we refrain from sharing specific results. However, we plan to offer a thorough review and interpretation of our findings in the subsequent phases of our research. This initial experiment is crucial for gathering essential data to evaluate our bioconversion system's efficiency and effectiveness in the reactor. As we progress, we will document our findings, hurdles, and adjustments to gain a comprehensive understanding of the system's workings. Our aim is to analyse the collected data meticulously to uncover valuable insights into the system's performance and identify potential improvements, paving the way for future advancements in our experimental series.

5. Future Works

As we progress with our project, we've pinpointed several key improvements aimed at boosting both the efficiency and usability of our system.

Firstly, by improving loading efficiency. The current method for loading containers, while effective, has room for increased efficiency. We are exploring the integration of an automated pump system for distributing food waste into containers, which promises to make the loading process more consistent and efficient. By automating this step, we aim to reduce manual labor and enhance time management significantly.

Secondly, a wheel design enhancement. Our observations have revealed that the existing wheel design struggles with larger gaps and transitions, such as those encountered at elevator entrances. To overcome this, we are contemplating the use of larger wheels. This change is anticipated to smooth out navigation across such disparities, decreasing the risk of the wheels getting stuck and thereby enhancing the system's mobility.

And lastly, a guider system improvement. Feedback on the guider system has highlighted several areas for refinement. We plan to rework the guider's attachment to the container to prevent leaks when the cage rotates. Making the guider's entrance larger is also on the agenda, aiming for better content collection during unloading. Moreover, considering alternative materials for the guider could address concerns regarding its weight and bulkiness, thereby improving its manageability and performance.

These enhancements are the cornerstone of our strategy to evolve and improve the system's design continually. Our focus on these particular areas is driven by the goal to elevate operational performance, ease of use, and the overall efficiency of the BSFL treatment process.

5.1 Feedback from Researcher (Adrian Fuhrmann)

Initial reactions to our reactor prototype have been overwhelmingly affirmative, emphasizing its ease of use and operational efficiency. Nonetheless, in our quest to fully optimize the reactor's capabilities, we've pinpointed certain areas ripe for enhancement. These recommendations are geared towards not just elevating the reactor's performance but also bolstering its safety and ease of operation. The sections below detail the envisaged improvements and the requisite research to bring these amendments to fruition.

1. Tray Locking Mechanism: Investigating the creation of a novel system of interconnected locks. This would enable operators to lock or unlock multiple trays in one go, simplifying operations significantly. The aim is for this system to uphold or enhance the reactor's existing safety and security measures, while making the reactor more user-friendly.
2. Augmented Funnel Shielding: Broadening the shield around the funnel to ensure a more effective containment. This enhancement is designed to prevent the spillage of frass and larvae, thereby keeping the operational area cleaner and minimizing waste.

The input we've received is instrumental in guiding the next stages of our reactor's enhancement. By targeting a decrease in the manual handling of trays and an improvement in the containment of byproducts, we anticipate a substantial uplift in the reactor's functionality and safety profile. These will be further explored in the later stages when researchers explore more on optimising the reactor.

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7. Appendices

7.1 BCA guidelines and dimensions around NUS campus

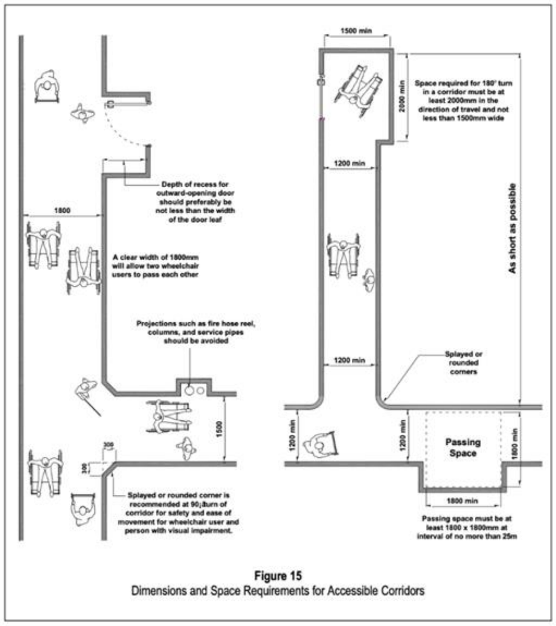


Figure 113: BCA guidelines for corridors

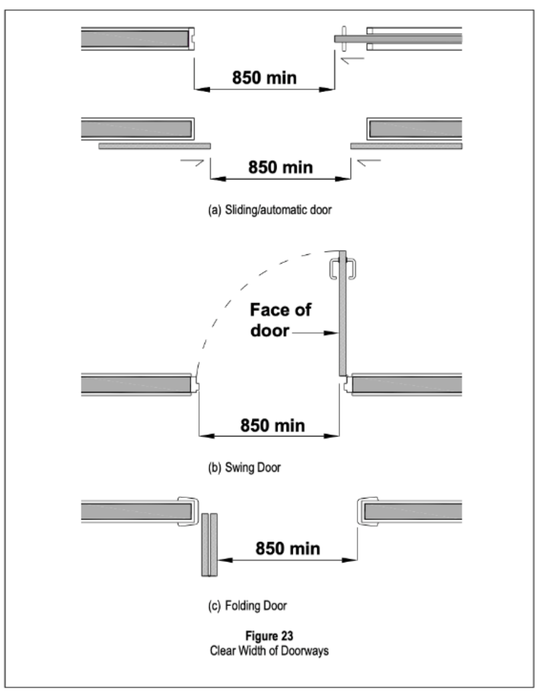
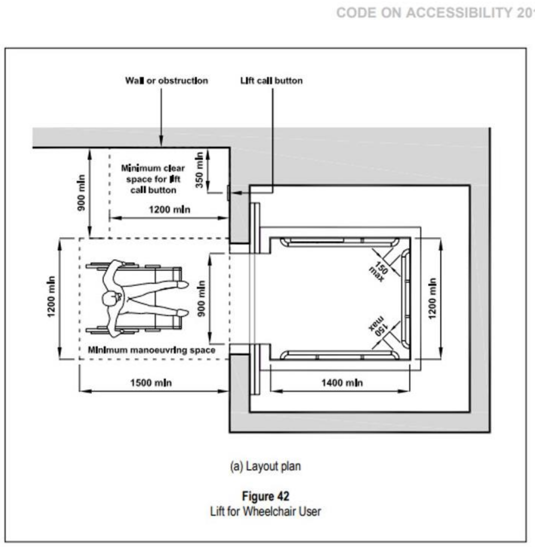


Figure 114: BCA guidelines for doors



(a) Layout plan

Figure 42
Lift for Wheelchair User

Figure 115: BCA guidelines for lifts

The data provided above originates from the guidelines issued by the Building and Construction Authority (BCA), which detail the specifications for corridors, doors, and elevators. Our focus was primarily on these areas because they were recognized as critical spaces that might impact the mobility and maneuverability of our reactor system. Comprehending and conforming to these standards was essential, as they shaped our design strategies to guarantee the reactor's operational effectiveness and adaptability in different environments.

