# Localized Multi-Pass Thermoforming Through Robotic Manipulation

*A gesture-based approach to moldless multi-draft angle PETG sheet forming*

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**Abstract.** In contemporary architecture, the demand for complex geometric variability in building envelopes necessitates innovative and automated manufacturing processes. With building envelopes frequently constructed from thermoplastic sheets, thermoforming emerges as a rapid shaping technique with exciting design potential. However, traditional applications are constrained by reliance on single-use molds and their limited ability to produce complex shapes due to single-orientation draft angles required for mold release. This research explores a novel robotic thermoforming process that enables moldless, variable forming with multi-axis draft angles, creating unique design outcomes previously unachievable through conventional methods. A custom robot end-effector has been developed to allow localized, iterative heating and manipulation of recyclable PETG thermoplastic sheets adaptable to various sizes and boundary profiles. The integration of design and manufacturing is further enhanced by a simulation program developed in Grasshopper, enabling predictive modeling of the thermoforming process. Iterative thermoforming is demonstrated through the fabrication of a multi-panel prototype, showcasing unique multi-formed parts and qualitative visual and material effects. This research advances the design and fabrication of building envelopes, particularly in the application of thermoplastics, offering potential for innovation in automated manufacturing within architecture.

**Keywords.** Robotic Thermoforming, Computational Fabrication, Thermoplastic Manipulation, Thermal Control, Generative Simulation

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## 1. Introduction

Thermoplastics are utilized in a wide range of building applications, including roof and facade sheeting and window frame extrusions. The low cost, lightweight properties, recyclability, and formability of thermoplastic sheets make them advantageous for building envelopes, where self-weight, impact resistance and translucency are critical. While thermoplastics such as UV-resistant Polycarbonate are common in these applications, recycled Polyethylene Terephthalate Glycol (PETG), used in packaging and bottles offers an opportunity to mitigate microplastic pollution if designs can be developed to meet comparable performance requirements.

Thermoplastic sheets are typically heated until they reach their glass transition temperature (Tg) before being formed by pressing against a mold using either a vacuum, positive air pressure, or motion-based force. These traditional manufacturing methods rely on molds or dies to mass-produce identical parts. Such processes are efficient for repetitive production but inherently limit design flexibility. Mold-based thermoforming processes for sheet material are manufactured from a single-draft angle, limiting overhangs in formal outcomes whilst safeguarding the removal of the part from a mold without damage. This restricts the geometric complexity of thermoformed sheet products.

To address these challenges, flexible and sustainable thermoforming methods that align with more diverse and differentiated design possibilities are needed. This research develops an iterative, moldless robotic thermoforming process to create unique PETG sheet surface parts that embody multi-axis draft angles and ornamental qualities. Employing localized heating and robotic manipulation of PETG sheet material demonstrates how thermoplastic panels can be realized with greater levels of design complexity than is achieved with current industrial techniques.

### 1.1. STATE OF THE ART

While 3D software enables geometrically complex surface designs that consist of variably formed parts, such designs are challenging to manufacture economically using established thermoplastic forming methods. Conventional techniques use molds with vacuum, air pressure, or mechanical force, limiting geometric variability and increasing production costs.

One solution to this is through the employment of programmable molds, that support geometric variation. Swackhamer et al. (Swackhamer and Satterfield, 2017) and Fereos et al (Fereos and Tsiliakos, 2014) introduced adaptive mold systems, yet these remain constrained to the fixed dimensions, single-pass global heating, and the absence of robotic integration, limiting their ability to achieve intricate features.

Robotic thermoforming improved flexibility. Lublasser et al. (Lublasser et al., 2016) and Chen et al. (Chen et al., 2019) demonstrated localized forming. Chen’s use of a custom robot end-effector for localized forming and a separate heat gun for the heating process is notable but remains constrained by a single trajectory. Weissenböck (Weissenböck, 2015) applied robot by grasping a laser cut sheet with patterns and presses it against molds, controlling a variable deformation of depth and angle, but this compromises material continuity, limiting its use in water-resistant applications, such as the building envelopes and roofing.

