Enhancing Juvenile *Xiphophorus* Fish Survival: Modular, Bio-Inspired Habitat Design Using MEX Additive Manufacturing

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Abstract

Xiphophorus species are critical to biomedical research, particularly in cell biology and cancer studies, creating a need for large-scale lab production. However, protecting juveniles from adult predation in artificial aquaponic systems remains a major challenge. This study presents a nature-inspired, fish-safe habitat designed to enhance fish survival, simplify cleaning, and facilitate feeding. Both subtractive (5-axis CNC machining) and additive manufacturing (AM) - Material Extrusion (MEX) methods were used in development. The final structure, printed with Hyper-PLA on a CoreXY platform, features fry-entry slots (~0.2 inches), an integrated feeding chimney, and a snap-fit, tool-less assembly. Additive manufacturing enabled rapid design iteration, while aquatic testing validated dimensional accuracy (±0.02 inches) and functional stability. The results demonstrate how additive manufacturing can translate biological needs into scalable, practical engineering solutions for research and conservation.

1. Introduction

Xiphophorus fish, such as swordtails and platyfish, are small freshwater species widely used in genetic, cancer, and developmental biology research. Their popularity in research labs and aquariums stems from their manageable size, live-bearing reproduction, and genetic diversity [1] . However, one major challenge in keeping *Xiphophorus* in artificial environments is the survival of juvenile fish. In tanks or aquaponic systems, adult fish often eat their own young—a natural behavior known as filial predation. This significantly reduces the survival rate of fry (baby fish) [2], [3].

Figure 1. *Xiphophorus* Fish [1]

In nature, juvenile fish find shelter in rocks, crevices, and dense vegetation to hide from predators. These natural structures help reduce stress and improve the chances of survival. Unfortunately, typical fish tanks lack this complexity. Most commercial solutions—like mesh boxes or floating nursery containers—are rigid, unattractive, and sometimes even stressful for the fry due to limited space and water circulation issues [4], [5]. Products like the Fluval Nursery Box offer some protection, but they isolate the fry in confined areas and do not allow them to interact with their environment in a natural way. Recent studies in marine and freshwater ecology have shown that structural complexity—such as curved surfaces, slot-like openings, and porous walls—plays a big role in helping juvenile fish survive and thrive [6], [7]. These insights have led researchers to explore new ways to design habitats that mimic nature. Bio-inspired structures, especially those with modular or coral-like forms, have been found to encourage safer and more natural behavior in young aquatic species [8], [9]. At the same time, advances in additive manufacturing (AM) have opened new possibilities for creating these structures quickly and affordably. 3D printing, particularly MEX, allows designers to build custom shapes that would be difficult or expensive to make using traditional tools. It also supports rapid iteration, easy customization, and low-volume production, all of which are important for research and educational use [10], [11].

The specific requirements for the system included ensuring fish safety through non-toxic materials and smooth surfaces, durability for prolonged submersion and repeated handling, ease of fabrication using accessible and low-cost manufacturing techniques, modular design for quick assembly and disassembly, ease of cleaning to maintain hygienic conditions in aquatic environments, simplicity in feeding via non-intrusive mechanisms, structural stability to prevent drifting or tipping, and above all, effectiveness in protecting juvenile fish from predation by adult fish or environmental hazards.

This paper presents a novel habitat specifically designed for juvenile *Xiphophorus*. The structure is collapsible, modular, and draws inspiration from natural hiding spaces found in aquatic environments. Key features include narrow entry slots sized exclusively for fry, an integrated feeding chimney for non-disruptive nourishment, and a snap-fit assembly system that eliminates the need for tools or adhesives. Fabrication was carried out using MEX 3D printing with Hyper-PLA filament. The objective of the design was to develop a functional, safe, and user-friendly habitat that enhances the survival rate of juvenile fish in controlled research or breeding environments.

2. Design Evolution and Fabrication Methodology

2.1 Subtractive Manufacturing Approach

The project initially employed a subtractive manufacturing method, beginning with a CNC-machined habitat produced using 5-axis milling and PVC material. While this early version demonstrated strength and precision, it presented several limitations. The CAD model, CAM toolpaths, and final CNC-machined product are shown in Figure 2. The habitat was fabricated as a single solid block, which posed challenges in terms of cleaning, transportation, and structural modifications. Additionally, it lacked an integrated feeding mechanism, and removing the unit from the tank disrupted both the fish and the aquatic environment. Although circular holes were drilled to permit fry entry, juvenile *Xiphophorus* showed little interest in using them. These drawbacks led to the pursuit of a more adaptable and fry-accessible design.

