SMART (Sustainable, Modular, Additively-manufactured, Robust, Tower-style) Urban Farming

Winner of Singapore Agency for Science, Technology and Research (A*STAR) National Additive Manufacturing Innovation Cluster (NAMIC)'s *1kg Challenge (2023)* – sponsored by ExtraBold, Stratasys, Carbon, Altech, Yinson Greentech.

Singapore Science and Engineering Fair (SSEF) 2024:

- Gold Award
- Special awards:
  - L'Oréal Special Award for Innovation in Sustainability,
  - The Institution of Engineers, Singapore (IES) Special Award
  - Singapore Association for the Advancement of Science (SAAS) Special Award for Science Communication
- 1 of 6 Singapore projects to be presented at Regeneron International Science and Engineering Fair (ISEF) 2024

Singapore National STEM Talent Search (NSTS) – Shortlisted for final judging (Top 8). Finals pending.
To be submitted for technology disclosure, and conference or journal publication.

Contents

i. Executive summary

Global food security and sustainability issues, and rapid urbanization call for high-tech, space-efficient, sustainable urban farming technologies. These urban farming technologies not only aid in food security and sustainability of cities, they also double as green spaces (which are highly important for livability and happiness in urban areas), reduces environmental impact and food waste (30-40% of farmed produce is never consumed [7]) from transport, and aids in shrinking manpower in agriculture (from 44% in 1991 to 26% in 2020 [4]). In Singapore, only 3.9% of vegetables consumed are produced locally, and only 1% of land is allocated for agriculture [3].

Indoor (home and office) farming is effective and recommended as it does not require additional space from the city. Space in urban areas are already premium and limited – and this makes space efficiency especially important. For example, to strengthen Singapore's food security, one of the main strategies that the Singapore Food Agency (SFA) is pursuing is to grow locally [1]. SFA [8] and NParks [9] also encourages Singapore residents to grow their own edibles, to bring Singapore closer to her 30 by 30 plan – to sustainably produce 30% of our nutritional needs by 2030 [2]. The extremely low local production (3.9%) [3] of leafy vegetables also calls for major improvements in local urban farming of vegetables.

Nutrient film technique (NFT) hydroponics is practical, as it has several advantages, such as saving water (up to 90%), is resilient/sustainable, enables for higher yields, and higher space efficiency. These are all desirable traits especially for urban environments and the future. However, current approaches are inadequate due to space and maintenance constraints. They require "dedicated" space and maintenance, and are still too large for tight indoor spaces like homes and offices.

This project outlines the development of a novel design of tower-style NFT hydroponics that focuses on space efficiency, increased plant options, intelligence, energy efficiency, and material efficiency. Complex internal and exterior geometry inspired by aircraft semi-monocoque fuselage, all with optimized dimensions are used. Optimization and analysis by finite element analysis (FEA) ensures the design is space efficient, material saving, and strong (safety factor>6 in all 3 loading conditions). To fabricate such a complex structure that aids in space efficiency and other design criteria, selective laser sintering (SLS), a laser powder bed fusion (LPBF) additive manufacturing (AM) process is chosen to be used. Not only can it fabricate these complex geometries without support structures, and with high material isotropy it is also low in cost for small batch production. Glass-bead filled polypropylene (PPGB), for its good mechanical properties, waterproofness, and high chemical resistance.

This NFT hydroponics system is 3.3-9.8x more space efficient; and 3.4-4.7x more material efficient than existing ones. A more energy-efficient full-spectrum LED lighting solution is developed. A low-cost system monitors and maintains critical variables for the system's operation and alerts the user if manual intervention is needed. Modularity allows different plants to be grown together.

It is highly practical as it only takes up under 0.3m^2 of space in a home, which is very little even considering small public flat such as Hong Kong's and Singapore's, at around 80m^2. Such a system also requires low maintenance, gives users fresh produce and acts as a functional decoration; hence home users will likely be receptive to having this in their homes.

Hence, using the key advantages of additive manufacturing, this system can be practically installed into space-limited urban areas (e.g. homes, offices), and effectively aid in tackling global food security and sustainability challenges.

ii. Industry overview

Rajaseger et al. [12] found that the combination of hydroponics with technological devices shows promise as a method for environmentally friendly and effective crop production. They, amongst others [13-15], also found that hydroponics systems have many benefits; the most important and applicable are:

1. Water saving: Plants grown in hydroponics systems use up to 90% less water than traditional farming methods. Agricultural farms around the world account for 70% of all water consumed annually; out of this 70%, 40% is lost due to poor water management [5].
2. Not affected by climate change issues (sustainable): Hydroponics is a soil-free system, instead using growth mediums. This means soil erosion, land degradation and other climate change affected issues will not be present.
3. Higher yields: Hydroponics allows for growth throughout the year without being affected by seasonal or climate constraints. It also enables precise control of variables (pH, nutrient concentration, nutrient composition, etc.) of plants, which largely increases yields by as much as 50%, especially for leafy vegetables.
4. Smaller land area needed: As stated, space-efficiency is the key factor for urban cities and space-scarce nations. For example, only 1% of Singapore's land is set aside for farming/agricultural purposes [2, 3]. Hydroponics can use vertical space and be arranged compactly, saving much more space than traditional agriculture, where all plants grow in a large plot of soil.

Outdoor and indoor hydroponics systems already exist in the market. Most of these systems that are targeted at edible greens [e.g. 16-18] use a subset of hydroponics, the Nutrient Film Technique (NFT). NFT hydroponics is used as it takes less space, saves water, has high efficiency, and is suitable for smaller plants with smaller root systems, typical of edibles [19, 20]. As the vast majority of these NFT systems are highly similar (arranged in "racks"), a good benchmark for a conventional NFT system, Modern Farmer's [17] array of outdoor and indoor hydroponics systems will be later put in comparison to the prototype in this project. Though these setups can provide modern agricultural farming methods and are able to provide good amounts of yield, they are still typically large, which make it basically impossible to integrate into a small public flat or office, and don't have intelligent systems for maintenance. An explanation of why this is so, and how my design improves it will be under "Design, functionality and durability".

The solution offered in this project offers an innovative design to NFT hydroponics, and fabrication using SLS 3D printing, which allows the main innovations to effectively come to life. Apart from other benefits, it largely increases the space-efficiency (ratio of no. of plants to land area needed), and makes it possible for a high yield NFT hydroponics setup to be incorporated into homes and offices. It is also more material-saving as complex geometries for strength can be manufactured, which reduces environmental impact and costs.

iii. Design, functionality and durability

The design criteria is shown in Table 1.

Table 1. Criteria for prototype design

Design criteria (in order of importance)	Reasons, description, details
Space-efficiency	It is imperative that this improved hydroponics setup is extremely space-efficient, even more so than any existing hydroponics setups, especially if it needs to be incorporated indoors, especially in homes and offices.
Increased plant options	Different plants grow in different sizes. For a household setting, a variety of plants must be able to be grown in the same system.
Maintenance, intelligence and cost	Maintenance must be low for a system designed for consumers. Intelligence, such as self-monitoring, is very important to an average user without knowledge or time to manage a hydroponics system manually. However, the more "intelligent" an urban farming system is, the more expensive. Hence, there is a balance of intelligence and cost to be made.
Energy consumption	Production of edibles should also be energy efficient, for sustainability (to align with energy conservation plans).
Amount of material used	Reducing material used reduces the need to produce new raw materials, which aids in environmental impact [6]. In an Additive Manufacturing (AM) context, reducing material used also directly and most effectively reduces cost [10, 11]. This is especially true in laser powder bed fusion (LPBF) technologies, as more material used equates to longer machine time, and material and machine time are main cost drivers [11].