Figure 116: Ground level pathway in E2A building, NUS

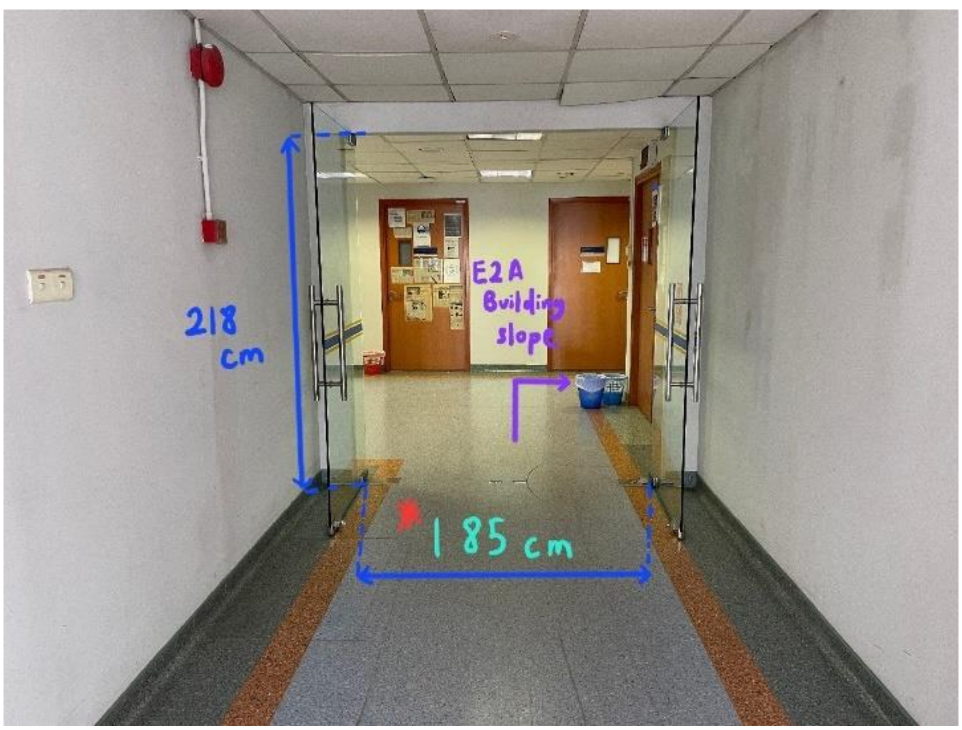


Figure 117: Connecting pathway in E2A building, NUS

Figure 118: Door in EA building, NUS

Figure 119: Lift in E2 building, NUS

Figure 120: Lift in E1A building, NUS

In order to affirm our design assumptions and guarantee precision, we undertook a detailed survey of the school campus, meticulously measuring specific areas and pathways relevant to the proposed mobility of our reactor. This evaluation verified that the dimensions stipulated in the BCA guidelines accurately reflected the real dimensions of spaces on the campus. This corroboration has given us the assurance to establish the dimensions of our reactor, ensuring it is optimally compatible and functional within the identified spaces, based on the accurate standards provided in the guidelines.

7.2 Calculations of food waste

Figure 121: Food waste calculations per food court per day

Interviews with cleaners at UTown food courts provided crucial information, revealing that they generate one full bin of food waste each day, equating to roughly 120 liters in volume. Despite acknowledging that food waste density may vary from one location to another, it was deemed important to secure a density estimate. Referencing existing literature, a density of approximately 1.565 kilograms per liter was identified. When this density figure is applied to the 120-liter volume, the resulting estimated total food waste mass is about 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

Following our preliminary sizing assessment and rough calculations, we ascertained that each container would require a torque of 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

Our experimental results indicate that the use of a smoother surface markedly influences the mobility of frass. Specifically, a smooth surface necessitates merely a 50-degree angle to achieve the full evacuation of all frass. This observation underscores the importance of smoother surfaces in improving the ease with which frass slides and is expelled from the container.