Thermoforming feedback mechanisms have enabled greater control of the forming process. Chy et al.'s model predictive control (MPC) method with temperature sensors (Chy et al., 2011) and Marchal et al. applied data-driven methods to predict material thickness (Marchal et al., 2023), yet neither was integrated with robotic thermoforming. Jalilvand et al. (Jalilvand et al. 2024) integrated Virtual Reality (VR) and Mixed Reality (MR) for heat transformation simulation, but its application was limited to use as a user interactive interface for training operators rather than as part of closed-loop control thermoforming process.

Whilst these advancements, existing methods rely on global heating, non-iterative forming, and regular shaped boundaries, lacking closed-loop feedback. Current research has not demonstrated capabilities in manipulating heated PETG sheets using diverse robotic trajectories to form parts with more than one draft angle, while the integration of temperature control, simulation models, and robotic tool path optimization remains underexplored. This research addresses these gaps by developing a closed-loop system that integrates heating, sensing, and parametric robotic manipulation with simulation-driven workflows, enabling a scalable thermoplastic fabrication approach capable of producing complex and variable geometries, that may provide future utility in building envelope applications.

## 2. Method

A closed-loop approach to iterative, multi-pass localized robotic heating and forming of PETG thermoplastic sheets was developed and evaluated for its ability to produce custom-formed parts that embody ornamental features derived from several differently orientated draft angles. A simulation model was also developed and evaluated against physically manufactured parts. The approach integrates robotic heating and forming with real-time temperature monitoring and simulation-based prediction.

### 2.1. ROBOTIC FABRICATION

#### *2.1.1. Experimental Setup*

We conducted four progressive experiments to develop an efficient robotic thermoforming process:

1. **Global Heating & Manual Forming:** PETG sheets (12" x 12") were heated using a heat mat (4–5 cm offset) to determine optimal heating times and forming techniques, with the sheet maintained in a horizontal orientation.
2. **Global Heating & Robotic Forming:** Forming paths from manual experiments were converted into robotic routines. PETG sheets (12” x 24”) were subjected to two cycles of global heating and robotic forming.
3. **Localized Heating & Manual Forming:** A heat gun was manually controlled to test targeted heating on vertically fixed PETG sheets. Six heating and forming paths were examined to establish optimal parameters.
4. **Localized Robotic Heating & Forming:** Building on the previous experiment, a

dual-head robotic end-effector was developed to combine heating and forming in a continuous, iterative robotic process.

The final setup included an ABB IRB 4600-60 robot with a custom dual-head end-effector incorporating a 120V, 12.5A (1.5 KW/h) heat gun, and a forming tool. A PETG sheet was secured in a laser-cut timber frame, as shown in Figure1-a, and toolpaths were generated in Rhino3D's Grasshopper and exported to ABB Rapid code via the Grasshopper plugin Visose Robots.

### *2.1.2. Workflow*

The robotic thermoforming process follows a seven-step workflow, integrating heating, sensing, forming, and simulation:

1. **Dual-Head End-Effector:** A custom end-effector was mounted on the ABB IRB 4600-60 robotic arm. Two tool center points (TCPs) were calibrated, one for localized heating and the other for forming activities.
2. **Temperature Monitoring:** An infrared sensor was incorporated into the end-effector, enabling closed-loop temperature control for accurate localized heating.
3. **Tool Path Generation:** Parametric heating and forming paths are defined in Rhino3D's Grasshopper, and exported to ABB robot-readable RAPID code.
4. **Sheet Boundary Frame:** A PETG sheet was clamped to a laser-cut plywood timber frame, allowing for non-rectangular panel shapes to be interchanged during a multi-panel robotic manufacturing workflow.
5. **Material Simulation:** A physics-based simulation model was developed in Rhino3D's Grasshopper to predict sheet behavior during forming. Results were evaluated against fabricated parts.
6. **Multi-Pass Forming:** Sequential heating and forming programs were executed to achieve iterative localized thermoforming on a single sheet.
7. **Robotic Milling:** Each panel was trimmed to its final shape using an HSD ES 929 electro-spindle with a 1/4" end mill. Toolpaths created in Rhino3D's Grasshopper.