Conventional NFT hydroponics – How it works

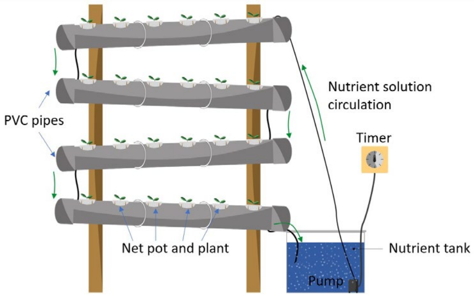


Fig. 1: Diagram of Conventional NFT

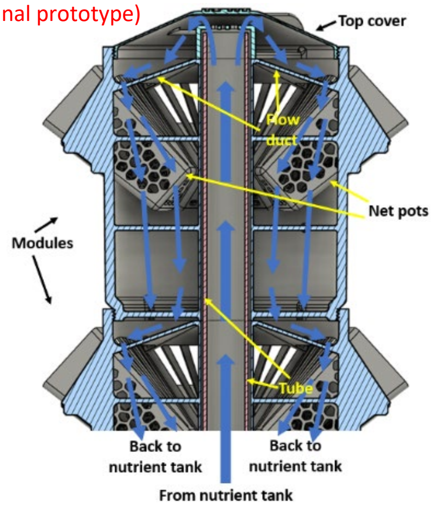
Fig. 2: One of Modern Farmer's conventional NFT systems

Typically made using Polyvinyl Chloride (PVC) pipes and drilled holes, conventional NFT systems (Fig. 1, 2) work by using a pump to deliver nutrient solution to the top pipe. The nutrient solution then flows through all the PVC pipes by gravity. Plants are grown in "net pots", which are placed in the drilled holes, and the nutrient solution reaches the plants' roots and growth mediums.

Innovative tower-style NFT hydroponics

The SMART Urban Farming system uses an innovative design of "tower-style" NFT system. As its name suggests, the NFT system is in the shape of a tall tower, and it is mounted to a nutrient tank (pail) below. A submersible water pump pumps nutrient solution from the nutrient tank to the top of the tower through a tube. Directed by flow ducts, nutrient solution then flows downwards through each "module" and hence every net pot (where it reaches the plant's roots and growth medium) and back to the nutrient tank, where the cycle repeats. This can be seen in Fig. 5, where the blue arrows represent the path of nutrient flow.

Fig. 5: Diagram of SMART Urban Farming system (final prototype)



Space efficiency

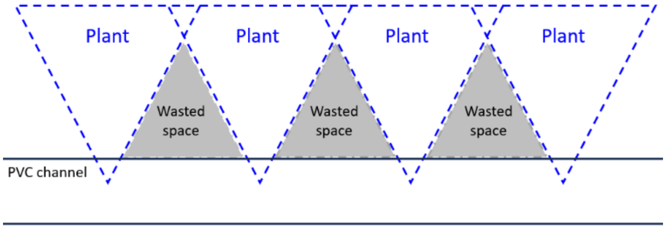


Fig. 6: Plant arrangement in conventional NFT (2D view)

Fig. 3: Lettuce in net pot. Notice the triangular shape of plant growth.

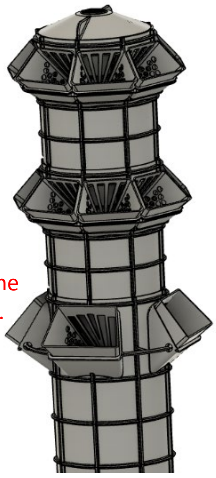


Fig. 4: Section of SMART system NFT tower

The conventional NFT system is already quite space-efficient, by using vertical space in "tiers". However, the tower-style design further increases space efficiency. Vegetables typically grow in a (in 2D) triangular shape, or (in 3D) cone shape (Fig. 3), but plants in conventional NFT setups are grown in a straight line. Hence, to give plants space to grow, the holes must be spaced some distance apart, and this wastes space (shaded grey), as shown in Fig. 6. Instead, the SMART Urban Farming system grows plants in a circular and outward manner (Fig. 7) This allows the plants to "interlock" with each another, hence wasting no space. A new and innovative net pot design is also such that many plants (8) can be put into one "layer"/"module". Instead of flowing horizontally in a conventional NFT system, nutrient solution instead flows vertically. This system also allows the "modules" to continuously stack atop one another with good stability, hence using a lot of vertical space and very high space-efficiency.

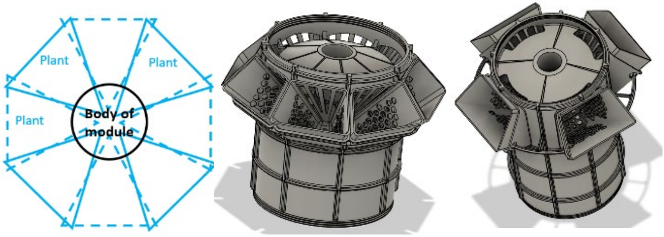


Fig. 7: Plant arrangement in SMART system (2D and 3D views)

Lighting efficiency (final prototype)

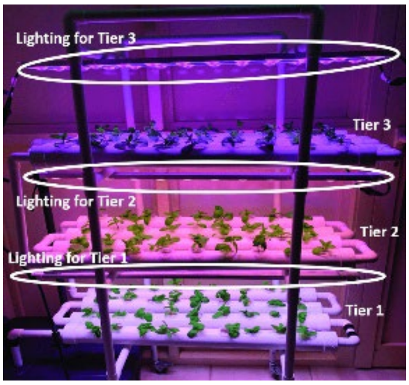


Fig. 8: Lighting in conventional NFT [22]

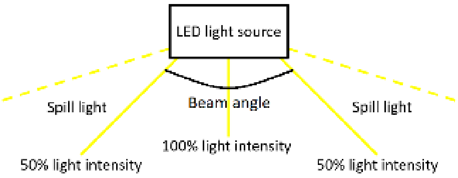


Fig. 9: Diagram of LED light spread

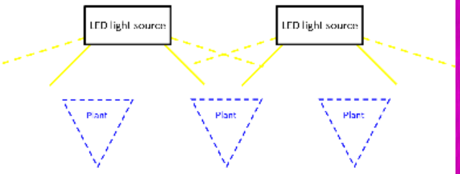


Fig. 10: Lighting of conventional NFT

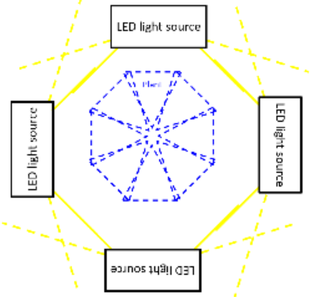


Fig. 11: Lighting in SMART system

Fig. 12: New full spectrum lighting on SMART system

For indoor farming systems, artificial lighting is the main driver of energy consumption (excluding optional air conditioning). A disadvantage of a conventional NFT system is that it is inefficient to install artificial lights for an indoor system. This is due to the "tier" style arrangement of the setup, and lights must be installed on every single tier of the system (Fig. 8). LEDs have a beam angle and spill light areas (Fig. 9), and here some of the beam angle and spill light is not directed at any plants (Fig. 10).

