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Thermoforming as Rapid Prototyping Strategy of Fishing Lures

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Abstract. Conventional hard-bait lure prototyping relies on manual shaping, full-body additive manufacturing or early-stage injection moulding, each associated with limitations in geometric repeatability, development time or tooling cost. This paper evaluates a hybrid approach combining thermoformed PETG outer shells with additively manufactured internal frames to produce batches of geometrically consistent lure bodies with tuneable internal mass layouts. Across several educational development projects, the process enabled fast replication of outer form, systematic variation of ballast and harness configuration, and prototype assembly suitable for qualitative hydrodynamic observation. Compared with full additive manufacturing or manual crafting, the method reduced fabrication effort for multi-variant batches and delivered mould-like surface quality. Joining reliability of shell halves emerged as the dominant limitation, with elastic polyurethane adhesives outperforming brittle cyanoacrylate and poorly controllable low-energy fusion. The results position thermoforming as a methodologically valuable prototyping tool where external geometry is stable but internal behaviour requires iterative adjustment. Future work should address seam design, cage-shell tolerances and sealing repeatability to support quantitative hydrodynamic testing and assess whether the process has potential beyond prototyping applications.

1. Introduction

Recreational fishing is widely practiced and provides a huge market of about 10 billion euros a year (EU only) for associated equipment [1]. Product development for artificial fishing lures that depend on functional hydrodynamics typically requires iterative prototyping to evaluate geometry, buoyancy, and behaviour. Conventional workflows rely on either hand-crafted trial pieces, fully additively manufactured bodies, or pilot-scale injection moulding. Each of these approaches exhibits limitations that impede rapid, repeatable progression from conceptual design to functional prototype. [2, 3].

Hand shaping remains an accessible route for hobbyists and small manufacturers; however, geometric fidelity, reproducibility and shape consistency across batches depend strongly on operator skill. This restricts the ability to isolate the influence of individual design variables, as two nominally identical prototypes may differ in subtle but behaviourally relevant ways. Full additive manufacturing, in contrast, offers excellent geometric control but is challenged by surface resolution, shell thickness limitations, sealing integrity, and extended build times when larger quantities of similar specimens are required [4, 5]. Furthermore, polymer injection moulding, although the standard for final lure production, demands substantial tooling effort and cost, and its use early in development cycles is impractical due to the lead time associated with tool manufacture and modification [6].

To address this gap, the present work examines a hybrid rapid prototyping strategy that combines thermoforming of PET shells with additively manufactured internal structures. The objective is to assess the feasibility of a process capable of producing families of geometrically consistent prototypes that approximate the appearance and build characteristics of injection-moulded lures, but at significantly lower development time and cost. The process comprises three key stages: (i) generation of a digital lure model, (ii) thermoforming of thin-wall exterior halves using a laboratory forming system, and (iii) integration of an adjustable mass-carrying internal lattice printed via fused deposition modelling (FDM). This concept was implemented across several student development projects, where identical outer geometries and variable internal configurations were rapidly manufactured for design iteration and functional testing.

Preliminary observations from these feasibility studies indicate that the method allows the reproducible manufacture of outer shells, a structured means of adjusting weight distribution, and shorter build times compared to full additive manufacturing. However, challenges arise in joining the two thermoformed halves, where adhesive bonding was found to outperform low-pressure thermal welding due to seam heterogeneity near wire insertions.

These findings motivate a more systematic evaluation of thermoforming-based hybrid prototyping as a development tool for small consumer products. Rather than focusing on lure hydrodynamics, this paper assesses the process strategy itself, its implementation, constraints, comparative advantages, and potential scalability. Particular emphasis is given to its position relative to existing prototyping approaches and its suitability for bridging early ideation and later injection-moulding production.

2. Background and Related Work

2.1 Rapid Prototyping Strategies for Small Consumer Products.

Development of small consumer products that depend on external geometry and internal architecture, such as fishing lures, typically employs up to three prototyping approaches, manual forming, additive manufacturing (AM) and pilot-scale moulding [5, 2]. Manual forming remains widely used in craft-oriented lure development because of its simplicity and negligible investment cost. However, its reproducibility and fidelity depend heavily on operator experience, making systematic iteration and comparative evaluation difficult, particularly when performance differences may stem from subtle shape variations rather than design intent.