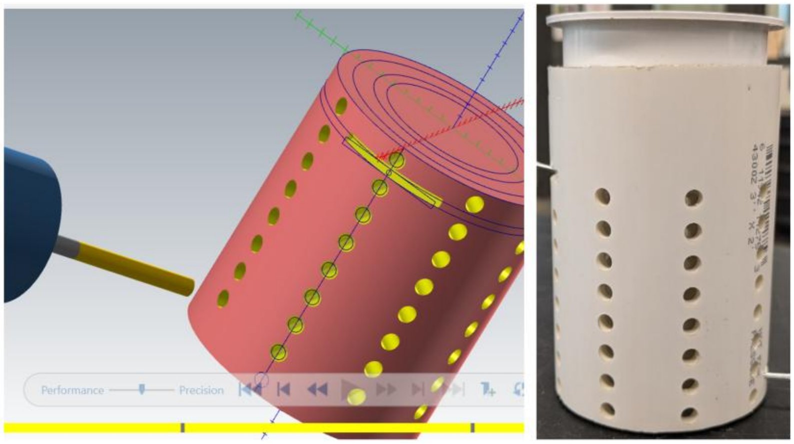

Figure 2. Fish Habitat using 5 Axis CNC Machining

These limitations stemmed from the inherent constraints of CNC milling, which produces monolithic structures. The absence of modularity made cleaning and handling cumbersome, while toolpath restrictions limited the ability to incorporate narrow fry-safe slots, foldable panels, or integrated chimneys for feeding. As a result, the CNC design could not meet the functional requirements of flexibility, ease of maintenance, and biological realism.

2.2 Additive Manufacturing Approach

AM, specifically MEX, was utilized to reimagine the habitat design. This transition provided significantly greater design flexibility, enabling the exploration of natural geometries, the incorporation of internal features, and rapid prototyping through multiple iterations. Most notably, AM facilitated the evolution from a bulky, rigid structure to one that is modular, collapsible, and more user-friendly for both researchers and juvenile fish. Unlike the CNC-milled version, the MEX approach enabled modular snap-fit joints, a central chimney feature, and fry-safe vertical slots in thin wall panels. These features were not only impractical to machine as a single block but also difficult to modify once fabricated. Additive manufacturing therefore provided a platform where iterative refinements and biologically inspired geometries could be implemented quickly and effectively.

2.2.1 Bio-Inspired Geometry and CAD Design

Nature often offers clever solutions. In designing the new structure, inspiration was drawn from aquatic plants such as Vallisneria, known for their long, narrow leaf slits. These forms were translated into vertical slots on the wall panels, specifically sized to permit passage for fry while excluding adult fish. Additionally, a chimney feature was incorporated, inspired by the structure of termite mounds. This chimney functions both as a feeding chute and as a handle for convenient lifting, thereby minimizing disturbance to the juvenile fish. The final design specifications are presented in Table 1.

Autodesk Fusion 360 was used to model all components of the habitat. Initially, printing the entire structure as a single piece was considered; however, early tests revealed that this approach would be inefficient, requiring excessive support material and complicating post-processing. Consequently, a modular design strategy was adopted. Each panel—including the walls, base, and chimney—was modeled to print either flat or upright, depending on its geometry. Flat printing helped maintain dimensional accuracy, while upright printing reduced the need for internal supports. All parts were exported as STL files and prepared for slicing using Creality Print 6.0.