The tower style design allows the plants to grow outwards and upwards from one central tower. Only 4-6 LED tubes need to be installed for the tower to receive sufficient light as the entire beam angle (and spill light) is directed at the plants (Fig. 11). This ensures that little to no light is "wasted", increasing lighting efficiency. As lighting is the main driver of energy consumption in indoor setups, this drastically decreases energy consumption. (Fig. 12)

Modular design

To accept plants of different sizes, different sizes of net pots must be used. The SMART Urban Farming system is highly modular, as it is constructed using "modules". The "small" module is designed for smaller plants that are typically grown in 2" net pots – these include herbs and most leafy vegetables such as lettuce and spinach. The "small" module can fit eight 2" net pots (eight small plants). The "medium" module is designed for medium sized plants that are typically grown in 2.5" net pots – these include fruiting plants such as strawberries and cherry tomatoes. The "medium" module can fit four 2.5" net pots (four medium plants).

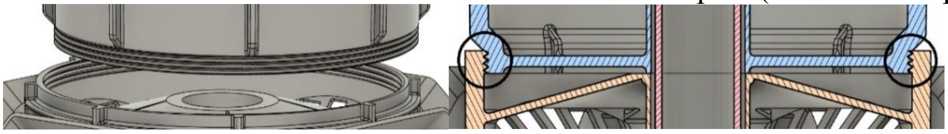


Fig. 13: M95x1.5 screw threads at both ends of every module

Every module has M95x1.5 threads at both ends (Fig. 13), and the tower is constructed by screwing every module together. Different-sized modules can be swapped by simply unscrewing the old module and screwing on a new one. Compared to existing systems, which only offer 1 type of plant size (usually small/2" size), or large modifications are required to accommodate more than 1 type of plant, the SMART Urban Farming system's high modularity enables users to easily, cheaply, and quickly modify the system to suit their growth needs.

Strength optimization features

In a tower-style design, strength optimization is especially important due to the tower's tall height and the heavy weight of plants. The structure is subject to three main loads:

(A) **Bending moment on tower:** The tower is securely mounted to the bottom, where it can be seen as a fixed point. As bending moment = Fd, where F = force applied and d = distance from point, the tall height of the tower now acts as a long lever arm (high d), causing a high bending moment.

(B) **Compression forces (and buckling) on tower:** Critical Buckling Load = $\frac{\pi^2 EI}{L^2}$, where E = Young's modulus, I = area moment of inertia and L = column length. A single module has a small L compared to its I, hence buckling is very unlikely and not a concern for structural strength. However, when looking at the fully assembled tower, this becomes significant, as the tower is very tall (high L), with the same I. Critical buckling load becomes smaller, and the combined weight of all the plants in the entire tower makes for higher compression force, making buckling a possibility.

(C) **Tension and compression forces on module:** This is a less significant issue as weight of plants in a single module is small, and most weight is acting only downwards. It is still important, so that the user does not damage the setup during handling.

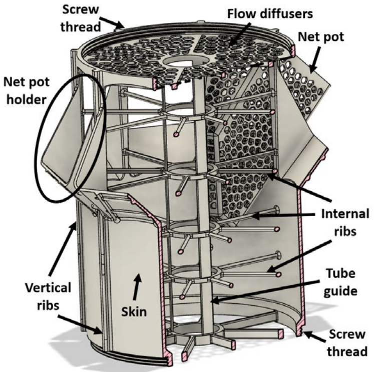


Fig. 14: Strength features of 1st prototype

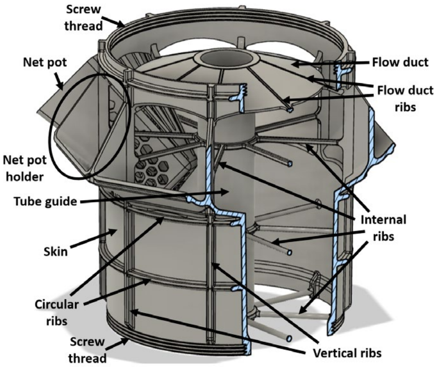


Fig. 15: Strength features of final working prototype

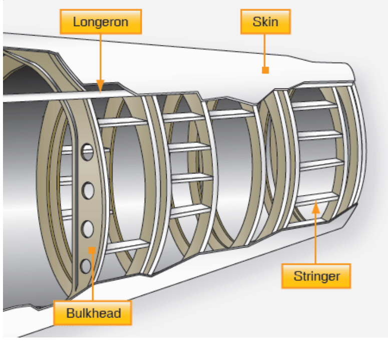


Fig. 16: Diagram of semi-monocoque fuselage design

a) *First prototype (Fig. 14)*

In this design, vertical ribs are used with internal ribs. Internal ribs are used to aid with tension and compression forces on the module, and to reduce buckling. Vertical ribs are used to resist bending moments. These vertical ribs act like longerons used in aircraft fuselage design, which most effectively resist primary bending moments and axial loads, and reduces buckling of the skin [25, 26].

b) *Final working prototype (Fig. 15)*

In the final working prototype, the ribbing structure is enhanced to reduce the forces acting on the skin. 1. Circular ribs (like "bulkheads" and "formers" in semi-monocoque fuselage, below) are added to maintain the circular shape of the tower and reduce buckling tendances, and puts less stress on the skin. Hence, skin thickness can be reduced from 1.4 mm to 1.1 mm, reducing mass significantly.

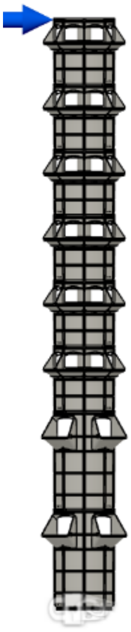
2. The length of the screw threads is also increased from 4.5 mm to 5 mm for better thread engagement. Though modules are shorter in the final working prototype (ratio of thread length to module length is significantly higher), the final working prototype is taller and hence requires better thread engagement.

3. "Net pot holders" are also thicker, longer and joined together in the final working prototype. This is to reduce flexibility and provide better support for the net pots when plants grow larger and center of gravity is further away from the tower.

This structure also mimics the semi-monocoque fuselage design (Fig. 16) used in most aircraft today. It provides better structural strength in bending moments, axial forces and makes reduces buckling tendencies of the skin by providing additional supports and splitting the skin into smaller sections [24, 25], enabling a thinner skin; it more evenly spreads load amongst all structural components and enables for a lighter weight while fulfilling structural requirements [23-26]. The final working prototype is designed to bear much greater structural load (the final working prototype is taller and accommodates more plants, hence more structural strength is required).

Strength simulations (FEA) – Refer to "Strength optimization features" for load cases

The SMART Urban Farming system was designed with regard to, and analyzed with finite element analysis (FEA) using Fusion 360 to validate the strength structures and integrity of the design. FEA was performed using polypropylene as the material. As the real prototype is made with PPGB, that has significantly better mechanical properties (stiffness and toughness), the safety factors are even more, and deflection are even less than simulated.



(A) In the bending moment simulation, the bottom thread of the last module was constrained and a 10 N force was applied perpendicular to the top module. The minimum safety factor is 6.7 and maximum deflection is 1.2 mm (Fig. 24).