Additive manufacturing is frequently framed as a solution to these shortcomings because it enables digital-to-physical replication without traditional tooling, offering relatively low entry cost and strong suitability for low-volume and customised production [5]. Advantages include geometric freedom, the ability to make frequent design modifications and the elimination of early tooling investment [7]. However, industrial reviews note several drawbacks that restrict AM as a full replacement for injection moulding. Surface finishing requirements, layer artefacts, porosity in thin shells, anisotropic properties and extended build time when multiple units are required [5, 8]. These drawbacks are particularly pronounced in applications where aesthetic surface fidelity, sealing integrity, or thin-walled repeatability are required [5]. Additionally, adding weights or internal structures require further manual modification steps.

Injection moulding, in contrast, remains the dominant production process for polymer consumer products due to its ability to achieve excellent dimensional accuracy, surface finish, and material performance in volume production [6]. Yet, its utility for iterative prototyping is hindered by relatively long tool lead times, capital expenditure, and the inflexibility of mould geometries once manufactured [2, 9]. Where design changes are frequent, injection moulding becomes economically prohibitive for early-phase evaluation.

In response to this gap, thermoforming has been promoted as an intermediate prototyping and low-volume manufacturing method because it offers thin-walled polymer parts at relatively low tooling cost and with faster cycle times than tooling and full-body AM [2]. Industry and manufacturing comparison studies specifically highlight thermoforming as favourable when the goal is to approximate an injection-moulded look and feel while maintaining responsiveness to geometric change [3]. This positioning makes thermoforming a promising candidate for applications such as lure prototyping, where multiple geometrically consistent units are needed to study internal configuration changes rather than surface morphology alone.

2.2 Principles of the Thermoforming Process.

The thermoforming workflow comprises heating, forming, cooling and trimming. First, a thermoplastic sheet or plate is heated above its glass-transition or softening temperature to reach a deformable state. Forming occurs against a mould surface via vacuum suction, assisted mechanical displacement or pressure forming. The geometry is retained during cooling before excess edges are trimmed. This makes thermoforming attractive for prototype production due to short cycle times and minimal tooling overhead [3].

Depending on thickness, two industrial subclasses exist. Thin-gauge thermoforming (<1.5 mm - provided by university), typical for packaging and aesthetic surfaces and thick-gauge thermoforming (>3 mm), where structural stiffness or larger components are needed [1, 3]. Common thermoformable polymers include ABS, PET/PETG, PS, PVC, PP and PC, selected according to transparency, impact performance, thermoformability and post-processing behaviour [6, 3]. Key challenges arise from material stretching during forming, which produces non-uniform wall thickness, potentially compromising local integrity. Geometry with deep draw or sharp curvature amplifies thinning effects. Furthermore, thermoforming inherently defines only the mould-contacting surface; secondary features or reverse-side precision require more advanced forming strategies or bonding of multiple shells [2].

Despite its advantages, thermoforming exhibits constraints relative to injection moulding, limited ability to produce sharp internal detail, variable wall thickness due to stretching, geometric complexity bounded by draw angle and surface curvature, and requirement to trim excess stock after forming [5].

Moreover, in rapid tooling contexts the mould itself is often produced additively. Layer-based tooling fabricated through FDM typically exhibits ridged surfaces and porosity, necessitating secondary finishing (e.g. sanding, sealing coatings or thermal smoothing) to achieve suitable vacuum fidelity and surface replication [5]. SLA- or MJF-printed tools may require less finishing but are constrained by build volume or mechanical resistance to repeated heating cycles [8]. In parallel, advances in polymer AM introduce resins with elevated heat deflection temperatures suitable for thermoforming tooling. For instance, Formlabs' high-temperature resins are marketed explicitly for small-scale thermoforming applications where conventional photopolymers might deform under process heating [10]. These developments illustrate that the success of thermoforming-based prototyping is strongly dependent on material selection not only for the shell, but also for the tooling substrate.

2.3 Fishing Lures as a Representative Product Class.

Given the limited academic literature on internal lure construction, practitioner and patent sources are used to document prevailing industrial design practices.