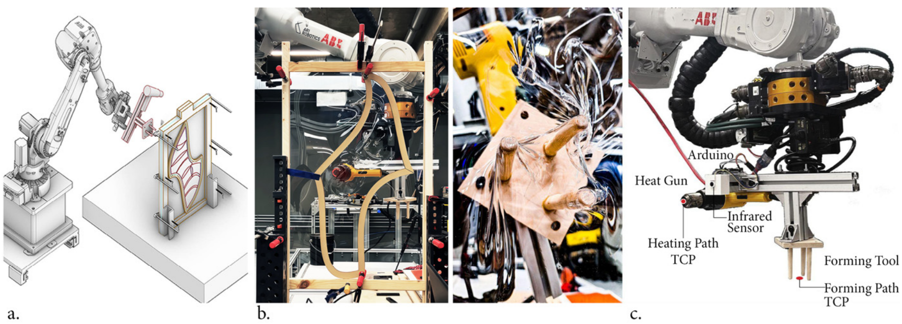



Figure 1. (a) Experimental setup with ABB robotic arm (b) Robotics heating and forming process photos (c) dual-head customized heating and forming end-effector.

### *2.1.3. Multi-End-Effector Design*

A custom-developed dual-head end-effector tool integrated a heat gun for localized heating and a three-pronged profile forming tool similar to those developed by Chen et al (Chen et al. 2019) that is used for manipulation tasks, as shown in Figure 1-b, c. Both attachments required a unique calibrated tool center point (TCP). The end-effector also incorporated an infrared sensor for temperature monitoring and an Arduino-based holding case. The Arduino microcontroller processed sensor data and transmitted it directly to an offboard computer via a data cable. The heating operation would cease on receipt of a temperature reading above 135 deg C.

## 2.2. SIMULATION PROGRAM

A material physics simulation model was developed in Rhino3D's Grasshopper using the Flexhopper plugin to predict the thermoforming result. It allowed for design prototyping and evaluation prior to fabrication. The model integrated four key inputs: heating tools and heating region's geometric profiles, the geometry of the sheet panel to be formed, forming tool paths, and the PETG sheet material's properties, as illustrated in Figure 2-a. The simulation modeled iterative heating and forming operations across different localized regions on a single mesh geometry, as depicted in Figure 2-b. The program was validated by comparative analysis of digitally simulated and physically fabricated prototypes, as detailed in this paper's Results.

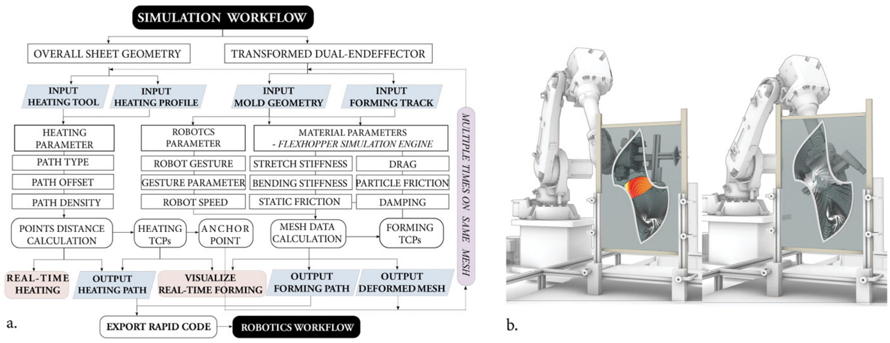



Figure 2. (a) Simulation Workflow (b) Simulation showing the anticipated results of the robotic parameters utilized in the experiment.

## 2.3. PROTOTYPE DESIGN AND VALIDATION

To evaluate the forming potentials of the method for architectural applications, we fabricated a multi-part prototype with an aperiodic tiling pattern (generated via Grasshopper's plugin Parakeet). Each panel's complex form was tested in simulation before robotic fabrication. The process involved multiple cycles of localized thermoforming, refining geometric complexity and visual effects. Panels were trimmed post-forming to a specific non-rectangular boundary shape and maintained an aperiodic tiling assemblage pattern. This prototype validated the method's controllability, qualitative design potential, and simulation accuracy.