(B) In the buckling simulation, the bottom thread was constrained and a 150 N force was applied to the top of the module (to simulate the module that is most likely to buckle). The worst buckling result on the small module has a safety factor of 6, and the worst buckling result on the medium module has a safety factor of 17 (Fig. 25).

(C) In the tension and compression force simulation, a 10 N force was applied to the side of each module. The minimum safety factor is 8.3 and maximum deflection is 0.1 mm (Fig. 26).

Fig. 24: Load case (A)

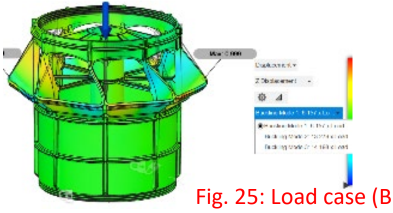


Fig. 25: Load case (B)

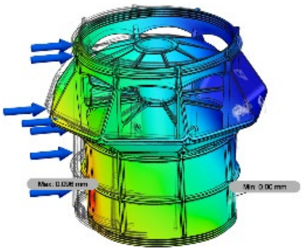
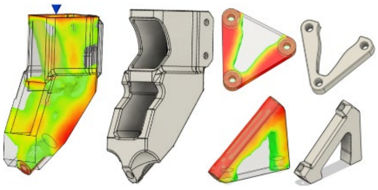


Fig. 26: Load case (C)



Some parts were also shape optimized, to only retain parts of the model that is critical for strength. This includes the LED rod mounts, LED mounts and pail mounts. The results were then modified to facilitate FDM printing (using ABS) (Fig. 27).

Fig. 27: Shape optimized parts (Left: FEA results. Right: Modified for FDM printing)

Intelligent monitoring, alert and maintenance system (supplemental, not related to AM)

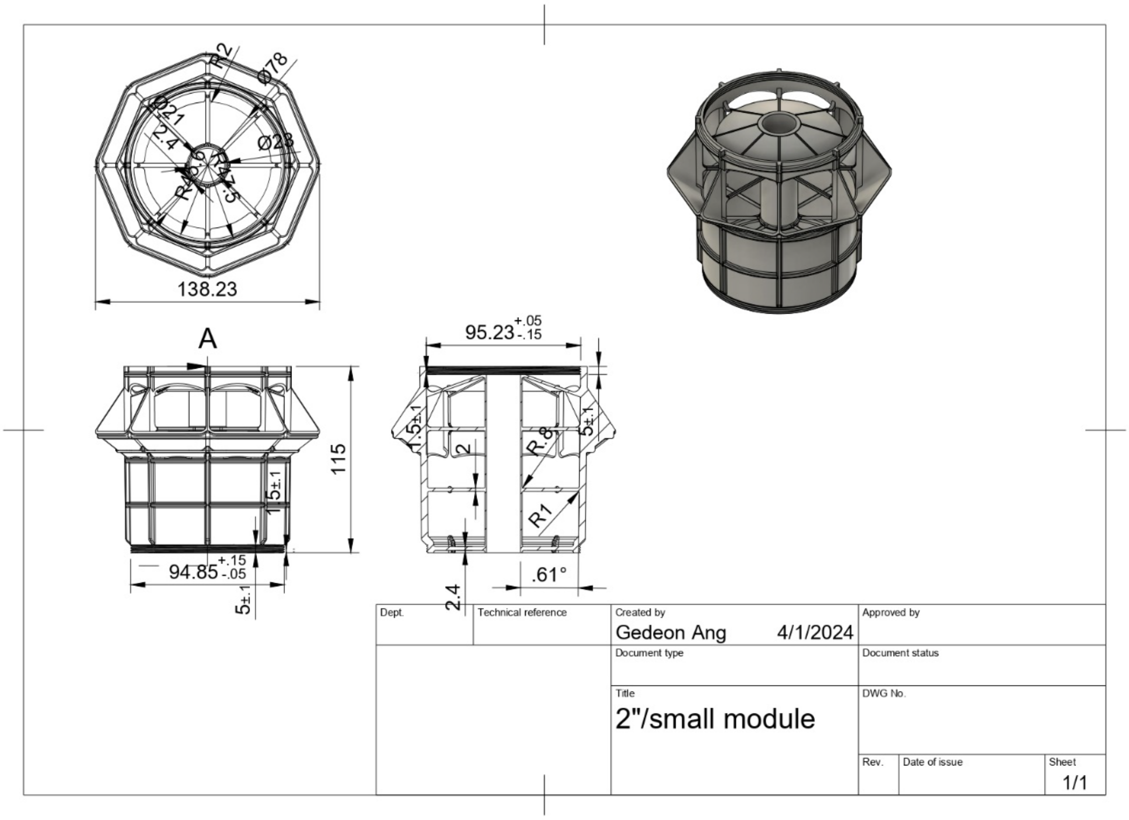
As NFT hydroponics depends on constant nutrient solution flow to deliver water and nutrients to the plant (unlike soil, water retention in growth mediums are typically insufficient), one of the drawbacks of NFT is that it is very sensitive to pump failure [19, 21]. A few days without nutrient solution flow can lead to the loss of an entire harvest. Hence, it is very important to monitor the pump in case of pump failure, so that the user can quickly replace it with a new pump.

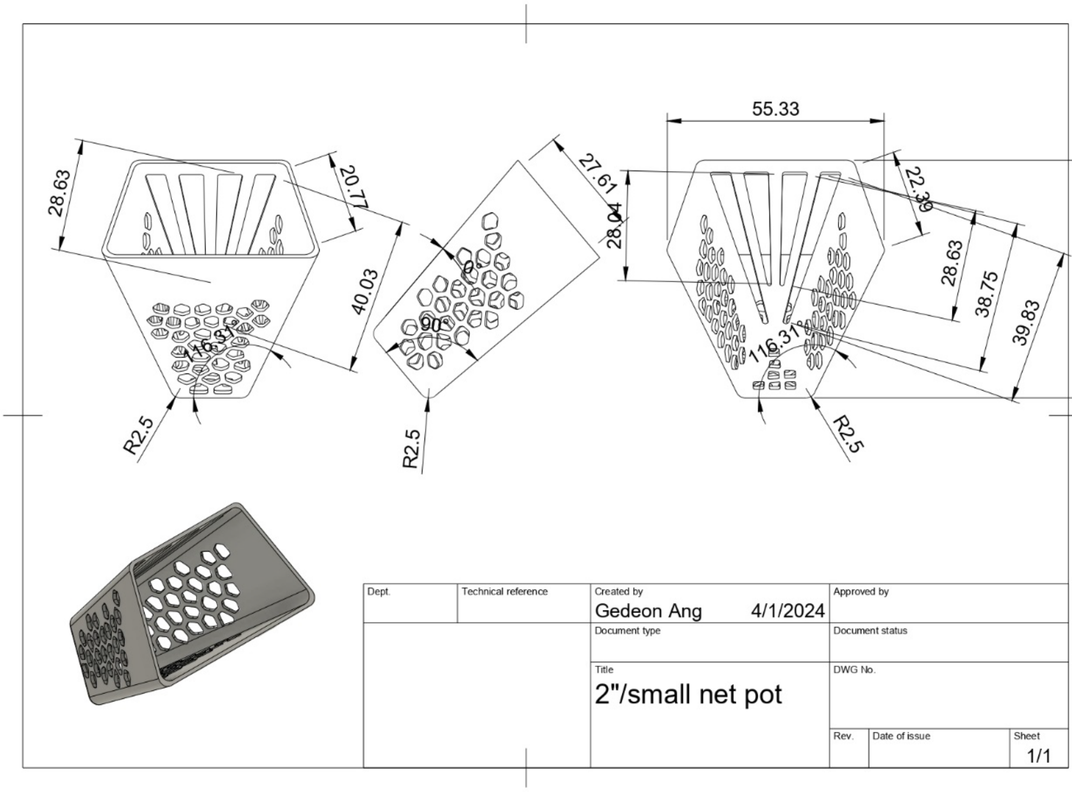
This system is developed to be low-cost parts (<$10).