Table 1. Final Dimension of the Product

Feature	**Description**	**Purpose**
Dimensions	178 x 127 mm	Aquarium-friendly footprint
Wall slots	0.20 in × 0.12 in	Fry-entry, adult exclusion
Chimney	16 mm ID vertical pipe	Feeding + lifting
Hinged base	Foldable panel	Flat-packing + easy deployment
Cleaning mesh	Below base	Waste collection during the lift
Ballast	Fill with stones	Prevent floating

2.2.2 Snap-Fit Assembly and Structure

To ensure the design was tool-free and easy to assemble, interlocking snap-fit joints were implemented. These joints were iteratively tested and refined based on the tolerances of the 3D printer used. A clearance of ±0.12 mm was determined to provide secure yet detachable connections. The snap-fit concept was inspired by a design from Brandon Santona [12]. The final build included side walls with slotted entries, a base panel supporting a removable mesh tray, and a lid incorporating the chimney structure. The assembly did not require any screws or adhesives, enhancing safety for aquatic environments and simplifying cleaning and disassembly. An isometric view of the final assembled design is presented in Figure 3.

2.2.3 Material Selection and Safety Considerations

The initial material choice was PETG due to its strength and durability in aquatic conditions. However, due to supply constraints, Creality Hyper-PLA was selected for the prototype. PLA offers ease of printing and a high-quality surface finish but is less suitable for prolonged water exposure. For future iterations intended for long-term use, PETG or ASA is recommended, as these materials exhibit better water resistance [10], [13]. A comparative analysis of materials is provided in Table 2 [14], [15]. Additionally, all sharp edges were rounded during

CAD modeling, and post-processing was kept minimal to prevent introducing harmful chemicals. After printing, each part was rinsed with clean water and carefully inspected prior to deployment.

Table 2. Comparison of Common Materials for MEX Process

Material	Pros	Cons	Suitability
PETG	Water-safe, strong, glossy surface	Unavailable	Ideal, not used
PLA (used)	Easy to print, smooth finish	Absorbs water long-term	Sufficient for short-term
ABS	Durable, UV resistant	Emits fumes, warps	Not fish-safe
ASA	Strong, UV-resistant	Needs enclosure	Good alternative to PETG

2.2.4 Printing and Post-Processing Workflow

Once the CAD models were finalized and slicing settings confirmed, as detailed in Table 3, fabrication was initiated using the Creality K1 Max printer. This printer was selected for its large build volume, reliable print speed, and consistent resolution. Prior to printing, the build plate was leveled and cleaned to ensure proper adhesion.

Figure 3 presents an overview of the sliced parts within the slicer software, the printer used for fabrication, and a close-up of the first layer during printing. To fabricate the complete habitat, the process was divided into two print runs. Run 1 included the lid, chimney, and one side panel, requiring approximately 4 hours and 33 minutes and 143.4 grams of Hyper-PLA filament. Run 2 consisted of the hinged base and the two remaining side panels, with a total print time of around 4 hours and 6 minutes and filament usage of 120.3 grams.

Each run involved 5–10 minutes of pre-processing tasks, including slicing, checking for overhangs, adding brims and supports as needed, and bed-leveling. Post-processing required an additional 8–10 minutes total, primarily to trim minor stringing using a hobby knife and to lightly sand snap-fit joints that were too tight. The side panels were oriented flat on the bed to reduce warping and preserve dimensional accuracy. The chimney, which contains a vertical hollow channel, was also printed flat to minimize support usage and create a cleaner internal feeding path. Mesh trays, due to their delicate geometry, were printed with brims to prevent edge lifting. The initial layers of each print were closely monitored to detect bed adhesion issues. Once stabilized, the prints proceeded unattended.

Post-processing was kept minimal and conducted with safety as a priority. No chemical treatments were used to avoid the introduction of potentially harmful residues. After rinsing each component with clean water and performing visual inspections for defects, the entire habitat was assembled manually. All parts fit securely via snap-fit joints, making the structure immediately ready for testing.

Printing was performed with Hyper-PLA extruded at 200°C through a 0.4 mm nozzle, while the bed temperature was held at 60°C. The total print time for one complete habitat was approximately 8.65 hours, with filament costs estimated at $14.41.