## 3. Results and Discussion

### 3.1. METHOD VALIDATION AND EXPERIMENTS OVERVIEW

The robotic thermoforming method and workflow were developed through four progressive experiments and evaluation of their results:

1. **Global Heating & Manual Forming**: Horizontally orientated PETG sheets (12" x 12") were heated using a heat mat. This resulted in the glass transition temperature (Tg, 135°C) being reached between 5–6 minutes.
2. **Global Heating & Robotic Forming**: PETG sheets (12” x 24”) were subjected to two cycles of global heating and robotic forming. Initial heating to 135°C took 8m53s, with reheating requiring 4m13s. However, reheating caused up to 30mm of deformation and collapse, compromising the integrity of the initial thermoformed features, as depicted in Figure 3.
3. **Localized Heating & Manual Forming:** To mitigate deformation from global heating, a heat gun replaced the heat mat. Six manual heating and forming paths were tested, with deformations occurring only within heated zones. Overlapping heating reinforced shaping without collapse. Key parameters included a 1m30s heating time, 0.5–1 cm heat gun offset, a forming arc of up to 12 cm with a pushing depth of 2–4.5 cm, and with tilting angle ranging from 0° to 90°.
4. **Localized Robotic Heating & Forming:** Building on the previous experiment, a dual-head end-effector was used to combine heating and forming in a continuous robotic process. This setup reduced the total forming time by 60% while enhancing precision and repeatability. Five repeatability tests confirmed consistency, with an average deviation of 1.61 ± 1.18mm (~3% of panel height), as shown in Figure 4. Various heating and forming paths were characterized, as shown in Figure 5. Heating paths included Linear, Spiral, and Arc. Forming paths combining gestures like Tilting, Pushing, Translation, and Rotation. This established a flexible robotic automation workflow that had specific design effects.

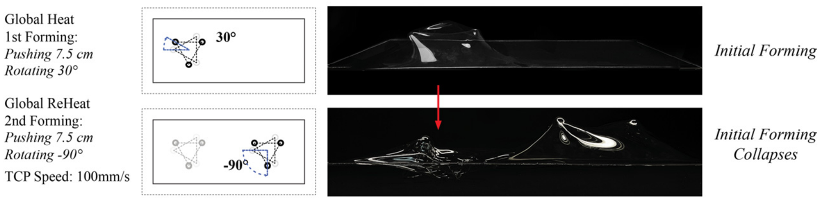



Figure 3. *A deformation collapse of 30mm occurs when global reheating is applied.*

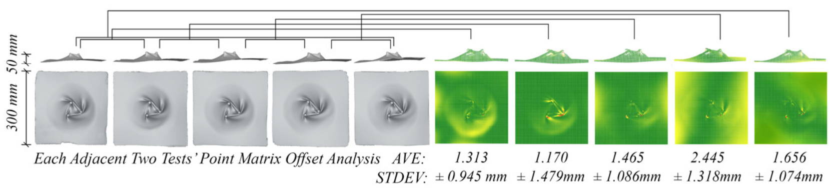



Figure 4. Repeatability Analysis: Conduct five replicates, adjacent tests paired for analysis.

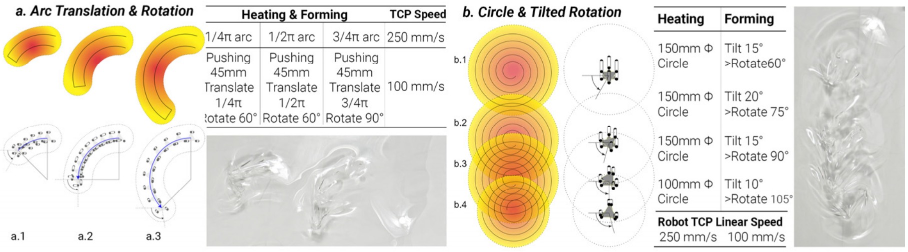
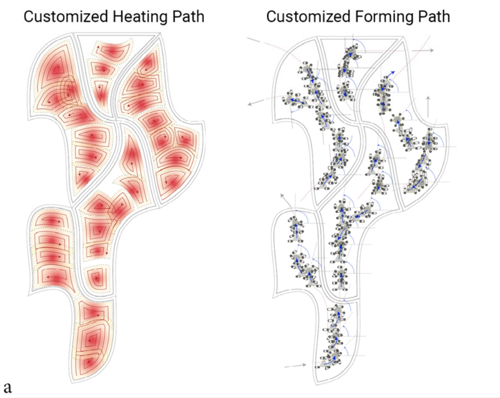



Figure 5. Experiment 4: Different types of heating and forming tests and manipulation parameters.