Using 2 water sensors (1 to monitor pump operation and 1 to monitor tank nutrient level), a Total Dissolved Solids (TDS) sensor, 2 mini water pumps (1 for water and 1 for nutrient), a buzzer, ESP32 microcontroller and custom PCB, the system can self maintain the most critical (water and TDS), and alert the user through wifi, Bluetooth or the buzzer should there be a need for manual intervention.

Differences between the first and final prototype can be found in Appendix B.

Technical drawings of main sections of tower (final prototype)

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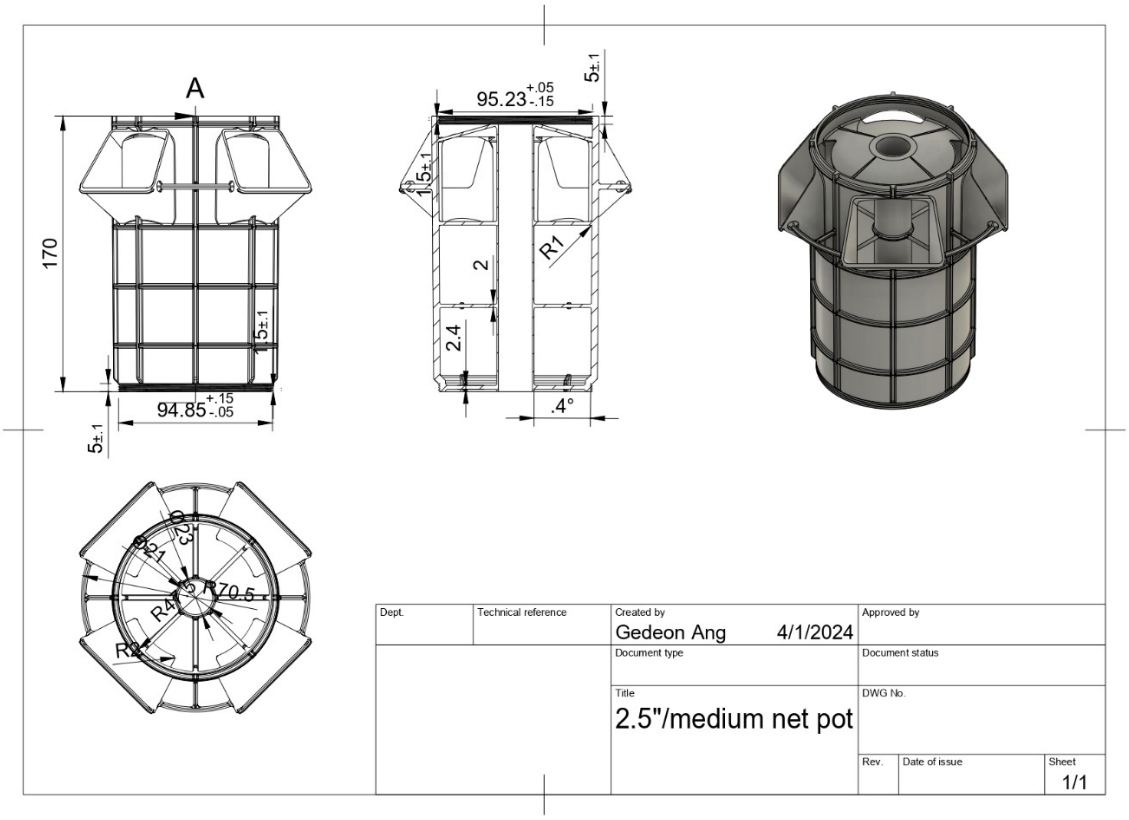
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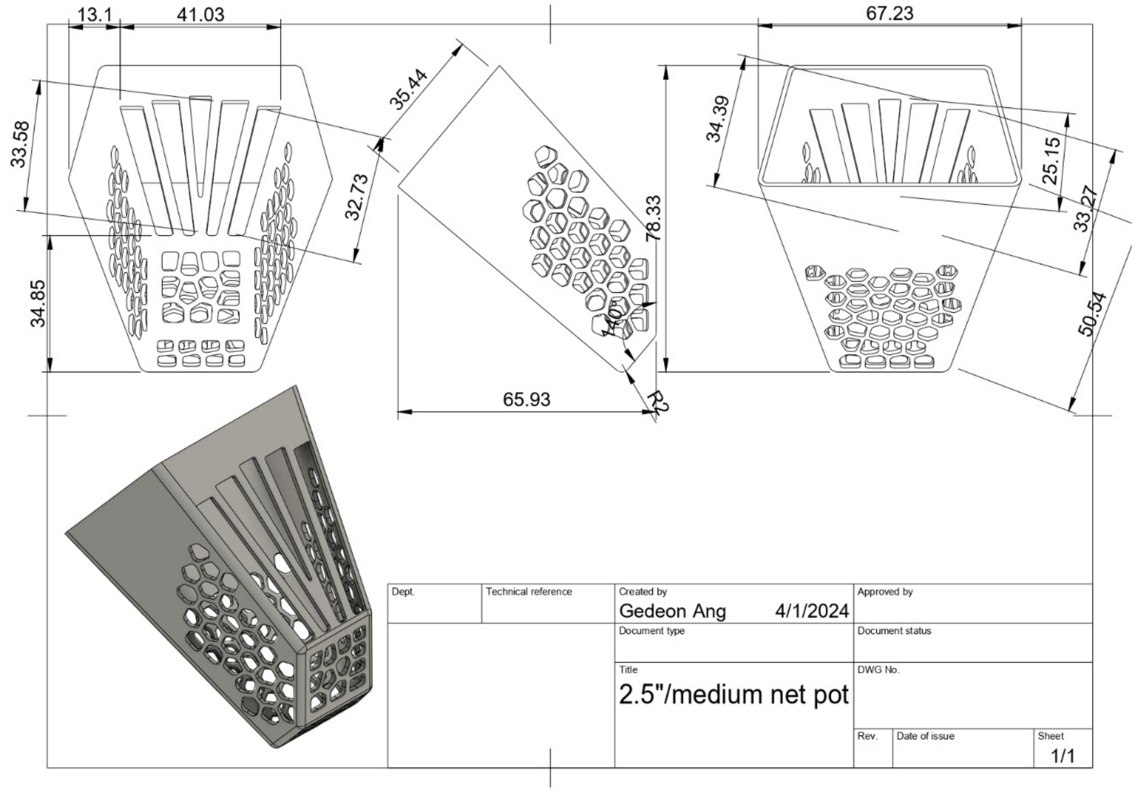


Tolerances are determined by the actual machine itself. However, models are designed such that a ±0.1mm tolerance across all values will enable the design to work as anticipated (modules will screw together, etc.). The most tolerance critical section is the screw threads; the other sections of the parts do not require specific tolerances and ±0.2mm would easily suffice.
Assembly is done by simply screwing all the modules to each other, and using M3 screws to attach the base mount to a laser cut aluminum plate, and to the pail.