From a functional perspective, angling equipment distinguishes broadly between natural bait (e.g. worms, small fish, invertebrates) and artificial lures. Artificial lures encompass soft plastic baits, metal spoons, spinner systems and hard-bodied lures such as plugs, crankbaits and jerkbaits, which are typically shaped and coloured to resemble prey fish or other forage organisms, although effective designs increasingly depart from strictly natural morphology [11].

Within artificial lures, hard-bodied "plugs", including floating and diving crankbaits, are characterised by a rigid volumetric body made from wood or polymer, usually equipped with one or more treble hooks and depending on type, a diving lip or bill at the head [12]. These lures normally operate as hollow shells in modern industrial production, assembled from two moulded halves which, after integration of internal components, are sealed by welding or adhesive bonding. Internal architectures provide ballast chambers or weight-transfer systems that influence diving depth, stability and action. Commercial descriptions and trade literature frequently emphasise integrated weight systems and internal rigging as central design features.

A structurally critical component of many hard-bodied lures is the wire harness, a stainless-steel linking element that connects line attachment point and hook positions through the body (Fig.1). Patents and technical descriptions report full-length wire frames or harness structures embedded in the lure body to guarantee load transfer and prevent failure of localised eyelets under high tensile load (e.g. [13]), even though systems with inserted wires were easier to manufacture (e.g. [14]). In parallel, practitioner communities and manufacturer-facing guidance document "through-wire" construction methods as standard practice for larger predator lures, in which a continuous wire is slotted or cast into the body and fixed by adhesive or overmoulding [15].

In addition to hollow-shell architectures, a second class of hard-bodied lures is based on solid wood or polymer bodies into which cavities are drilled and filled with molten lead or other ballast before being sealed. These constructions provide robust structural continuity but render subsequent changes to weight distribution more cumbersome. By contrast, multi-chamber hollow designs with internal frames facilitate some degree of adjustability, albeit at the cost of more complex tooling.

In the present work, X-ray imaging (Fig.1) of commercial lures confirms the prevalence of continuous or seperate internal wire harnesses and discrete ballast volumes as standard engineering solutions for load transfer and hydrodynamic tuning. Building on this empirical evidence, hard-bodied lures are treated here as an archetype for products in which outer geometry must closely resemble injection-moulded parts, while internal mass distribution remains an active design variable, making them suitable candidate artefacts for evaluating hybrid thermoforming-based prototyping strategies.

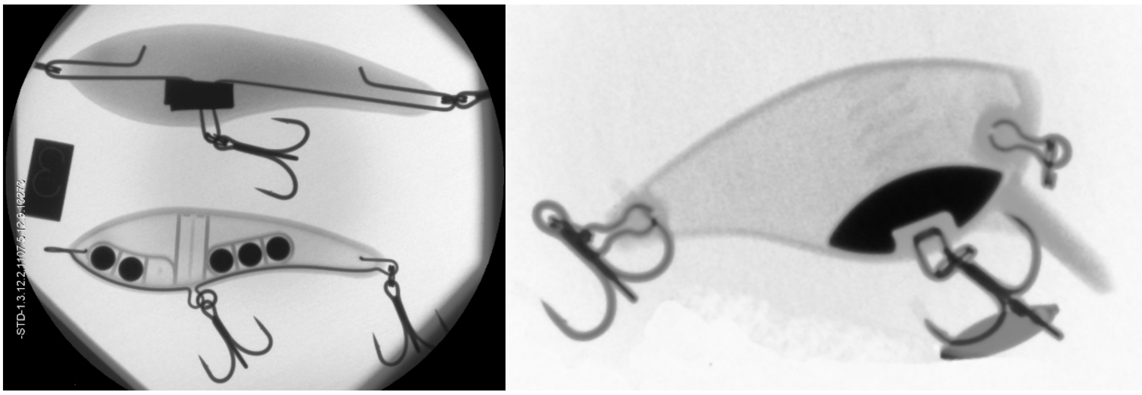

Fig. 1. X-ray images of hollow polymer lures, “through-wire” harness (left), inserted wires (right).

2.4 Joining Strategies for Thermoformed Structures.

A defining challenge in the use of thermoformed shells for functional products is the joining of thin-walled elements into structurally stable assemblies. Unlike injection-moulded parts, which typically incorporate interlocking features, ribs and welding surfaces, thermoformed components exhibit low joining land thickness, variable wall distribution, and reduced dimensional precision, restricting available methods and the reliability of connections [2].