7.5 Calculations for torque requirement

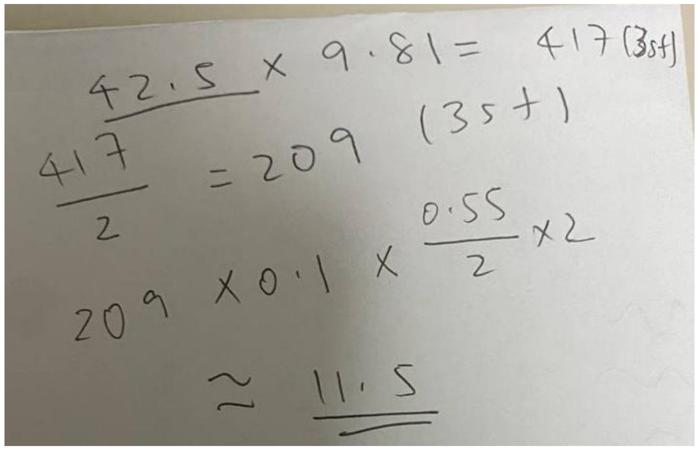


Figure 126: Calculations for torque required for roller system

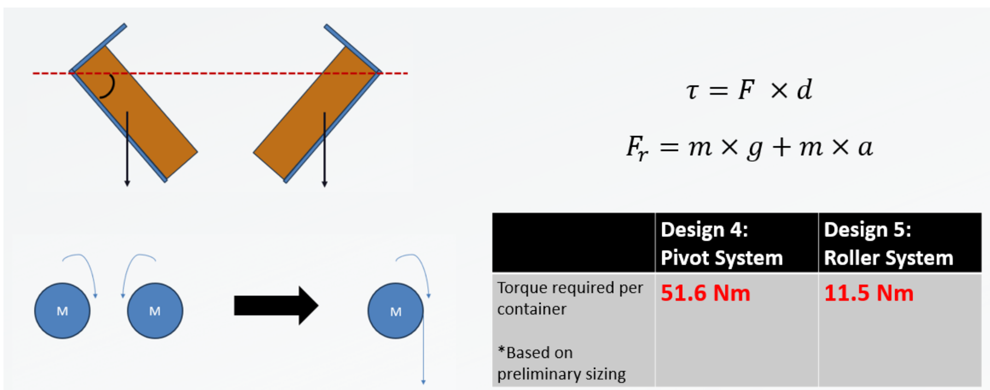
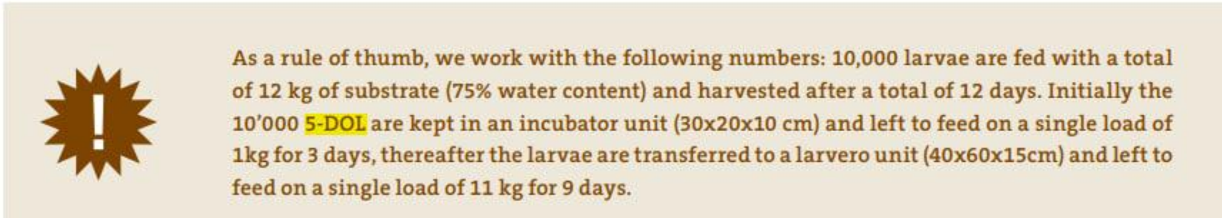


Figure 127: Comparison between pivot system and roller system

After performing computations using our initial roller system sizing, we found that 11.5 Newton-meters (Nm) of torque are needed. Even with this lower torque requirement, it is still not feasible for our chassis to have several motors. As such, we have decided to investigate a different approach by taking a closer look at a manual system, realising that it might better suit our needs in terms of both functionality and cost.

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

The literature review suggests a ratio of 10,000 larvae for every 12 kilograms of food waste. Given that our containers have a capacity for 40 kilograms of food waste, it can be estimated that around 33,333 larvae would be needed per container (derived from 40/12 x 10,000).

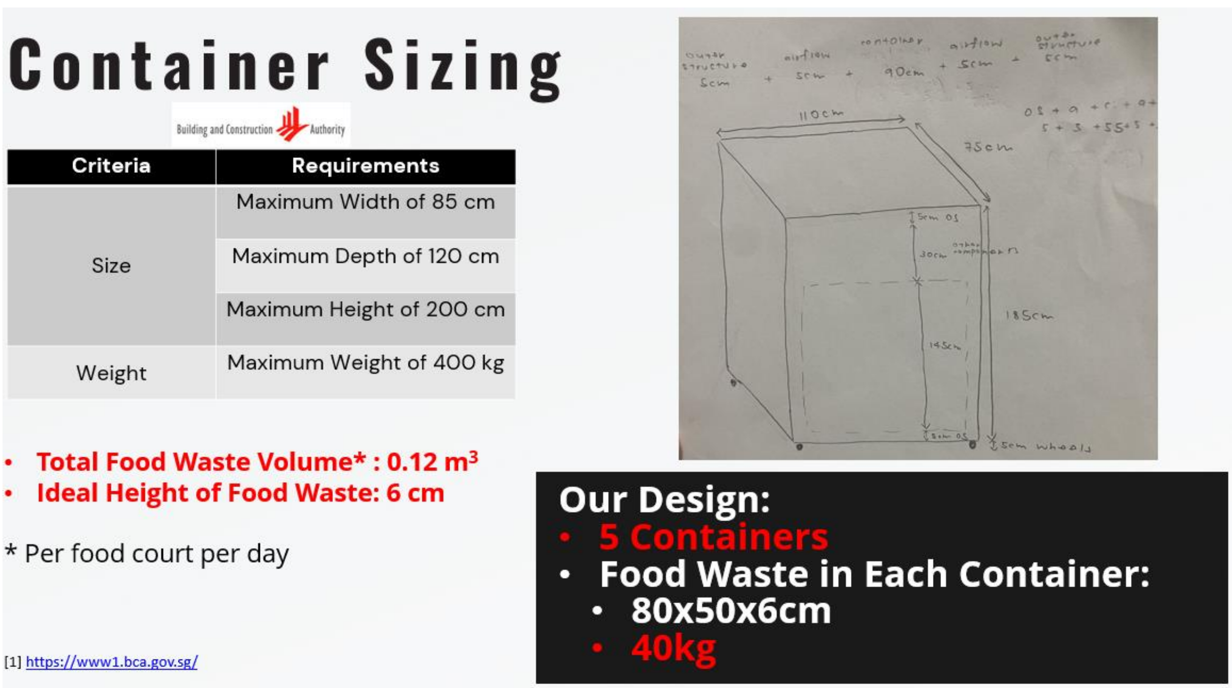
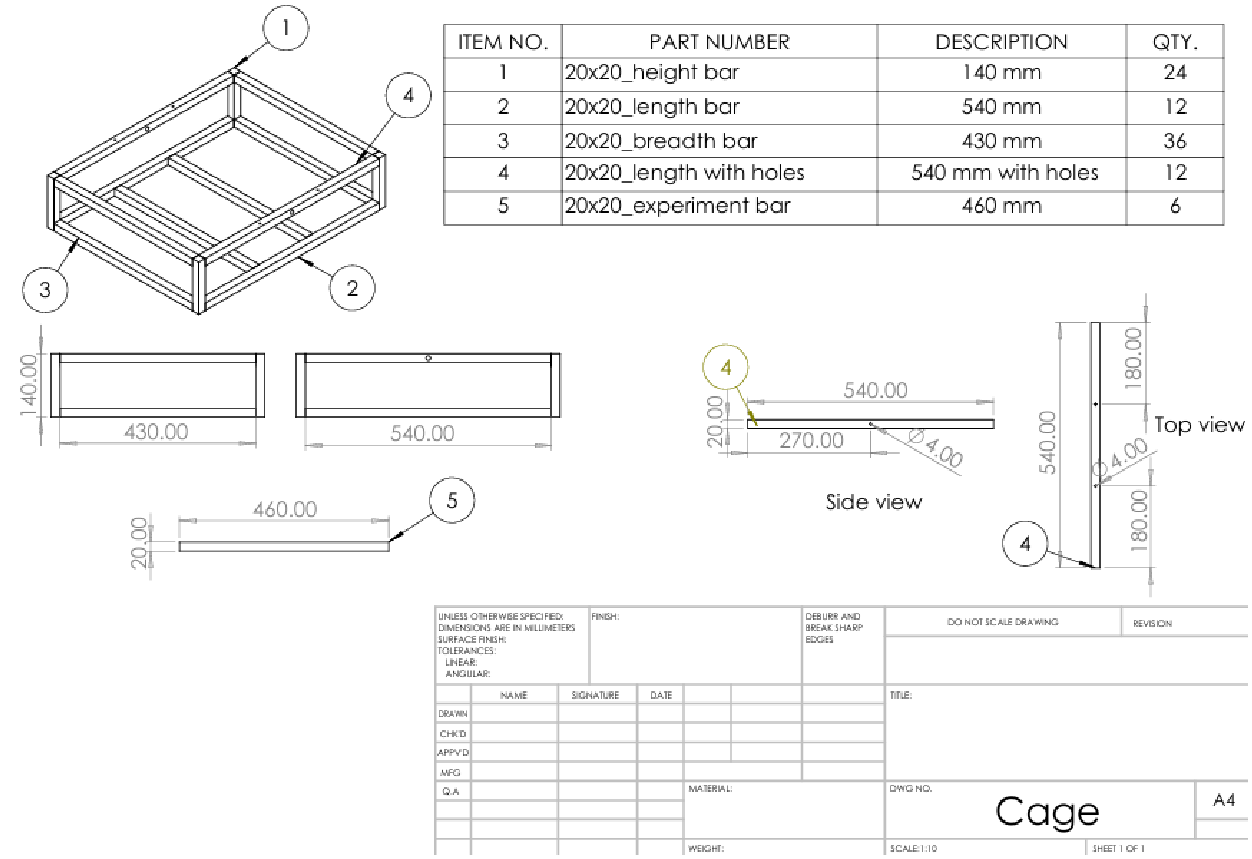