Lifespan

Although specific physical tests should be done to even more accurately determine the lifetime of the parts produced, it is estimated to be at least a few years, to forever. The prototype has been in testing and use for a few months with no indication of any structural or physical degradation. The PPGB material used is waterproof (largely under 1% water absorption), highly chemical resistant to both acids and alkalis and very mechanically resilient, hence it is unlikely that constant nutrient solution will degrade the material in any way. FEA simulations also show overly high safety factors of >6, indicating that the setup is very strong, stable and reliable (the real prototype is even higher as it is made out of PPGB (which has higher stiffness and toughness), while FEA was performed using just PP). FEA was performed using polypropylene as the material.
SLS printed parts also have relatively high material density.

Health, safety and quality

PP/PPGB is a food safe material, hence the prototype will be safe for use in growing edible plants. Quality wise, assembly and use will be of no concern as long as required tolerances (as stated above) are hit. Plastic threads are not meant to be screwed and unscrewed often, and SLS may result in small amounts of powder to be released when the modules are screwed and unscrewed. However, the design is not meant to be screwed and unscrewed often, and it is only done so when the user wants to modify the setup. There will be no plants growing then, so this will not pose a risk.

iv. Design Integration and Utilization of DDM materials and process

SLS 3D printing

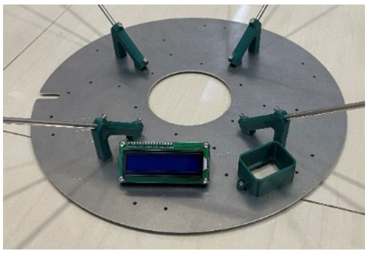
As can be seen in Fig. 4-8, the exterior and interior geometry is highly complex, and is basically impossible to manufacture using any other method other than 3D printing. 3D printing is also the most cost-effective method of production in low volumes and prototypes [30-32]. SLS (Appendix A1) is chosen for its ability to create (almost any) and highly complex geometries without support structures, as surrounding non-sintered powder acts as natural supports [27-28]. It also shows high isotropy (4-16% anisotropy with PA12 (Appendix D2)), lower when using high energy density during the process) compared to other forms of polymer AM such as Fused Deposition Modelling (FDM, Appendix A2); though resin printed parts are almost fully isotropic, they are not UV resistant and mechanical properties start to degrade significantly in just 2 weeks [29]. SLS's high isotropy and ease of printing complex geometries, at relatively low costs, makes it the most suitable method to produce parts for this design.

However, SLS results in notable surface roughness of the part. This could be significantly reduced by vapour smoothing, tumbling or other processes. However, this would add to production cost. The parts could also operate untreated (without any post processing).

PA12 material is used for the first prototype due to its lower cost of production, and PPGB is selected for the final prototype due to its high resistance to acids and alkalis, waterproofness (very high resistance to moisture absorption), and rigidity and toughness.

FDM 3D printing

FDM 3D printing is used for the supplemental/non-critical parts of the design, such as LED light mounts, sensor mounts and other parts. For these parts, mechanical properties, isotropy or complex geometries is not critical, hence FDM was used for its low cost and fast prototyping. ABS material was chosen as it is highly versatile. It is not only low cost, but exhibits good mechanical properties such as impact resistance and strength. All parts designed for FDM printing are designed for no need of support structures (except 1 part – which only needs a very small amount of supports. This reduces waste and increases production efficiency). Heat set inserts are added to some parts for fasteners post printing.



AM is not the only process used. The bottom 2mm aluminum base plate is laser cut as it is much more cost effective to produce it this way. It could also be waterjet cut or machined, as geometry is relatively simple (just 2D). Rods used to hold up LED lights are 5mm stainless steel rods, which are evidently not additively manufactured also.

AM is only used for the parts that require it (as explained above – due to highly complex geometries, fast prototyping and small batch production cost).

AM allows for much lower use of material as compared to conventional manufacturing. The strength optimization allows for the setup to be 3.4 - 4.7 x more material efficient (uses 3.4 - 4.7 x less material, per plant grown in the setup). This greatly reduces the environmental impact of production.

It also allows for much higher space efficiency of 3.3 – 9.8 x higher (this is measured by number of plants that can be grown per m^2 of land area).

These can be illustrated in Table 3 below.

Table 3. Space-efficiency and material efficiency comparison of different NFT hydroponics systems

System	Space required/m^2	Material used/kg	No. of plants	Space-efficiency/ plants per m^2	Material efficiency/ plants per kg
SMART system	0.12	3.2	88	733	27.5

MF design 4	0.48	13.5	108	225	8
MF design 6	0.58	9	72	124	8
MF vertical system	0.16	Unlisted	32	200	-
MF design 2	0.48	5.5	32	75	5.8

Recyclability, end of life

The materials used, PP and ABS, are both recyclable, and as estimated earlier, it would take minimally a few years for the parts to reach their end of life. This is good in terms of environmental impact as parts do not need to keep being re-produced, and could be recycled.

v. Digital and physical infrastructure: Systems integration, utilization, value chain leverage, agility, lean and continuous improvement

A key advantage of using additive manufacturing is that parts can be produced without the cost and time for tooling. This means that many different manufacturers can produce parts at the same time. Such decentralized manufacturing allows parts to be produced directly where it is needed, without costs, time, inconvenience, and environmental impacts from shipping parts across the globe. The larger number of manufacturers not only reduces price (to the consumer) due to competition in supply, but also allows for a more resilient supply chain, as other manufacturers can compensate for a lapse in production of another.

Production of these parts is only practical when parts are densely nested in SLS printing to largely reduce costs from the material (refresh rates), labor and machine costs (time of running the machine). As SLS printers are very expensive (to purchase and run), often requiring decent volumes of production to be economical, they are totally out of reach for hobbyists.
However, this system also requires FDM printed parts. The (hobbyist) 3D printing community is active and huge, and many hobbyists own a low-cost FDM printer (such as the ever-popular Ender 3 that costs under $200). Hobbyists could print the FDM printed parts for themselves or others at a low cost, and SLS parts would be supplied by larger manufacturers that have the capability to produce SLS parts at a more significant scale. This is already natural collaboration/synergy between hobbyist makers and large manufacturers.

Printing is also very fast (many setups can be printed in the same build, and one can be produced in under 24 hours), allowing very agile responses to market conditions (supply and demand).

This form of manufacturing also allows for design changes for little to no additional costs, as tooling costs and time are not required. As the system is highly modular, parts can be added or modified for specific requirements of different homes in countries/cities for no extra cost or time. This adds flexibility and further aids in the food security of targeted regions.

Sharing design files under open-source licenses such as Creative Commons licenses will even allow individuals to modify the design to their preferences and engage a service provider/bureau to fabricate the SLS parts that they are unable to do so on their own.

Once the design is highly established and finalized, and demand has reached a level that calls for true, large-scale mass production, injection molding could be used (with design changes) to reduce costs significantly at very large volumes of production.

vi. Cost Benefit/Value Analysis

The printing of the second prototype by an external vendor costed $390 (USD). Many costs are difficult to evaluate, so prices given are just estimations with overheads of 15%.