Mechanical fastening (e.g., clips, screws) is generally unsuitable for thin thermoformed parts due to insufficient wall thickness to resist pull-through or stress concentration without reinforcement. Industrial design guidance therefore recommends integrated bosses, thicker local pads or bonded backing plates where mechanical fasteners must be used, all of which introduce extra processing steps that diminish the speed advantage of thermoforming [3, 6].

Thermal Fusion-based techniques, like hot-air welding, solvent welding, spin or ultrasonic welding, are theoretically applicable and widely used in multi-part plastic housings. However, their performance is highly sensitive to sheet gauge and temperature control, as localized heating can deform thin PET or ABS shells before fusion occurs [16, 17]. Ultrasonic welding, though attractive for high-volume production, requires precisely designed energy directors and support geometry, which are rarely present on prototype-oriented thermoformed parts [16, 17].

Adhesive bonding is generally regarded as the most practical joining strategy for thermoformed components in prototyping and low-volume manufacturing. Acrylics, polyurethane-based structural adhesives and cyanoacrylates all offer effective bond formation without excessive thermal input, and accommodate the dimensional tolerances typical of vacuum-formed parts [6, 8]. Industrial training literature emphasises adhesive joining particularly where surface finish, thin-wall sensitivity or lack of interlocking features prevent reliable welding [6].

Hybrid joining strategies combining mechanical alignment and adhesive sealing appear in industry practice for consumer housings and appliance trim, where locating ribs or lips provide positional registration and adhesives deliver strength and hermetic closure [16, 17, 3]. Similar approaches may be transferrable to thin-wall hollow lure constructions when external flushness and internal watertightness are required.

The effectiveness of joining methods in thermoformed assemblies is therefore a function not only of material chemistry but also of wall thickness, geometry, and process control. For the application investigated here, thin PET shells around a structurally relevant internal frame, adhesive joining is the most compatible technique due to local heat sensitivity of 0.8 mm PET during fusion attempts, consistent with observations in the experimental section.

3. Proposed Hybrid Process Strategy

The proposed hybrid process combines thermoformed PETG shells with additively manufactured internal frames to obtain geometrically consistent, mould-like fishing-lure prototypes while retaining flexibility in internal mass distribution. The strategy was implemented and refined across several student design-and-build projects at Berliner Hochschule für Technik, which serve as empirical evidence for feasibility, process windows and joining challenges.

3.1 Digital Design and Model Generation.

Lure geometries were modelled in CAD based on typical hard-bodied crankbait or jerkbait shapes and benchmarked commercial references. The key design decision was to decouple outer geometry from internal architecture, enabling repeated use of the same external shell with different internal frame layouts and ballast configurations. CAD data for the external body was converted into positive thermoforming tools, while separate parameterised models defined the internal “cage” structures and through-wire harnesses.

Internal frames were designed as 3D-printed components that locate and constrain lead weights at discrete positions, provide a defined path or groove for the stainless-steel through-wire, and generate bonding land to improve shell alignment and sealing. Examples include lattice cages with dedicated channels for the harness and recessed volumes for ballast.

3.2 Tooling Manufacture and Surface Conditioning.

Thermoforming tools were manufactured additively from PLA using FDM printers (e.g. Ultimaker 3, Bambu Lab P1S). Typical print configurations used 0.4 mm nozzle diameter, 0.2 mm layer height, 15 % infill and grid patterns, in some cases with adaptive layer heights around strongly curved lure contours to improve surface resolution.

After printing, tools were drilled with 2 mm vent holes along critical contour lines to make a vacuum evacuation possible. Tools were then mounted on wooden carrier plates and sealed at the base using aluminum tape or equivalent to avoid leakage.

In one group, a partial surface finishing was performed, sanding and local sealing of one half of a 3D-printed tool with cyanoacrylate, showing visibly improved surface quality on the formed part compared to the untreated half [18]. This corroborates general thermoforming guidance that layer-based tooling often requires finishing to remove print artefacts and improve vacuum contact.

Fig. 2. Surface finishing by sanding and coating (r), result (l) [18].