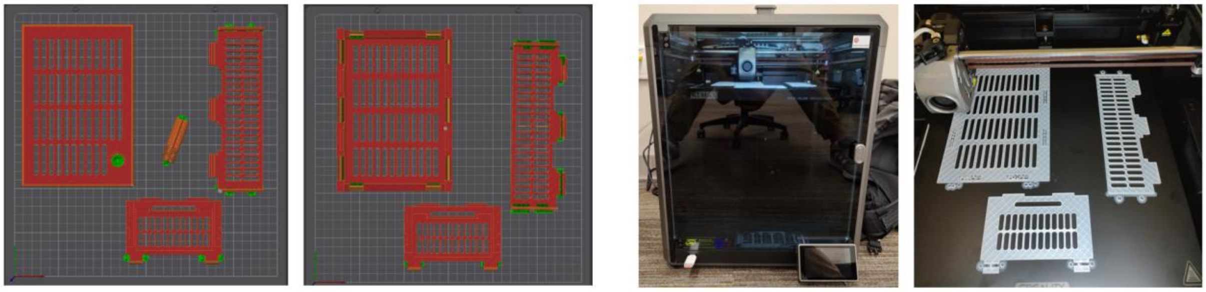

Figure 3. Slicing & Print Orientation, Creality K1 Max Printer and Printing Process

Table 3. 3D Printing Parameters

Parameter	**Value**
Printer	Creality K1 Max
Material	Hyper-PLA
Nozzle Diameter	0.4 mm
Layer Height	0.20 mm
Infill	15% Grid
Wall/Top Layers	2 / 5
Supports	Tree (chimney only)

The finished product was lightweight, modular, and visually clean. The chimney not only allowed convenient feeding but also served as a safe and effective handle for lifting the habitat out of the tank. Overall, the shift to MEX-based additive manufacturing gave better control, faster iteration, and cleaner integration of functional features compared to the earlier CNC approach.

3. Results

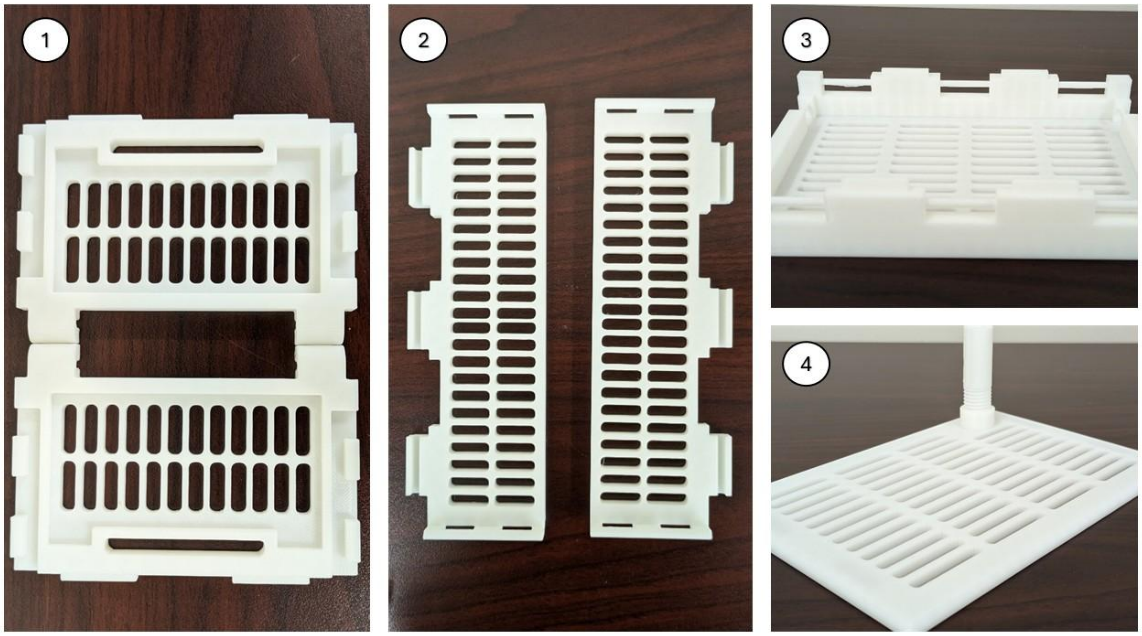

Figure 4. 1- Printed Sides, 2- Printed Flaps. 3- Printed Base, 4- Printed Lid

The initial evaluation focused on verifying dimensional accuracy and fit of the printed parts. Figure 4 displays all the fabricated components after minimal post-processing. Following assembly, the 3D-printed habitat underwent performance testing in both a laboratory setting and a functional aquarium environment. The printed parts closely matched the intended CAD specifications. The fry-entry slots were measured to be near the designed width of 0.20 inches, and the majority of the components remained within a tolerance of ±0.02 inches. The snap-fit joints functioned as expected, securely holding the structure together without requiring any tools, yet