Figure 129: Container sizing calculations

Given the target height for food waste at 6cm, with the container's dimensions defined as 80cm in length and 50cm in width, the container's total capacity for food waste is calculated to be 0.12 cubic meters (using the formula length × width × height = 0.8m × 0.5m × 0.06m =

$0.12m^3$). With an assumed food waste density of 1.565 kilograms per liter, this capacity translates to an approximate food waste weight of 40 kilograms (determined by the formula volume × density = $0.12m^3 \times 1565\ kg/m^3 = 40kg$).

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

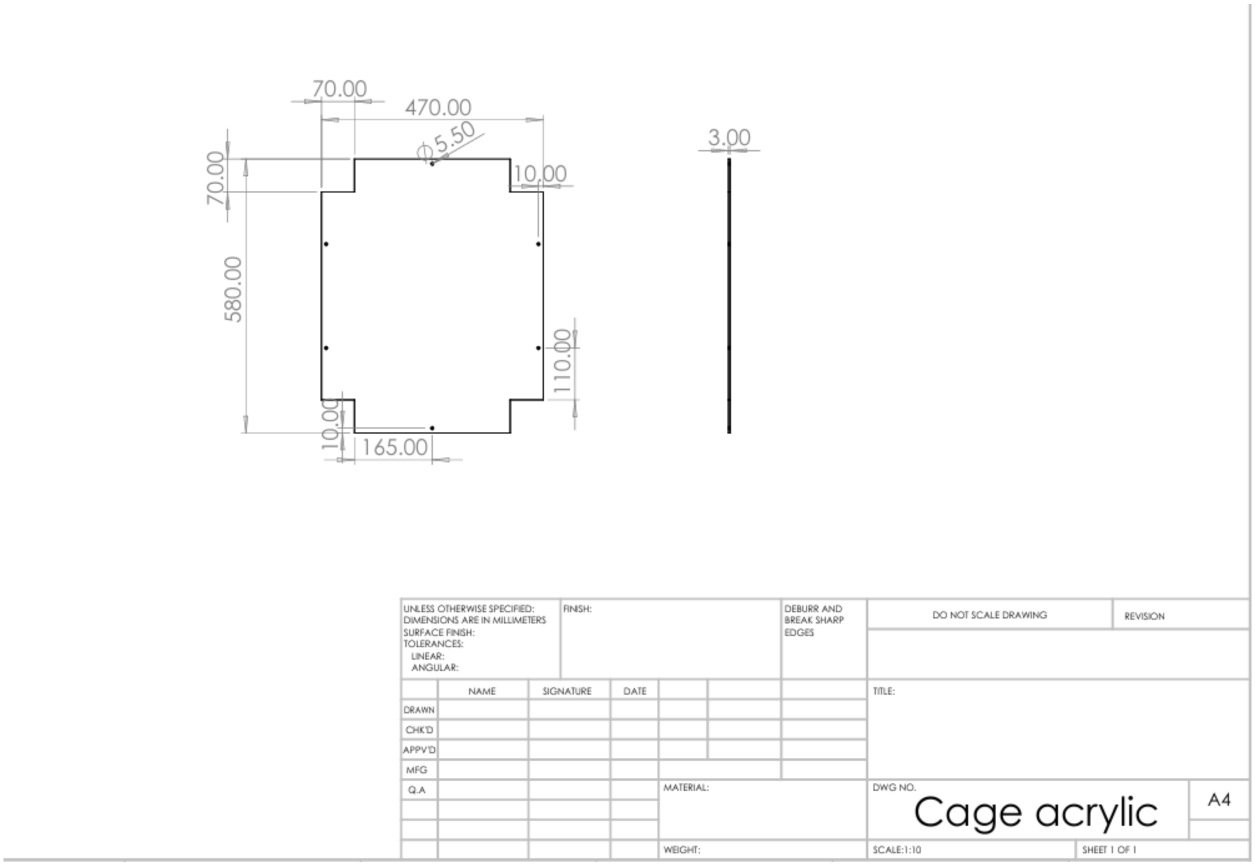


Figure 131: Dimensions of cage acrylic

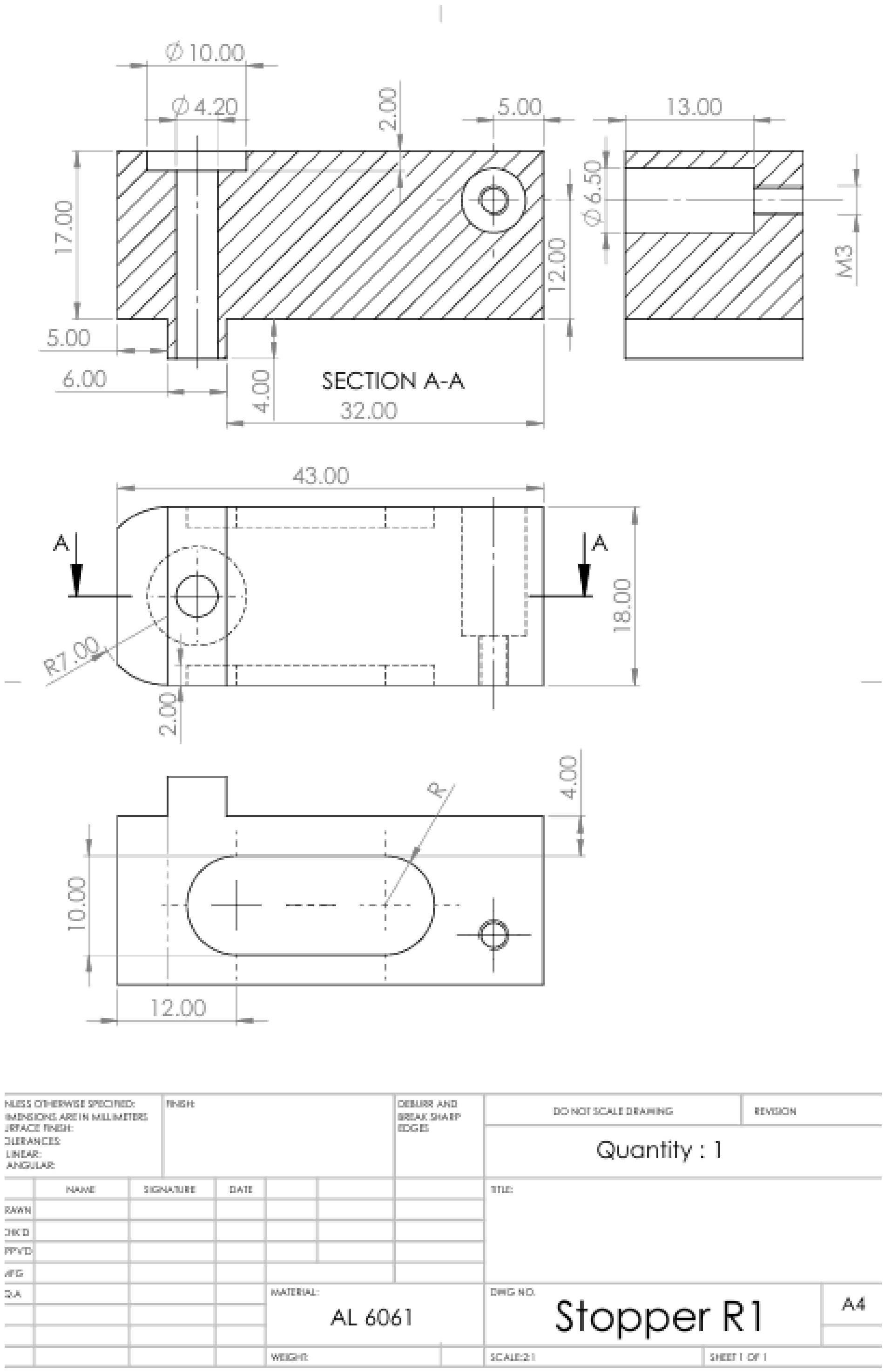
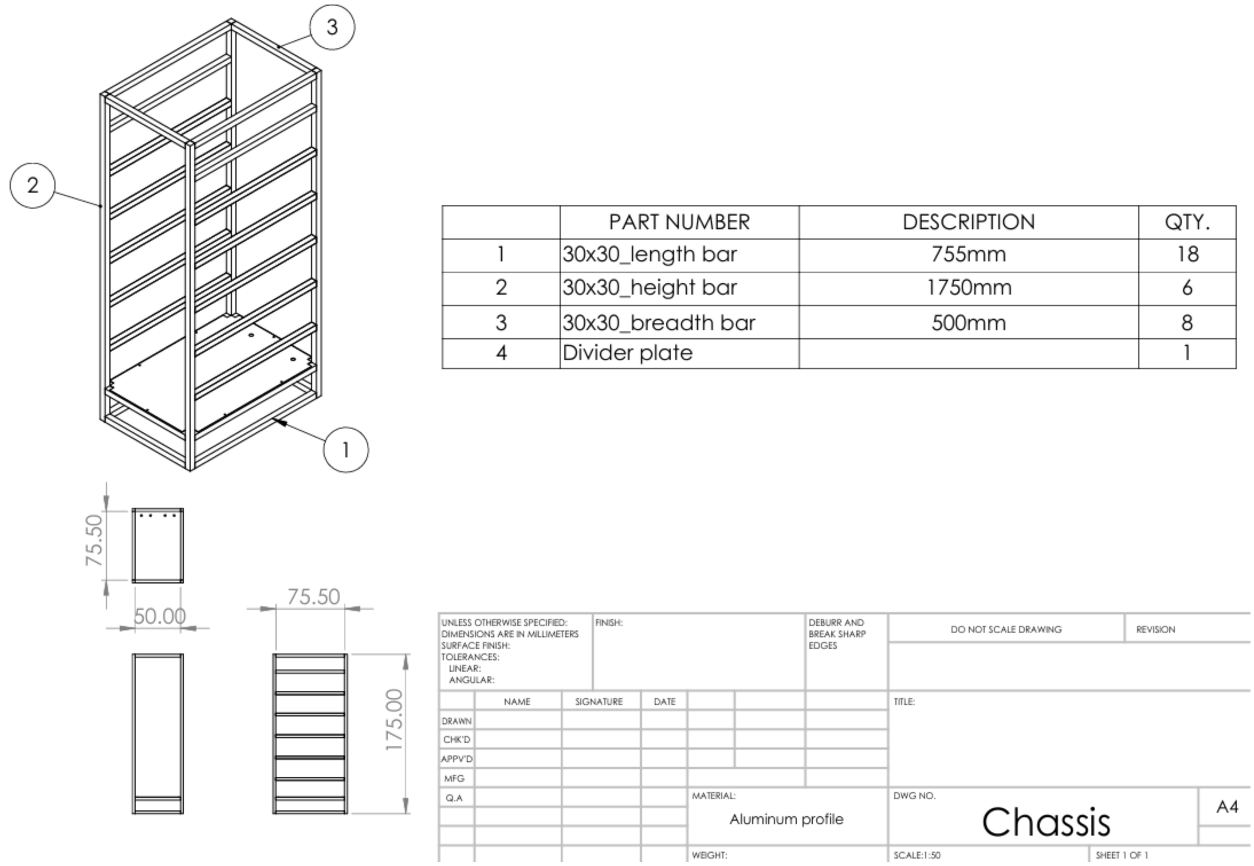