## 3.2. PROTOTYPE DESIGN AND ASSEMBLY




| Heating Specification | | | | | Robot Specification - 4600 ABB | | |
|---|---|---|---|---|---|---|---|
| Parameter | Voltage (V)<br>120 VAC | Current (I)<br>12.5 amp | Power (PkW)<br>1.5 KW/h | Frequency (I)<br>60 Hz | TCP Orientation<br>180 degree/s | ExtAxis Linear<br>5000 mm/s | ExtAxis Orientation<br>1080 degree/s |
| **Time and Energy Consuming of Each Panel in Prototype** | | | | | | | **TCP Linear Speed** |
| | **Panel 1** | **Panel 2** | **Panel 3** | **Panel 4** | **Panel 5** | **Total** | |
| **Heat Energy** | 0.288 kW·h | 0.252 kW·h | 0.252 kW·h | 0.252 kW·h | 0.108 kW·h | 1.152 kW·h | |
| **Heating** | 12’ | 10’30“ | 10’30“ | 10’30“ | 4’30” | 48’ | 250mm/s |
| **Forming** | 1’20” (8*10”) | 1’10” (7*10”) | 1’10” (7*10”) | 1’10” (7*10”) | 30” (3*10”) | 5’20” | 100mm/s |
| **Wait** | 8’ (8*1’) | 7’ (7*1’) | 7’ (7*1’) | 7’ (7*1’) | 3’ (3*1’) | 32’ | / |
| **Calibration** | 10’ | 10’ | 10’ | 10’ | 8’ | 48’ | / |
| **Milling** | 3’ | 3’ | 3’ | 3’ | 2’ | 14’ | 25mm/s |
| **Total** | 140’40” | 31’40” | 31’40” | 31’40” | 18’ | 147’20” | / |

b

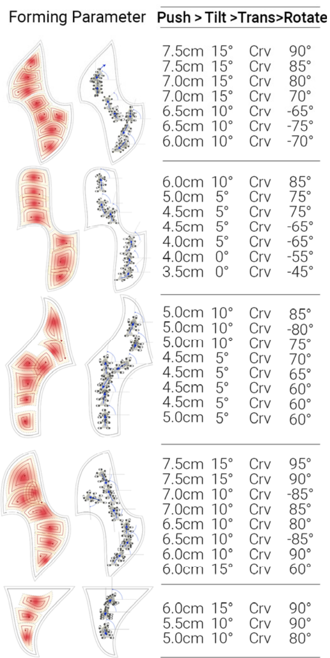



Figure 6. (a) Prototype Localized heating paths and Forming paths (b) Time and energy consumption of each panel (c) Parameters Catalog of Each Panel

A multi-part PETG prototype (1.6 m×0.8 m) was fabricated using the developed methods from experiment 4. The prototype comprised five custom-shaped sheets, each undergoing 5–7 iterative heating and forming operations with different robot toolpaths as shown in Fig 6-a. Adjacent regions of robotic manipulation had overlapping effects, while manipulative forming operations embodied variations in tilt angle, rotation, and trajectory that partially aligned with the boundary profile of each panel. The deformation followed graduated parameters aligned with each panel’s boundary profile, as shown in Fig 6-c.

Data on the entire prototype's manufacturing process was recorded and resulted in an overall work-cell sheet calibration time of 48 min, an overall heating time of 48 min, a shared forming time of 37 min 20 s, and a milling time of 14 min, as shown in Fig 5-b. Relative to the global heating method in experiments 1-2 which used a 120V, 12.5A heat mat that required 8 min and 53 s to heat one sheet, resulting in 12.8 KW of energy consumption, the final developed method from experiment 4 offers a considerable improvement in energy consumption – using the 120V, 12.5A (1.5 KW/h) heat gun for 1.5 min to heat one forming area resulted in a total of 0.05 KW of energy expenditure.

The multi-part PETG prototype illustrated the potential of the localized forming method to create custom-shaped panels with unique ornamental and optical properties, as illustrated in Fig 7. The integrated workflow, combining heating, sensing, and multi-pass forming operations with edge trimming, provided a scalable approach for thermoforming in architectural applications. The optical characteristics of PETG, such as translucency and refraction, further enhanced the aesthetic appeal of the panels, making them ideal for building envelopes requiring differentiation in geometry or visual effects and offering substantial benefits in its application for building envelopes.

a. b. c.