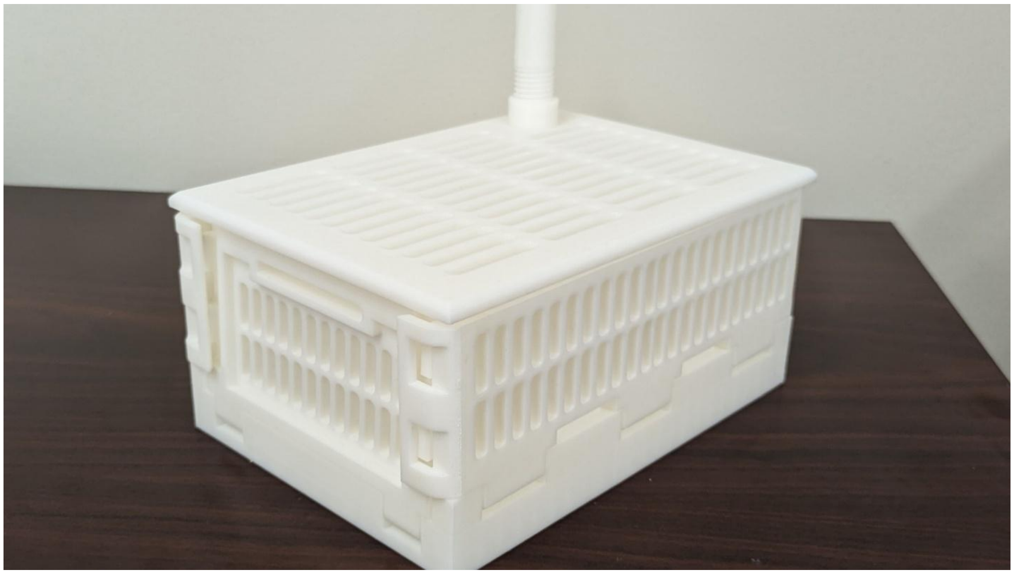

Figure 5. Final Product after Assembly

allowing for easy disassembly for routine cleaning and maintenance. The fully assembled habitat is shown in Figure 5.

3.1 Field Experiment

A primary concern during evaluation was whether the structure would remain stationary when submerged. Given that 3D-printed plastics are typically lightweight, it was important to ensure that the habitat would not float or shift during use. To address this, small aquarium-safe rocks were inserted into the base cavity of the habitat. This simple and non-invasive method provided sufficient weight to anchor the structure while maintaining water quality and ensuring fry safety. Throughout the testing period, the habitat remained stable without drifting or tipping, even in the presence of active swimming by nearby fish.

The most critical phase of validation involved observing the behavior of juvenile *Xiphophorus* fry in response to the habitat design. Unlike the earlier CNC-milled prototype, which incorporated circular holes and saw limited interaction from the fry, the revised design featured elongated vertical slots inspired by aquatic plant stems. This geometry was more inviting and accessible to the juveniles, encouraging entry and prolonged occupation. While these initial observations were qualitative, future work will incorporate quantitative behavioral metrics to strengthen the analysis. For example, fry interactions can be measured by counting the number of entries and exits per unit time, the duration of occupancy within the habitat, and the proportion of fry observed using the shelter versus remaining in open water. Preliminary trials indicated multiple fry entries within a 30-minute observation window, suggesting increased engagement compared to the CNC prototype. These metrics will provide a numerical basis for evaluating fry response and allow more rigorous correlation with survival outcomes. The functionality of the integrated feeding chimney was also verified. Food introduced through the chimney was guided directly into the shelter's interior, enabling feeding without disturbing the structure. This approach minimized stress on the fry and supported more consistent behavioral observation.

3.2 Additive Manufacturing and Subtractive Manufacting Cost Breakdown (Single Unit)

Table 4 presents a detailed cost analysis for fabricating a single juvenile fish habitat unit using the MEX 3D printing process. The total cost per unit was calculated as $304.74, incorporating all stages of production and overheads. The material cost was estimated at $14.51, based on the use of 263.7 grams of Hyper-PLA filament priced at $0.055 per gram. To account for operational expenses, machine depreciation and energy consumption were combined, calculated at $6.74 for 8.65 hours of active printing at a blended rate of $0.78 per hour.