Figure 132: Dimensions of cage stopper



	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

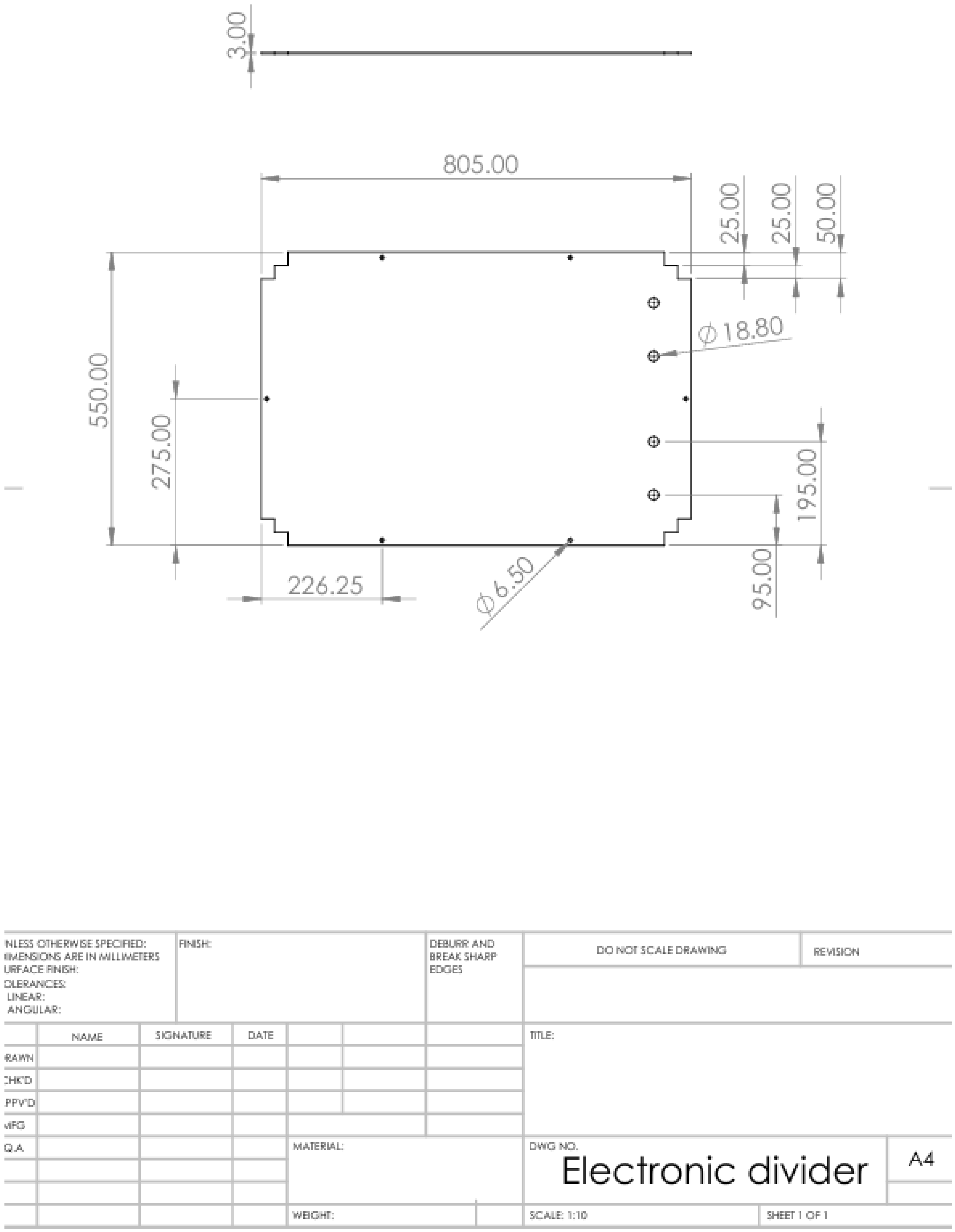


Figure 134: Dimensions of electronic divider acrylic

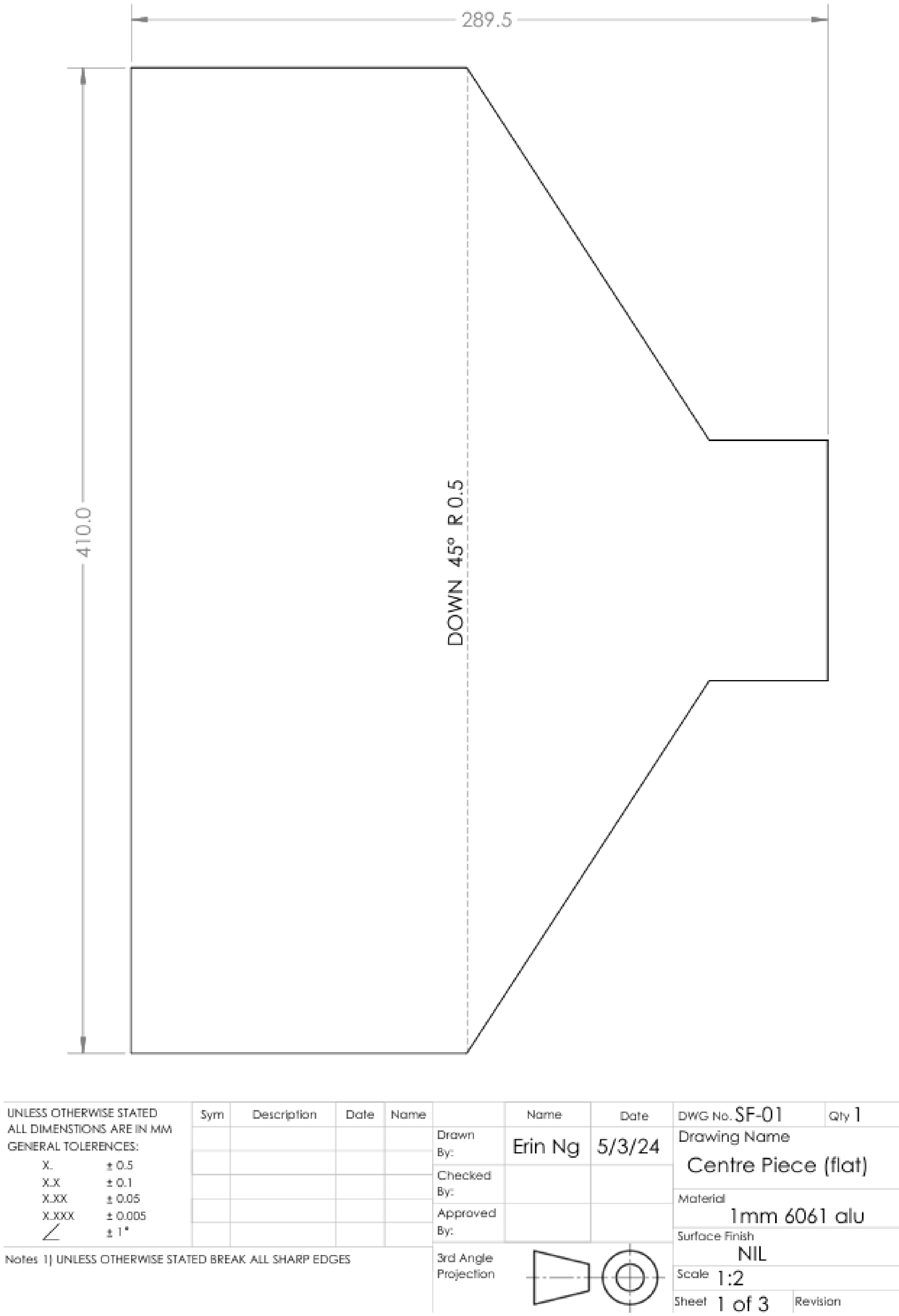


Figure 135: Centre piece of guider

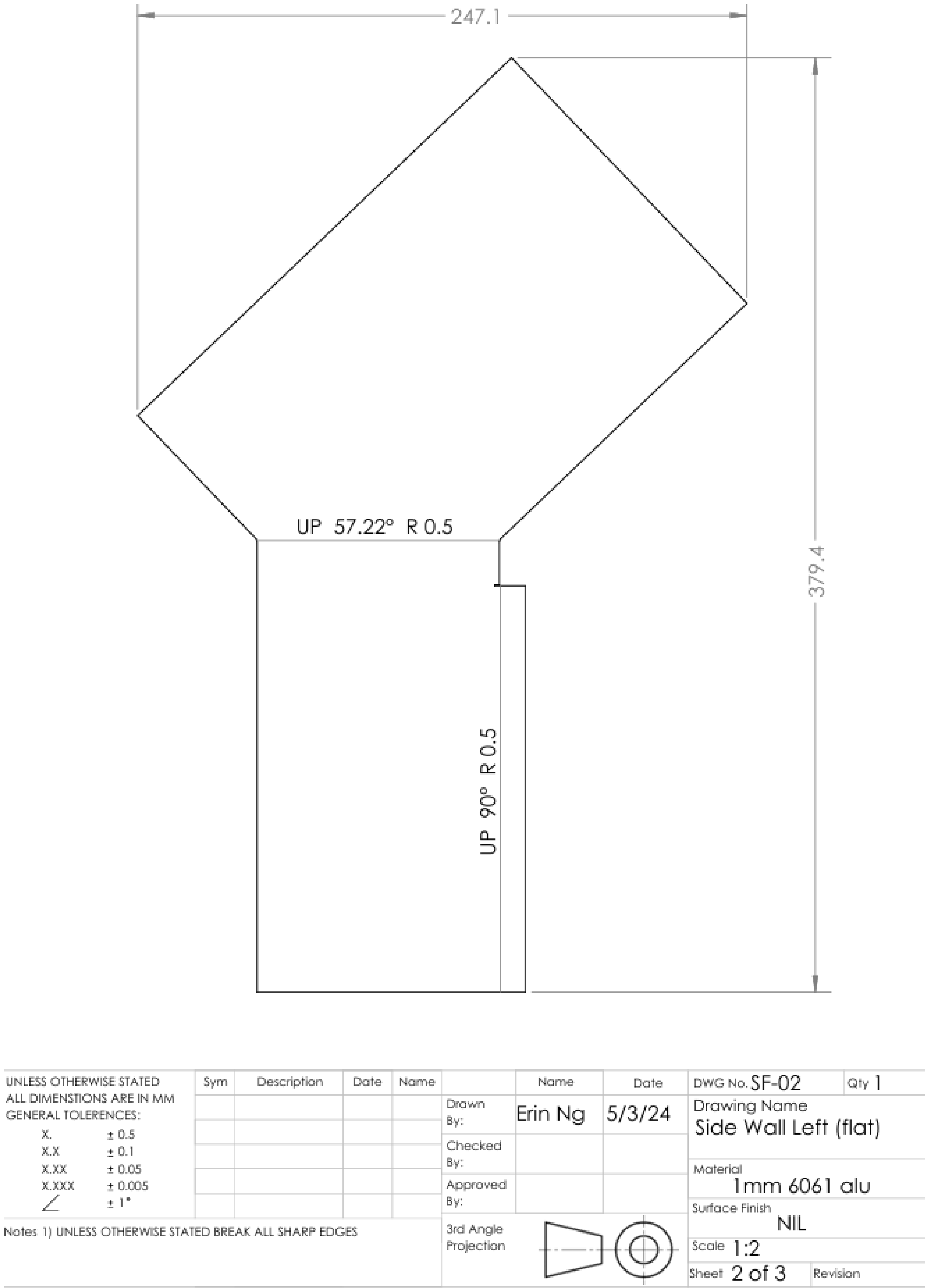


Figure 136: Side left wall of guider

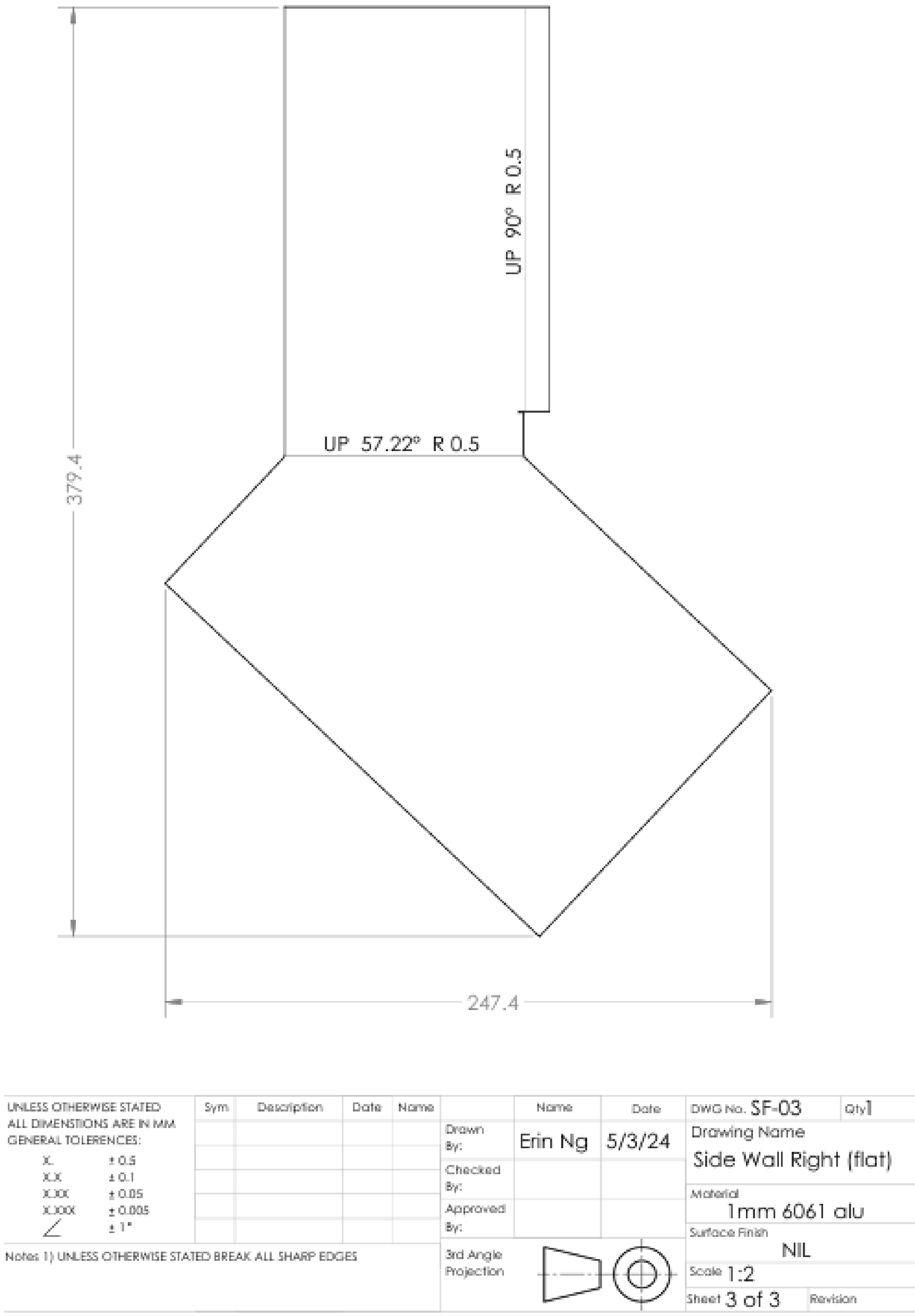


Figure 137: Side right wall of guider

The present thesis includes a comprehensive collection of dimensional blueprints, meticulously drafted using SolidWorks software by the author, and incorporates a revised design of the guider by Ms. Erin to accommodate necessary adjustments for the bending of sheet metal. These blueprints have been explicitly tailored to support the manufacturing processes undertaken in the central workshop. The tangible realization of these components was adeptly carried out by Mr. Hamilton and his dedicated team, exemplifying a high level of craftsmanship and commitment. The inclusion of these detailed blueprints is pivotal for achieving the precision and accuracy indispensable to the manufacturing process. This approach not only highlights the project's emphasis on detailed preparation but also showcases the importance of collaboration with skilled professionals to ensure the production of components of superior quality and functionality.

7.8 Calculation of pivot screw

Thread[1)] d	Nominal stress area $A_{s,nom}$ [mm²]	Minimum ultimate tensile load $F_{m\,min}$ ($A_{s,nom} \times R_{m,min}$) [N]								
		Property class								
		4.6	4.8	5.6	5.8	6.8	8.8	9.8	10.9	12.9/12.9