3.3 Thermoforming of Shell Halves and Process Parameters.

Thermoforming was carried out on a platen thermoforming machine Illig UA 100Ed ((ILLIG GmbH) in the plastics processing laboratory. PETG sheets with nominal thickness 0.75 - 0.8 mm were clamped in a frame and heated from both sides before positive forming over the printed tools. Representative process parameters, derived from multiple project configurations, are summarised in Table 1.

Table 1. Process parameters for thermoforming process [**18-22**].

Material	PETG sheet, thickness 0.75–0.8 mm	
Heater settings (temp.)	Upper heater: 3 zones at 420 °C	Lower heater: 3 zones at 360–380 °C
Heating time	17–18 s per cycle	
Pre-blow time	activation after 0–0.5 s	duration approx. 0.5 s
Vacuum delay and duration time	vacuum applied with ca. 4 s delay (active during forming phase)	
Cooling time	6–11 s depending on group and tool design	
Demoulding air time	5–10 s	

The total cycle time for thermoforming process was in the range of 30 and 45 seconds.

Twelve or more matching halves were typically produced per configuration, allowing for multiple assembly variants per outer shape [19]. After forming, shells were trimmed and their joint edges lightly sanded to increase straightness and contact area for subsequent bonding.

3.4 Manufacture of Internal Frames and Weighting Systems.

Internal frames were fabricated using FDM 3D printing in PLA, with grid infill and local thickening in regions contacting the shell or carrying weights. Designs evolved from simple weight holders to more integrated cages that span the lure length, captured the through-wire harness in a dedicated groove and provided multiple chambers for discrete lead spheres or cylindrical weights.

In several variants, weight layouts were explicitly documented and tuned (e.g. combinations of 5-6 mm lead balls at defined longitudinal distances) to achieve different static buoyancy and trim angles while preserving constant outer geometry [20]. The internal cage was also used structurally to bridge front and rear hook positions, better reflecting the tensile load path expected during fish strikes and retrieval.

3.5 Assembly and Joining - Practical Observations and Literature Context.

Assembly comprised the integration of four key elements: thermoformed shells, internal frame, through-wire harness and ballast. The stainless-steel wire was bent into a continuous harness with eyelets at the front (line attachment) and at bottom and rear (hooks), then routed through the cage groove to ensure load transfer along the full lure length. Weights were inserted into cage chambers according to the desired mass distribution, and the combined cage–wire assembly was placed into one shell half before closing with the second.

Multiple joining strategies for the shell halves were experimentally evaluated like thermal spot welding with a soldering iron (local melting of the PETG at the joint line), cyanoacrylate bonding on a butt joint, elastic automotive windscreen adhesive (polyurethane) in the joint region, silicone sealant injected into a designed peripheral groove.

Thermal spot welding was found to be difficult to control on 0.75–0.8 mm shells. Local overheating caused groove collapse, inconsistent seam formation and in some cases, re-opening of previously sealed regions when subsequent spots were added. This aligns with general guidance that fusion welding of thin thermoplastic sheets is highly sensitive to temperature, pressure and joint geometry, and that repeatable welds require carefully designed joint features such as energy directors, shear joints or tongue-and-groove interfaces - features typically designed into injection-moulded parts, but not present on simple thermoformed edges [16, 17].

Cyanoacrylate bonding of simple butt joints yielded initially watertight seams, but exhibited brittleness under flexure and tended to crack along the joint when the lure body was slightly deformed, leading to water ingress during tests. By contrast, elastic polyurethane windscreen adhesive maintained joint integrity under bending and impact and was judged to be the most robust option despite higher application effort and curing time.

Silicone sealant applied into a peripheral groove around the cage and wire harness also produced durable joints but introduced additional mass; in one group this unaccounted sealant mass significantly increased lure weight and required additional balancing [19].

Fig. 3. Joining of lure sample: model of two halves (ur), wire harness (ul), cage, weights, harness, lower shell and sealant (b) [18].

The single component PU glue (CAREAL10, Conel GmbH, Germany) has been used according to datasheet curing information after previous sanding and cleaning of the region, a strategy that has been applied also for all other joining strategies.