The labor and handling cost, amounting to $72.00, reflects an estimated 2.06 hours of active involvement by personnel (including design setup, printer preparation, monitoring, and light post-processing) compensated at a rate of $35 per hour. Additionally, a fixed software usage cost of $120.00 was included to reflect expenses associated with CAD design and slicing operations. An expert preparation fee of $80.00 was also considered, representing one hour of consultation or setup support from a 3D printing specialist at a standard rate of $80 per hour. A nominal overhead cost of $5.00 was added to account for general facility and equipment use.

Table 4. Additive Manufacturing Cost Summary (For Single Prototype)

Category	Description	Cost Estimate
Material	263.7g Hyper-PLA × $0.055/g	**$14.51**
3D Printing Energy + Depreciation	8.65 hrs × $0.78/hr (includes electricity and machine depreciation)	**$6.74**
Labor & Handling	Design, slicing, printer setup, monitoring, post-processing (2.06 hrs × $35/hr)	**$72.00**
Software License	Fixed design & slicing software use	**$120.00**
Expert Prep Time	1 hr of 3D printing expert time × $80/hr	**$80.00**
Overhead	General facility cost estimate	**$5.00**
Total		**$304.74**

Overall, this granular breakdown demonstrates how multiple contributors, including fixed overheads and skilled labor, impact the unit cost of additive manufacturing in low-volume production contexts.

Table 5. Subtractive Manufacturing Cost Summary (For Single Prototype)

Category	Description	Cost Estimate
Material	Raw stock material - PVC ($14 × 1 part)	**$14.00**
Machine Time + Energy	CNC machining (0.3 hr machining + 0.5 hr prep + 0.01 hr inspection @ $400/hr)	**$42.50**
Labor & Handling	CNC prep + machining supervision (6.48 hrs × $50/hr)	**$324.00**
Software License	Fixed CAM/software cost	**$20.00**
Expert Prep Time	1 hr MasterCAM expert @ $100/hr	**$100.00**
Overhead	General facility cost estimate	**$5.00**
Total		**$505.5**

Table 5 shows the cost breakdown for making one juvenile fish habitat unit with CNC machining. The total came to $505.50 per unit, with material costing $14 and machine time about $40.50. The biggest expense was labor at $324, since setup and supervision take several hours for a single part. Software and expert setup added another $120, and small overhead charges brought the rest. Overall, most of the cost comes from the skilled time needed, which makes one-off subtractive manufacturing quite expensive compared to batch production.

3.3 Cost Comparison Across Manufacturing Scales

To assess the cost-effectiveness of the modular fish habitat, a comparative cost analysis was performed for both subtractive and additive manufacturing methods across production volumes ranging from 1 to 100 units using the ABC model [16]. The analysis incorporated labor, material, machine depreciation, software time, energy consumption, and overhead based on the updated classroom cost framework. It should be noted, however, that this cost comparison is not fully "apples-to-apples." Certain elements of the additive design, such as flat wall panels, could theoretically be fabricated with 2D laser cutting at a lower cost. Nevertheless, critically integrated features like snap-fit joints, the foldable base, and the chimney could not be achieved with simple 2D processes or single-block CNC milling. These functional advantages, rather than the slots alone, highlight the necessity of additive manufacturing for this application.