M3	5,03	2010	2110	2510	2620	3020	4020	4530	5230	6140
M3,5	6,78	2710	2850	3390	3530	4070	5420	6100	7050	8270
M4	8,78	3510	3690	4390	4570	5270	7020	7900	9130	10700
M5	14,2	5680	5960	7100	7380	8520	11350	12800	14800	17300
M6	20,1	8040	8440	10000	10400	12100	16100	18100	20900	24500
M7	28,9	11600	12100	14400	15000	17300	23100	26000	30100	35300
M8	36,6	14600[2)]	15400	18300[2)]	19000	22000	29200[2)]	32900	38100[2)]	44600
M10	58,0	23200[2)]	24400	29000[2)]	30200	34800	46400[2)]	52200	60300[2)]	70800
M12	84,3	33700	35400	42200	43800	50600	67400[3)]	75900	87700	103000
M14	115	46000	48300	57500	59800	69000	92000[3)]	104000	120000	140000
M16	157	62800	65900	78500	81600	94000	125000[3)]	141000	163000	192000
M18	192	76800	80600	96000	99800	115000	159000	–	200000	234000
M20	245	98000	103000	122000	127000	147000	203000	–	255000	299000
M22	303	121000	127000	152 000	158000	182000	252000	–	315000	370000
M24	353	141000	148000	176000	184000	212000	293000	–	367000	431000
M27	459	184000	193000	230000	239000	275000	381000	–	477000	560000
M30	561	224000	236000	280000	292000	337000	466000	–	583000	684000
M33	694	278000	292000	347000	361000	416000	576000	–	722000	847000
M36	817	327000	343000	408000	425000	490000	678000	–	850000	997000
M39	976	390000	410000	488000	508000	586000	810000	–	1020000	1200000

Figure 138: Bossard table for minimum ultimate tensile loads for the different thread size for the different type of property class