Figure 7. (a) Physical Prototype displayed as an installation. (b, c) Close-up photos capturing the ornamental-like qualities achieved through various draft-angles.

## 3.3. SIMULATION VALIDATION

A simulation workflow was developed to predict robotic thermoforming results and guide design development prior to fabrication. To assess its accuracy, 3D-scanned PETG sheets using Revopoint MIRACO Pro scanner with 48 megapixel resolution were compared with simulated models. AESUB Blue 3D Scanning Spray was used to enhance the visibility of the sheets during scanning. A section through a scan model is provided in Figure 7, capturing several orientations of draft angles achieved through the forming method. These geometries would be difficult to replicate with reusable mold, which typically requires destruction for mold removal.

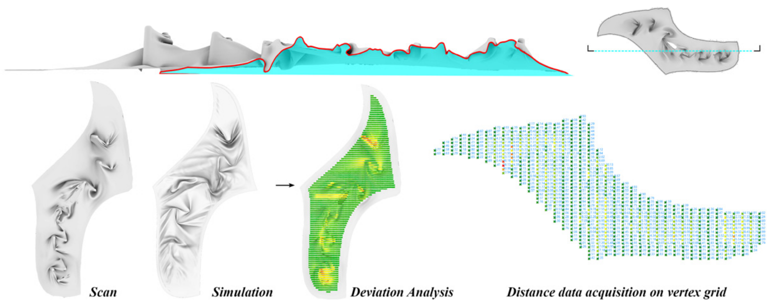



Figure 8. 3D Scanning Analysis and Quantitative Analysis of Vertex Deviation

To evaluate the simulation method, 3D scan results were compared to simulated models. Height differences at corresponding points between the two surfaces were assessed in Rhino3D's Grasshopper, as shown in Figure 8, revealing an average deviation of 10.34 ± 8.33 mm. Whilst this is not sufficiently accurate for industry applications, for the forming of a sheet surface with bounding dimensions of 750mm x 340mm x 75mm, the error was in the range of 1.37 – 13.7% relative to each axis, indicating the simulation provided a sufficient proof of concept for further refinement. The model effectively replicated softened PETG behavior in the multi-cycle robotic thermoforming process. However, forming effects with greater deviations indicate the need for refinement in the elastic properties of the simulation surface. Additionally, the highest deviation points suggest an offset discrepancy, likely due to insufficient modeling of heat transmission, cooling, and re-solidification, potentially causing spring-back when the tool retracted from the soft, cooling PETG sheet.

## 4. Conclusion

This research introduced a localized robotic thermoforming process that overcomes limitations in single draft angles embodied in established methods. PETG sheets were shaped into variably formed panels with multiple draft angles, unattainable through reusable molds. The approach enables mass-customized fabrication of thermoplastic panels with significant geometric variability. By integrating parametric design, robotic control, and iterative forming with sensor feedback, PETG sheet forming capabilities have been enhanced to produce additional geometric complexity, while the moldless process reduces material waste, addressing demand for customizable, sustainable fabrication in building manufacturing. The multi-part PETG prototype and its approximation in material-physics simulations demonstrate potential for building envelope applications. Additionally, the observed increase in stiffness and flexural strength of the PETG panels after manufacture suggests possibilities for investigations that might enable an enhanced spanning capability in formed sheets, potentially offering a reduction in sub-framing requirements in building envelope applications.

Future research can refine these developments by evaluating post-forming material stiffness, improving forming tool durability, enhancing simulation accuracy, and exploring alternative thermoplastics such as polycarbonate. Additionally, the use of multiple robots for concurrent operations could improve efficiency and scalability, supporting broader adoption in industrial applications.

In conclusion, localized robotic thermoforming is a fully automated workflow that integrates sensor-feedback on material temperature throughout manufacturing. This approach leverages the manipulation of heated plastic to form a final geometry, operating as a generative fabrication-based approach. The combination of local heating and manipulation enables iterative and scalable manufacturing that could be undertaken on much larger sheet dimensions, suggesting that with further development, the approach has great potential for large-scale thermoplastic sheet-forming applications, including building envelopes.

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