SLS printing

For small quantities, the average material cost for 1 kg of SLS printing powder (PA12, PP) is around $100. The mass of the second prototype is around 1.5 kg. Assuming a nesting/packing density of 20% and refresh rate of 30%, the material cost will be at $165. This will be significantly cheaper when purchasing at larger volumes

Hence, at a small batch production scale, and without an external vendor, cost of production is estimated at $250.

FDM printing

FDM parts were printed on my self-built high speed 3D printer. The price of ABS is $10/kg, and machine wear and electricity costs around $0.5 per hour. The printer (modified Voron Trident) and slicer (SuperSlicer) have been tuned well for high speed yet strong printing. It takes ~40h to print 1 kg of the material; and the mass of FDM parts are ~250g. Hence, the cost is $10 for the FDM parts.

In total, the prototype would cost around $350 in total assuming a small batch production run, including other parts of the setup. We notice that this price is higher than many conventional NFT hydroponics systems, which cost around $250 for a similar yield system. However, we must consider the space efficiency and other benefits of this system. The median listing home price per square foot was $718 in Los Angeles, so the space efficiency of this setup alone could largely already offset its higher cost. The SMART system also has many other benefits such as intelligent monitoring and maintenance, which would brings lots of convenience to a user. Hence, although this system is more expensive than other/conventional NFT systems, the higher cost is largely offset by the benefits it provides.

Injection molding is much more cost effective than Additive Manufacturing for medium to large scales [34]. However, the cost of injection molding is mainly dependent on the cost of mold production [34-35]. A complex geometry produced by injection molding will drastically be more expensive due to complex features in mold production such as sliders and overmolding. Some structures in this design cannot even be produced by injection molding. The design can be modified for injection molding, such as compensating some complex strength structures by using more material. Even if it is modified for molding, mold production will be expensive due to complex mold features, likely above $20000 for an aluminum mold (for the 2"/small module for example). For true mass production for adoption in thousands of homes and offices, injection molding is the more practical approach. However, additive manufacturing brings along many benefits, such as fast production, design iterations (if needed) and delivery times, and no need for high initial costs of tooling.

vii. Conclusions

The SMART Urban Farming system is designed, simulated and tested. Fabricated using SLS 3D printing, it meets all the design criteria. Space efficiency is 3.3 - 9.8x higher, material efficiency is 3.4 – 4.7x higher, it's high modularity enables increased plant options, it is energy efficient and has a low-cost intelligent monitoring, alert and maintenance system. This is achieved through the complex geometry that can be created using additive manufacturing, which enables an innovative design of tower-style NFT hydroponics and optimized strength structures. FEA and physical testing is used to validate the design. Hence, this design is highly practical for installation in small indoor spaces such as homes and offices, Can effectively aid in solving food security and sustainability issues of small, space-scarce cities/nations, and is a space-efficient, integrated solution for urban farming needs.

viii. References

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ix. Appendices

Appendix A1 – SLS

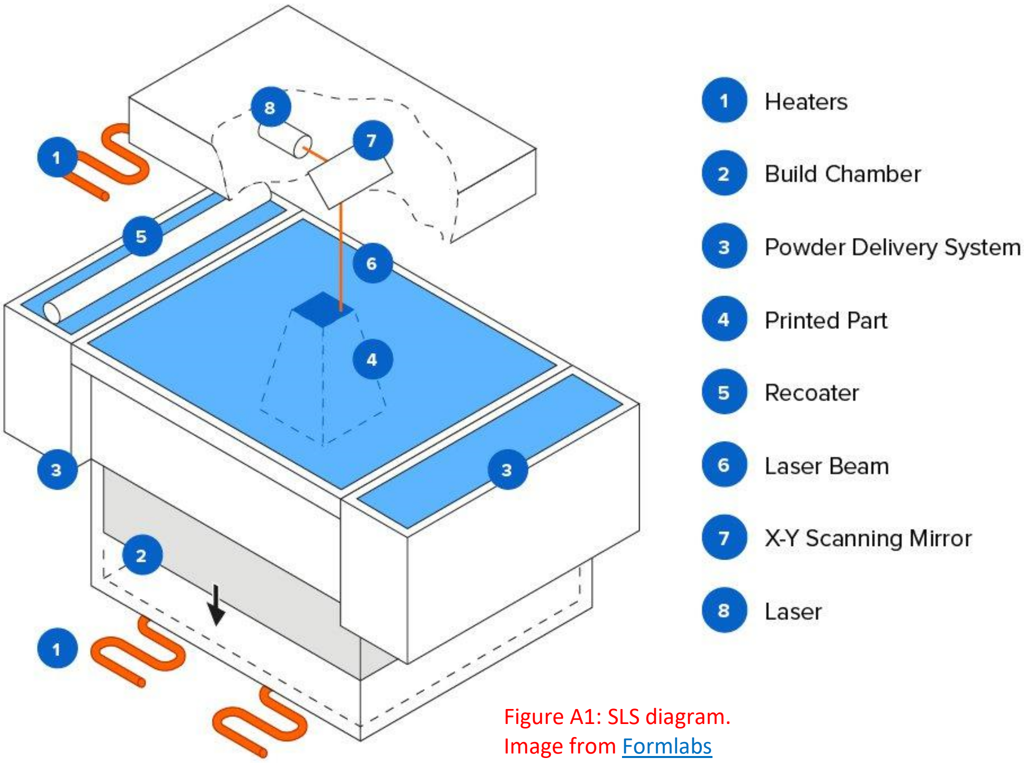


Figure A1: SLS diagram.
Image from Formlabs

Printing process

1. The recoater coats a thin layer of powder on top of the platform in the build chamber.
2. The heaters heat the powder to a temperature slightly below that of their melting point.
3. The laser scans a 2D cross section of the part, heating it at or just below its melting point, sintering powder together.
4. After one layer is complete, the platform lowers one layer into the build chamber.
5. The recoater coats another layer of powder.
6. The laser scans a 2D cross section of the part again, heating it at or just below its melting point, sintering powder and the previous layer together.
7. The process continues until the part is completed. No support structures are needed as surrounding non-sintered powder supports the part during printing.