These experimental findings are consistent with industrial comparisons of adhesive bonding versus ultrasonic welding for plastic assemblies. Literature notes that ultrasonic welding, while fast and clean, requires minimum wall thickness, stiff support conditions, and specifically designed weld zones, and can be problematic for very thin or flexible parts. Under such conditions, structural adhesives often provide more tolerant and design-flexible joining solutions [23]. In the context of thin thermoformed PETG shells with limited weld land and prototypes produced on laboratory equipment, adhesive and hybrid adhesive–sealant strategies emerge as the most practical joining methods.

4. Experimental Demonstration and Observations

The proposed hybrid process was implemented across five student-led development projects at Berliner Hochschule für Technik, each producing thermoformed lure shells, additively manufactured internal frames, integrated wire harnesses and sealed assemblies. These implementations provide empirical evidence for process feasibility, limitations and operational effects not captured analytically.

4.1 Shell Forming Quality and Shape Consistency.

Across projects, thermoforming consistently produced geometrically faithful shell halves when PETG sheet thickness was 0.75–0.8 mm, and the printed tool surface was smooth enough to achieve vacuum conformity. The variation of material thickness of thermoformed halves has been measured with a micrometer screw in regions where it was possible, especially in joining regions. Therefore, some specimen have been cut using a bandsaw, but an overall thickness was not controlled.

Surface defects correlated strongly with tooling condition. Tools with untreated layer lines caused matte, faceted surfaces, while sanded and sealed tools yielded clearer and sharper detailing, confirming the influence of tool finish on shell fidelity [18]

Notably, multiple projects produced >10 matching halves per configuration, demonstrating repeatability sufficient for controlled design iteration [20, 21]. Dimensional repeatability and surface quality have only been monitored / qualified in terms of assembling and joining conditions. The interesting criteria here was to fit the internal structure into the thermoformed parts. No measurements have been applied, due to the uneven shape.

The number of achievable cycles largely depends on how long the time between the cycles (and thus the cooling period) is.

4.2 Assembly Accuracy and Compatibility.

The internal cage concept successfully constrained weight positions and provided mechanical registration for the wire harness, reducing assembly misalignment compared with freehand placement. However, wire harness deformation and tolerance mismatch occasionally prevented smooth seating of the cage, requiring re-bending of the harness or local removal of frame material [20]. This revealed the subtle but relevant finding, that the thermoformed shell accuracy was sufficient for repeatable alignment, but internal cages and harnesses introduced alignment errors when their fabrication tolerances were not strictly controlled.

The water thightness was tested different by different groups. Immersion into a bucket or bathtub were the most common methods, leaving the lures on the ground for up to 5 minutes and controlling for air bubbles during the test or introduced water droplets afterwards. This led to improvements during the manufacturing steps of later models, Nevertheless, transportation, handling in the water channel (depth up to 650 mm) and initial preparing steps caused leakage in some cases to previously waterthight housings. Especially brittle glues and to tight tolerated housings were affected.

Fig. 4. Manufactured lures [18-22].

4.3 Function Observations and Early Hydrodynamic Indications.

Functional testing was qualitative rather than quantitative. Completed prototypes were swum in test channel in KEE lab or small water bodies to assess gross buoyancy, trim and action. Two practical findings emerged as expected.

1. Mass distribution strongly influenced behaviour. Front-heavy configurations produced nose-down sinking; rear-biased setups produced tail sit; symmetric placements increased stability but reduced dive tendency [20].

2. Shell sealing quality influenced test outcomes. Seams that cracked or absorbed water altered buoyancy over minutes, suggesting sealing reliability, not shell geometry, limited hydrodynamic evaluation in these trials.

Thus, design iteration was demonstrably achievable, but systematically meaningful hydrodynamic performance evaluation requires improved seam sealing repeatability. Fig. exemplarily shows tested lures in KEE water channel.