In the context of assessing the structural integrity of the pivot screw mechanism within our prototype, a detailed analysis was conducted to determine the maximum load capacity of an M4 screw, assuming the lowest property class (4.6) to prepare for the worst-case scenario. According to technical specifications provided by Bossard, an authoritative source in fastening technology, the ultimate tensile strength of an M4 screw classified as 4.6 is documented at 3510 Newtons (N).

To derive the ultimate shear strength, a factor of 60% (0.6) of the ultimate tensile strength is applied, a standard estimate for materials of this class. This calculation reveals that the shear strength of such a screw is 0.6 times 3510N, equating to 2106N. When converting this force into kilograms to provide a more intuitive measure of the load capacity relevant to practical applications, the conversion factor of 9.81 m/s^2 (acceleration due to gravity) is utilized, resulting in a calculated load capacity of approximately 214.7 kg.

7.9 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 139: Different light duty caster wheels from prestech

The illustration above displays an array of light-duty caster wheels provided by Prestech, complete with detailed specifications including wheel diameter, mounting hole dimensions, and total wheel height. Notably, the figure also encompasses data regarding the load capacity of each wheel, an essential aspect for assessing the appropriateness of each caster for particular uses in our project. This comprehensive examination facilitates a meticulous selection process, guaranteeing that the casters selected align with the exact needs for mobility and load support crucial for achieving peak efficiency and functionality in our design.