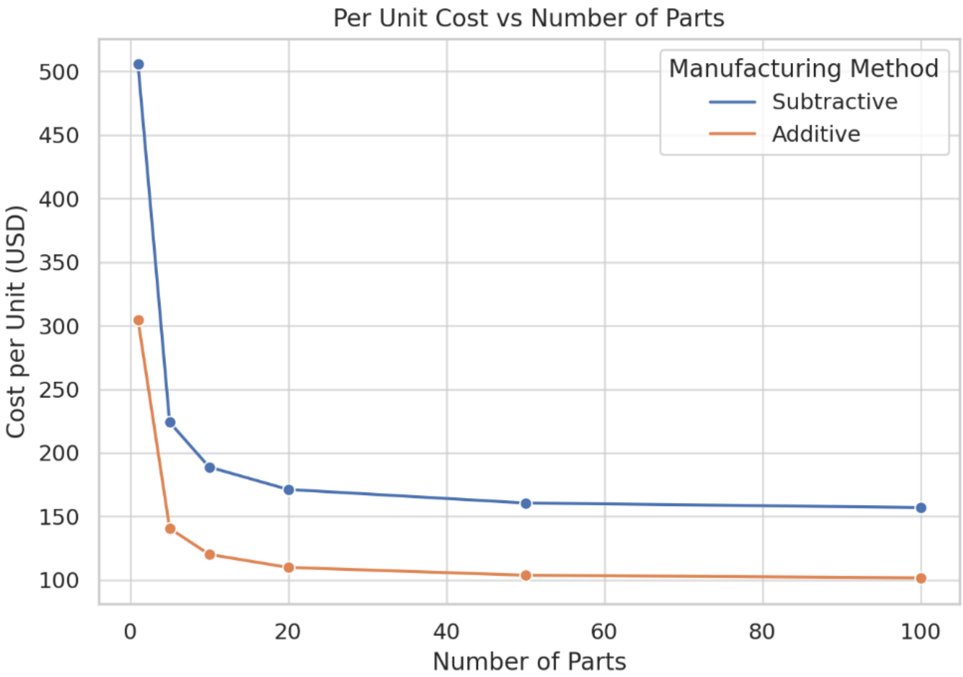

Figure 6. Comparison of per-unit manufacturing cost between subtractive and additive methods across different production volumes

Subtractive Manufacturing Summary

Subtractive manufacturing, implemented using 5-axis CNC milling, showed notably high costs at low production volumes. As seen in **Figure 6**, producing a single unit costs approximately **$505.50**, primarily due to labor-intensive setup, material waste, and high hourly machine rates. The cost per unit decreased to $157.07 at a batch size of 100 due to economies of scale, but the method remained less efficient in terms of flexibility and design integration. The subtractive approach constrained the incorporation of integrated features such as snap-fit joints or embedded feeding chimneys, which required separate tooling or post-processing.

Additive Manufacturing Summary

Additive manufacturing using MEX demonstrated superior scalability and cost efficiency, especially for lower and medium production volumes. As outlined in **Figure 7**, the cost to fabricate a single unit was approximately $304.70, significantly lower than its subtractive counterpart. The cost reduced further to $101.79 at a 100-unit batch. These savings were achieved through streamlined modular printing, minimized tooling time, and reduced labor due to tool-free assembly and batch-friendly slicing processes. Furthermore, 3D printing enabled the inclusion of biologically inspired features like fry-entry slots and internal feeding chimneys without additional processing steps, making it an ideal candidate for rapid prototyping and scalable deployment.

Comparative Insights

Figure 6 confirms that additive manufacturing outperforms subtractive manufacturing at every volume point assessed. While subtractive costs start high and taper gradually, additive costs start lower and level out more quickly. This cost behavior reinforces the conclusion that for complex, modular, and bio-integrated habitat designs intended for small- to medium-scale production, additive manufacturing is the more economical and adaptable method.

Table 6 presents a qualitative comparison between subtractive and additive manufacturing approaches based on key design and functional criteria. Subtractive manufacturing, typically performed via CNC milling, is constrained by tool access and the need for 3D toolpath planning, limiting the complexity of geometries that can be fabricated. In contrast, additive manufacturing using MEX 3D printing offers significantly greater design flexibility, allowing the creation of intricate and biomimetic structures that better suit biological applications. Modularity is another area where additive manufacturing excels; the ability to produce separate, snap-fit components enables tool-free assembly and easy customization, features not possible in the monolithic subtractive design. From a usability perspective, the subtractive design poses challenges during cleaning and handling, as lifting the single-piece unit risks disturbing the fry. On the other hand, the additive habitat is designed for easy disassembly and rinsing. Behaviorally, the additive design also shows higher fry attraction due to its plant-inspired slit geometry, which more closely mimics natural hiding spaces, as opposed to the less-inviting circular openings in the subtractive version. While CNC machining requires less time per unit for active fabrication (~16 minutes), 3D printing, though longer in total (~8.65 hours)—is largely automated and requires minimal supervision, reducing the overall labor burden. This comparative analysis highlights the superior suitability of additive manufacturing for creating modular, behaviorally-informed, and user-friendly fish habitats.