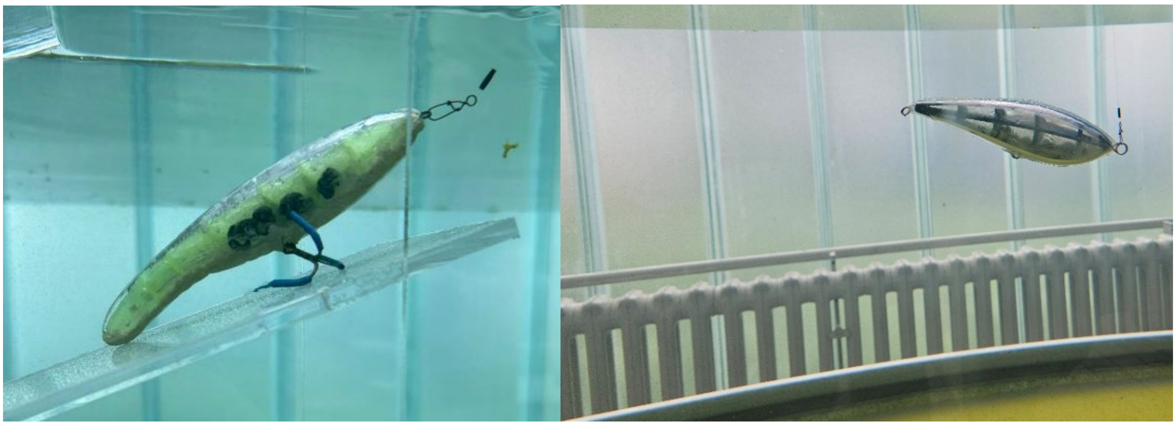

Fig. 5. Water tests of sample lures [21,18].

5. Comparative Assessment and Discussion

The hybrid thermoforming / AM process occupies a distinct position within the spectrum of lure development workflows. It offers rapid external replication similar to injection moulding, but with lower tooling burden and higher adaptability than moulded parts, while exhibiting stronger geometric consistency than manual forming or full-body AM in batch scenarios. The comparative assessment below synthesises findings from the experimental implementations and relates them to established prototyping strategies.

5.1 Comparison with Fully Additive Manufacturing.

Full-body AM providing seamless integration of external form and internal mass layout, but it suffers from surface roughness, tension-sensitive wall regions, and porosity-based leakage when thin shells are required. Several groups required sealing varnish or epoxy coating to make printed lures watertight, adding time and mass; notwithstanding layer-induced surface texture that remains visible even after finishing. In contrast, thermoformed shells inherently produce smooth, mould-like surfaces without finishing effort except trimming.

Build time also diverges significantly between approaches: printing 10+ full-body lures requires repetitive 6–20 hour print cycles depending on resolution, while thermoforming produced 12–20 shells in approximately one hour including heat-up, forming and trimming phases, followed by printing only internal cages. Thus, the hybrid method accelerates batch iteration where external shape is invariant and only internal structure varies.

However, full-body AM delivers precise internal integration and inherent sealing via material continuity, whereas the hybrid process revealed joining reliability as a critical failure mode. This indicates that thermoforming is advantageous where outer-shell replication dominates, but full AM retains benefits for one-off prototypes where geometry and sealing complexity are coupled.

5.2 Comparison with Manual Crafting.

Manually carved wood or resin prototypes exhibit high variability between nominally identical bodies, especially regarding symmetry, cross-section precision and hinge continuity. This variability masks the effect of small internal design changes, reducing interpretability of performance differences. The hybrid process therefore provides geometric repeatability across sample sets, allowing clearer attribution of behavioural changes to internal variables.

Moreover, manual crafting typically embeds weights by drilling and backfilling with lead shot or poured alloys, limiting reversibility and forcing destructive modification to test alternative mass layouts. The thermoforming approach, by contrast, enables non-destructive reconfiguration because ballast compartments are located within replaceable internal cages. This supports iterative design logic, sensitivity testing and exploratory exploration of mass placement strategies; activities poorly suited to hand-built wooden lures.

5.3 Comparison with Injection Moulding.

Injection moulding remains the major production method for surface quality, dimensional control and integral joint design. Commercial lures benefit from moulded tongue-and-groove seam geometries, designed welding interfaces and local rib reinforcement. However, industrial sourcing reports highlight tooling costs and lead times spanning weeks, which are disproportionate when design parameters such as internal weights or alignment features change frequently. The hybrid process preserves injection-moulded appearance while avoiding these upfront commitments.

An alternative to this would be injection moulding with an exchangeable tool. However, this requires a flexible core tool. This requires a one-time high investment.

Nevertheless, injection moulding offers predictable sealing integrity, whereas hybrid lure sealing proved fragile without carefully selected adhesives. This emphasises that thermoformed shells can approximate industrial styling but not yet industrial sealing robustness. In a development cycle context, this is acceptable; in production contexts, sealing and joint features would need redesign to mirror moulded construction logic.