Appendix A2 – FDM

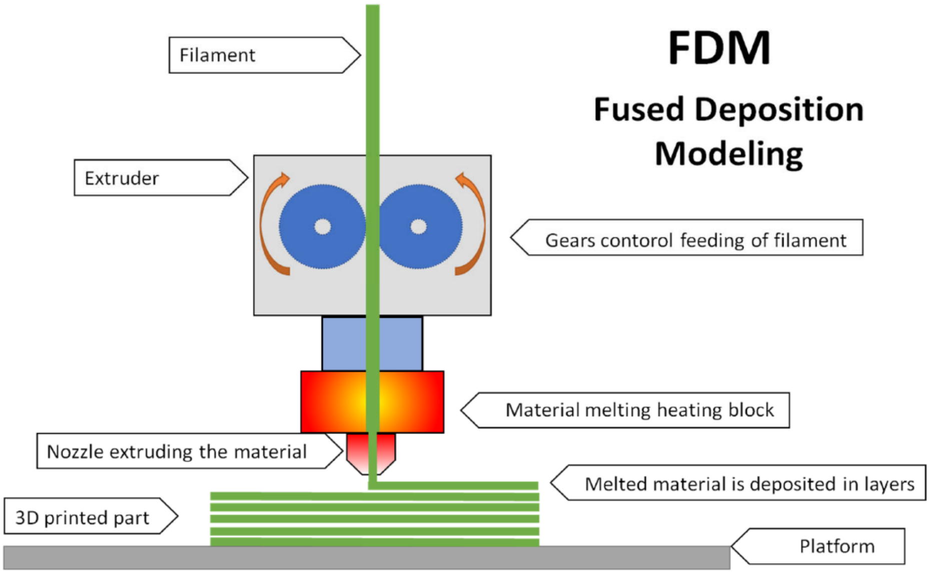
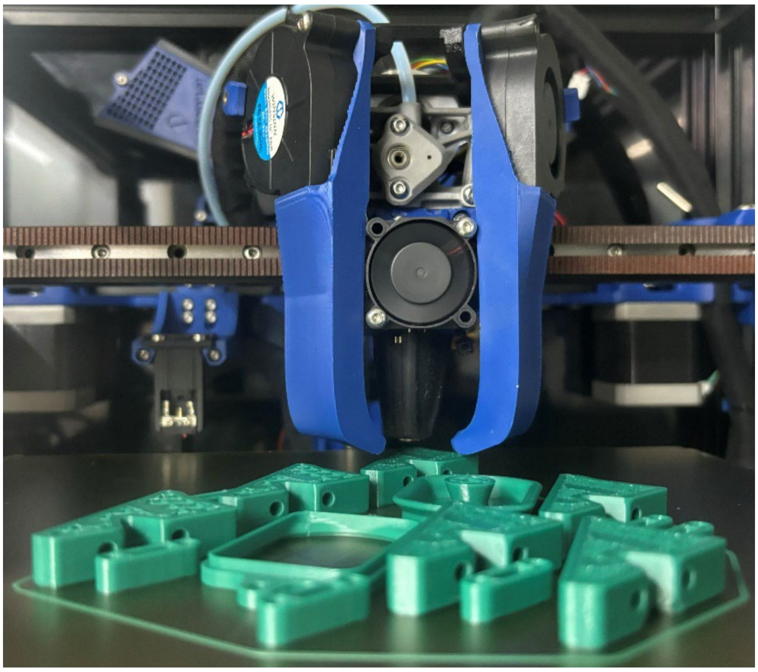


Figure A2: FDM diagram.
Image from MDPI

Printing process

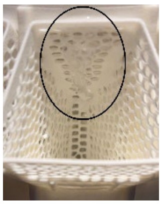
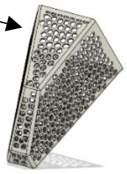
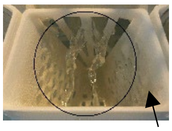
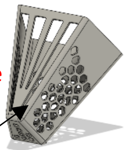
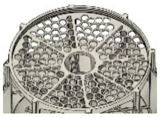
1. The extruder feeds thermoplastic filament into the hot end, where the filament melts.
2. The molten filament is pushed through the nozzle, and it is extruded on the build platform.
3. Thin strands of filament are extruded in the 2D cross section of the part.
4. The build platform descends, or the extrusion head moves up, by one layer.
5. The extruder extrudes molten filament on the previous layer.
6. The process repeats until the part is complete.

FDM parts were printed in Acrylonitrile Butadiene Styrene (ABS) with a self-built high-speed printer capable of printing engineering grade materials.



Appendix B – Intelligent monitoring and alert system

Table 2. Improvements (in no specific order) – testing of final prototype will be shown in later section.

Improvement	Reason for improvement	Details
Net pot shape  Fig. 18: Water slides off top of 2” net pot of 1st prototype	Enable meaningful flow of nutrients into net pot Fig. 19: 2” net pot, 1st prototype   Fig. 20: Water flows into 2” net pot, final prototype  Fig. 21: 2” net pot, final prototype	In the first prototype small holes (in a Voronoi pattern) were used on every side of the net pot (Fig. 19) to anchor roots effectively. However, surface tension unexpectedly became a severe issue. During testing, nutrient solution simply slid off the top surface of the net pot instead of flowing into the net pot and growth medium (Fig. 18). In the final prototype, slits were used on the top surface of the net pot to allow nutrient solution to directly flow into the net pot (Fig. 20), and larger holes were used on every other side of the net pot. The net pot dimensions were also adjusted for higher space-efficiency and to better accept growth mediums (Fig. 21).
SLS printing material	Excellent water, chemical resistance and mechanical properties	The final prototype is printed with glass-bead filled polypropylene (PPGB) (Appendix D). It exhibits high resistance to acids and alkalis, is waterproof and very resistant to moisture absorption. It is also rigid and tough.
Flow aid  Fig. 22: 1st prototype flow diffusers	Guides nutrient solution into net pots  Fig. 23: Flow ducts, final prototype	Flow diffusers are changed to flow ducts. Flow diffusers in the first prototype were unable to allow nutrient solution to fall evenly, and hence nutrient solution could not flow to the net pots reliably (Fig. 22). In the final prototype, flow ducts were used instead to directly guide nutrient solution into the net pot (Fig. 23).
Strength features	Bears larger structural loads for more plants	Refer to earlier section on “Strength optimization features” for details.
Angles and dimensions	To increase space-efficiency and strength of tower	The modules were made shorter (130mm to 110mm for small modules) and angle of net pots were slightly decreased. This resulted in a space efficiency increase of over 20%, while providing sufficient space for root growth. Other slight changes were also introduced.

Appendix C – First prototype

Pictures of the first prototype are shown. The first prototype of the SMART Urban Farming system was SLS printed using PA12 (Appendix D2), courtesy of the National Additive Manufacturing Innovation Cluster (NAMIC) by A*STAR, as part of the entry for the 1kg Challenge, a nationwide competition to strengthen awareness and adoption of additive manufacturing for novel sustainable designs. Later in this competition, the SMART Urban Farming system, entered as "PrintFarm", won the top prize, the ExtraBold Sustainability Prize.

The first prototype did not have a good lighting solution, nor a monitoring and alert system. These were added as improvements as part of the final prototype.

Figure C3: Modules of the first prototype

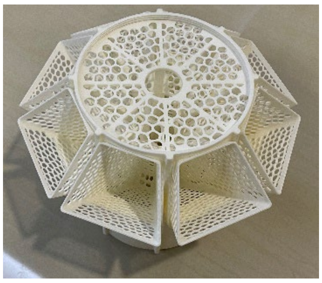


Figure C1: The first prototype, "PrintFarm", at the 1kg Challenge Exhibit at the Visual Arts Centre

Appendix D1 – PPGB material data

Flexural strength: 33 MPa
Flexural modulus: 2000 MPa
Elongation at break: 58%
Heat deflection temperature (0.45 MPa): 58 °C
Color: Light Grey
BASF Forward AM PP-GB offers high toughness,
excellent chemical resistance, structural tightness and low moisture absorption.

Appendix D2 – PA12 material data

Tensile modulus: 1650 MPa
Tensile strength: 48 MPa
Elongation at break: 15 – 20%
Flexural strength: 41 MPa
Flexural modulus: 1.73 GPa
Heat deflection temperature (0.45 MPa): 154°C

PA12 has good mechanical properties such as toughness, tensile strength and impact strength. This material can also be flexed without fracture. It has a melting point of 176°C with low water absorption.