While certain elements, such as flat wall panels, could be fabricated more cost-effectively with 2D laser cutting, features like snap-fit joints, the integrated chimney, and foldable bases remain more practical through additive manufacturing.

The final habitat design met all targeted functional requirements: it successfully shielded the fry from adult fish, supported natural behaviors, maintained stability under aquatic conditions, and facilitated convenient feeding and maintenance. Most importantly, the results underscored the potential of additive manufacturing as a powerful tool for creating accessible, affordable, and animal-conscious solutions in aquatic research and husbandry contexts.

Table 6. Comparison Between Subtractive & Additive Manufacturing Processes

Feature	**Subtractive (CNC)**	**Additive (MEX 3D Printing)**
Design Complexity	Limited by tool access and 3D toolpaths	Highly flexible; supports complex, organic forms
Modularity	None; single-piece structure	Fully modular with snap-fit joints
Cleaning & Handling	Difficult; lifting disturbs fry	Easy to lift and rinse without disturbance
Integrated Features (chimney, fry slots)	Limited; requires multiple parts or post-processing	Fully integrated; designed and fabricated in a single workflow
Fry Attraction	Low; circular holes rarely used	High; plant-inspired slits encourage entry
Build Time per Unit	~16 minutes (active machining only)	~8.65 hours (mostly unattended printing)
Alternative Methods (Laser Cutting)	Suitable for 2D flat panels, but limited for complex geometries	Supports complex multi-feature geometries in a single build.

4. Conclusion and Future Work

This project provided a valuable opportunity to explore both subtractive and additive manufacturing techniques in the development of protective habitats for juvenile *Xiphophorus* fish. Each method presented distinct advantages and trade-offs:

- **Subtractive manufacturing (CNC milling):**
  - Offered high structural integrity and mechanical precision
  - Limited by its monolithic design, making the habitat difficult to clean, transport, or modify
  - Lacked integrated features such as a feeding mechanism or customizable access points

- **Additive manufacturing (MEX):**
  - Enabled complex, modular, and customizable designs

    - Facilitated the integration of slotted panels, snap-fit joints, and a central feeding chimney
    - Mimicked natural hiding spaces, encouraging fry to engage in instinctive protective behavior
    - Allowed feeding without disrupting the structure, enhancing usability, and fish comfort

The transition to MEX-based additive manufacturing resulted in a more effective and user-friendly habitat that aligns closely with the behavioral needs of juvenile *Xiphophorus*, supporting improved survival in controlled environments.

From a fabrication perspective, one of the primary advantages of utilizing 3D printing was the ability to rapidly iterate. Dimensional adjustments, design variations, and part replacements could be executed efficiently without the need for new tooling or fixtures. The modular design approach enabled tool-free assembly and simplified maintenance—critical attributes for research environments or aquaponic systems where ease of cleaning and adaptability are essential. The assembled structure consisted of components printed with Hyper-PLA and incorporated smooth, fry-safe edges. Although Hyper-PLA proved adequate for prototyping purposes, it is not recommended for long-term submersion. Future implementations should consider the use of PETG or ASA due to their superior water resistance and mechanical durability[10], [13]

Future Work

- Investigate long-term durability of PLA vs. PETG or ASA in aquatic conditions
- Introduce biofilm-resistant or biodegradable materials for improved sustainability
- Expand the modular design for larger habitats or community-based configurations
- Incorporate smart sensing features for monitoring fry activity and water quality

Looking ahead, this project paves the way for smarter and more biologically aligned habitat systems. Potential enhancements include integrating environmental sensors to monitor water quality or fish activity, applying multi-material printing for soft or flexible regions, and scaling the design for different fish species or aquatic environments. We also see potential applications in educational and research facilities, where low-cost, customizable, and modular habitats could improve animal welfare and experimental control.

In summary, this study demonstrates the potential of additive manufacturing to address fundamental challenges in biological and ecological design. Through the integration of bio-inspired geometry and engineering precision, we developed a modular, fry-safe habitat that supports the behavioral needs of juvenile *Xiphophorus* fish. The results confirm the feasibility of the design and indicate positive fry engagement with the structure. However, long-term controlled experiments are required to rigorously assess its effect on survival outcomes. Accordingly, this work should be regarded as an initial step toward improving juvenile *Xiphophorus* survival, providing a foundation for future investigations and design refinements.

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