5.4 Scalability Considerations.

From a scaling perspective, the hybrid process scales well in count but poorly in automation. Thermoforming can produce many shells per hour if labour is available for trimming and joining, but the assembly remains artisanal. Conversely, AM of internal cages remains scale-limited by print throughput, although multi-part nests or higher-output printers mitigate this effect.

Hence, the method behaves as a low- to mid-volume prototyping strategy but does not displace mass manufacturing frameworks; mirroring its use in other industries for pilot production, appliance housings and design studies.

5.5 Manufacturing and Design Implications.

The observed constraints reveal design implications useful beyond fishing lures:

1. Seam design will dominate prototype survivability. A repeatable joining concept (tongue-and-groove, lap joint, adhesive track) would materially elevate test reliability.

2. Internal frame tolerancing requires refinement. Misalignment arose not from shell variation but from cage–wire interfaces; thus cage design standards should match shell tolerances.

3. Thermoforming is best deployed when design variables lie inside the part, not in its shell. Where external morphology changes frequently, full-body AM may be superior; where outer shape is fixed and internal exploration matters, thermoforming is beneficial.

4. Replicability supports design research. Being able to hold exterior geometry constant while modifying ballast enables controlled testing unavailable to hand-built prototypes, positioning this process as a methodological tool for design science and consumer product development.

In summary, the hybrid approach demonstrates feasibility as a rapid, repeatable, mould-analogue prototyping workflow suitable for research and development settings where appearance uniformity and internal flexibility are more important than mass production robustness.

6. Summary and Outlook

This study proposed and demonstrated a hybrid prototyping strategy combining thermoformed PETG shells with additively manufactured internal frames for the development of hard-bodied fishing lures. Across five independent student implementations, the method consistently produced geometrically repeatable external housings and allowed systematic manipulation of internal mass distribution while maintaining constant outer morphology. This capability constitutes a practical development advantage over manual crafting, and a throughput advantage over full-body additive manufacturing when batches of external shapes are required.

The experimental results confirm feasibility but also identify joining reliability and internal assembly tolerancing as principal bottlenecks. Shell sealing integrity rather than shell geometry limited hydrodynamic observability, and tolerance incompatibilities between printed cages and bent wire harnesses contributed more to alignment variation than thermoforming variation. In near future, further measurements must be undertaken to examine dimensional repeatability and surface quality of the thermoformed shells, especially over the number of replicas, to exclude these effects from possible differences in swimming behaviour.

Comparative assessment shows that the hybrid method does not rival injection moulding in seam quality or weld integration, but it achieves injection-moulded visual fidelity at much lower tooling cost and with greater flexibility for iterative internal design. As a consequence, the process is most appropriately positioned as a pre-tooling development framework, effective whenever outer geometry is stable and internal configuration space is under investigation. Future research can build on these findings along several axes:

Joining engineering as design of lap joints, adhesive channels or tongue-and-groove interfaces suitable for thin thermoformed shells to enhance sealing reliability.

Integrated cage–shell tolerance design, parametric alignment features, snap-fit indexing or progressive wire fixing templates if adaptable to thermoforming, to reduce assembly misfit.

Hybrid tooling development, or the application of heat-resistant AM moulds to reduce finishing effort and improve shell surface resolution.

Quantitative behavioural studies I, proceeding with controlled hydrodynamic testing of lure variants produced under this process to examine whether the development efficiency translates into more interpretable feedback cycles.

Quantitative behavioural studies II, a comparison with injection moulded lures of same shape and weight distribution could give further insight into comparability of received results from this prototyping approach.

More broadly, the demonstrated process illustrates how thermoforming can be reframed as a research instrument for design iteration in consumer product contexts that traditionally leap prematurely to injection tooling or oversimplified hand prototyping. By enabling batch-wise replication of outer form with manipulable internal architectures, this approach contributes methodological value to prototyping research and small-scale product innovation.

Depending on extended lures testing scenarios the watertightness at higher pressures (approx. 1 bar) could be considered as well. It is mainly not necessary, as in lure testing, the specimen want’s to be observed and 10 m deep test facilities are rare.

The development process can be supported by using simulation of thermoforming process (e.g., with software Ansys).

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