

# *Data-efficient determination of machine-specific process windows in thermoforming using the example of PCR materials*

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**ABSTRACT:** In an industrial context, process windows for thermoplastics in thermoforming processes are still often determined through time-consuming trial-and-error approaches. This results in increased effort when commissioning new machines, implementing new technologies, or substituting sheet materials. One key reason is the lack of methods that allow for efficient, process-related assessment of material behavior and a quantitative definition of a “target state” of the heated sheet in relation to geometry and process conditions.

In this study, we present the In-Situ Thermoforming Characterization (ITC) method as an application-oriented approach that enables format-independent evaluation of material behavior directly within the forming station of a thermoforming system. The method was successfully applied to a material substitution case, replacing conventional virgin polypropylene (PP) with post-consumer recyclate (PCR) — in this case, recycled PP (rPP) — in the production of a defined cup geometry. The results enabled the transfer of existing process knowledge from the virgin material to the recyclate, thereby accelerating material qualification. Based on the collected data, material behavior under process conditions could be mapped within the design space, making it possible to identify machine settings that deliver equivalent forming results in our test setup.

Overall, the method shows strong potential for efficient and precise determination of machine-specific process windows.

**Application:** The presented method offers a quantitative, practical comparison of material conditions for different materials during forming. This means that empirical values and data collected using a single material with one or more formats can be utilized for process optimization, such as material substitution across competing materials for thermoforming applications.

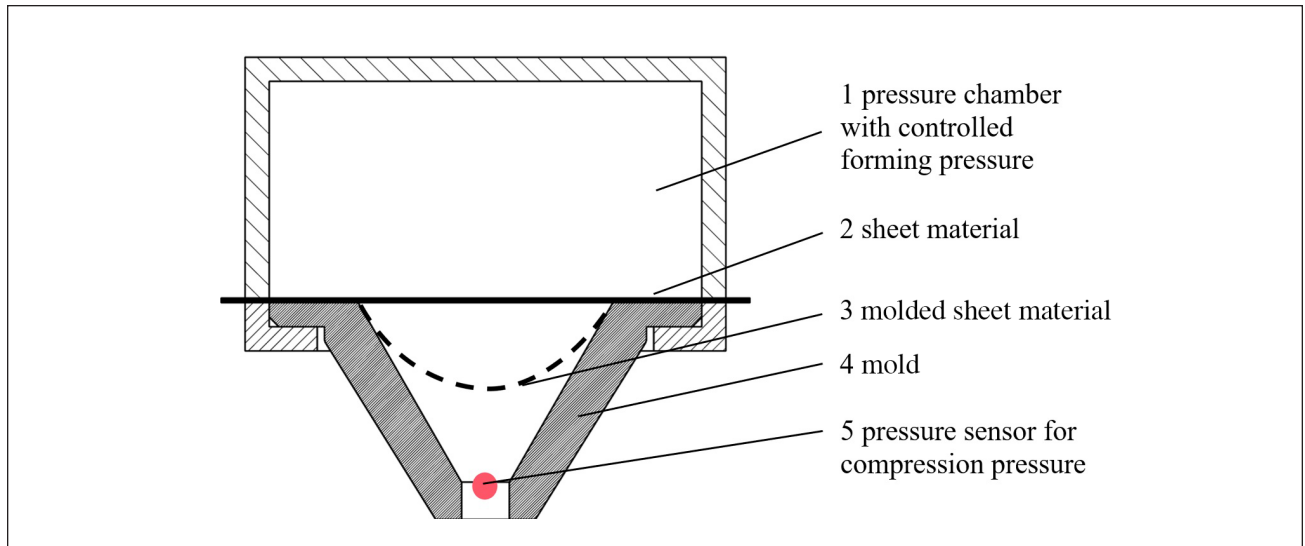
**A**ccurate process adjustment in processing plants requires a thorough understanding of material properties and influencing factors. Standard data-sheets for packaging materials often fall short in complex processes like thermoforming, typically providing only basic room-temperature characteristics and rarely including glass transition or melting temperatures. While supplementary characterization methods, such as hot tensile tests or differential thermal analyses, exist, they offer limited insights into thermoplastic processing, as material temperature and strain behavior continuously change during production. Existing models often rely on steady-state properties or are tailored to specific materials and machine configurations and thus fail to capture the dynamic nature of real-world production. Furthermore, heating methods, fluctuating cycle times, and climatic conditions are not considered. The method presented in this study proposes correlating an inline-measurable quantity, functioning as a soft sensor, to bridge the gap between transient material behavior, adaptable machine conditions, and forming quality in thermoforming.

## STATE OF THE ART

The setup of thermoforming processes still relies heavily on empirical knowledge to define machine parameters—especially for material heating—to meet quality standards. Heating occurs via radiant or contact methods over a fixed time determined by cycle time and heater configuration. Since cycle time is usually fixed for economic reasons, heater temperature or power settings remain the main control variables. In plug-assisted thermoforming, plug depth and forming air timing are also critical for part quality.

Machine-specific conditions such as insulation, heat shield design, sheet width, and heating zone geometry further constrain adjustability. Differences in preheating (e.g., with or without rollers) lead to varying initial material temperatures. These technical variances, combined with the material-dependent forming behavior of thermoplastics and product-specific demands, complicate process planning. Therefore, efficient evaluation methods to assess the compatibility of machine, material, and product design are of high industrial relevance. Scientifically, several approaches exist to characterize thermoplastic behavior and support its practical application.

# THERMOFORMING



**1. Draft of the experimental setup in a forming station of a thermoforming machine: 1 – pressure chamber with controlled mold pressure; 2 – heated sheet material; 3 – molded sheet material; 4 – conical mold without venting holes; and 5 – pressure sensor.**

For material characterization of surface-hardened polypropylene (PP), Prosser et al. integrated a 3D forming setup into the temperature chamber of a uniaxial tensile tester [1]. Standard climate chambers, including those for hot tensile testing, rely on convective heating, requiring 5–8 min for full temperature stabilization [1,2]. Such durations are incompatible with the short cycle times of industrial thermoforming, where radiation and conduction are preferred. As a result, discrepancies in material properties between laboratory and processing conditions — due to prolonged conditioning effects like polymer relaxation or moisture changes — remain a critical concern.

To replicate thermoforming-like stress and strain conditions, bubble inflation rheometers allow computational analysis of biaxial deformation in polymers and elastomers, improving simulation accuracy. However, the heating methods used differ from those in industrial thermoforming, limiting direct comparability [3].

González-Ausejo et al. assess thermoformability qualitatively by evaluating formed parts and using a square grid to visualize local elongation [4]. While common in industry, this method is limited to the specific format and equipment used, preventing a quantitative analysis of overall material behavior. For initial material qualification, standardized uniaxial hot tensile tests provide a more comparable and reliable benchmarking approach.

Moser presents a comprehensive analysis of thermoforming process operations and their impact on part quality [5]. Material behavior is monitored via plug-assist forming force, with stretching energy used as a feedback variable in inline control to adjust heating. This approach effectively stabilizes the process. However, as Martin et al. show, factors such as part and plug geometry, friction, temperature gradients, and system-specific design elements (e.g., piston seals) limit the transferability of results to other setups [6].

Mieghem et al. apply digital image correlation (DIC) to calibrate material models by optically measuring thermally induced sheet sag under radiant heating [7]. The method requires visual access and a standardized random pattern on the plastic surface. While effective under specific conditions, sag is influenced by web width, clamping, and transport mechanics, limiting data transferability across systems. The approach is not applicable in contact-heated setups.

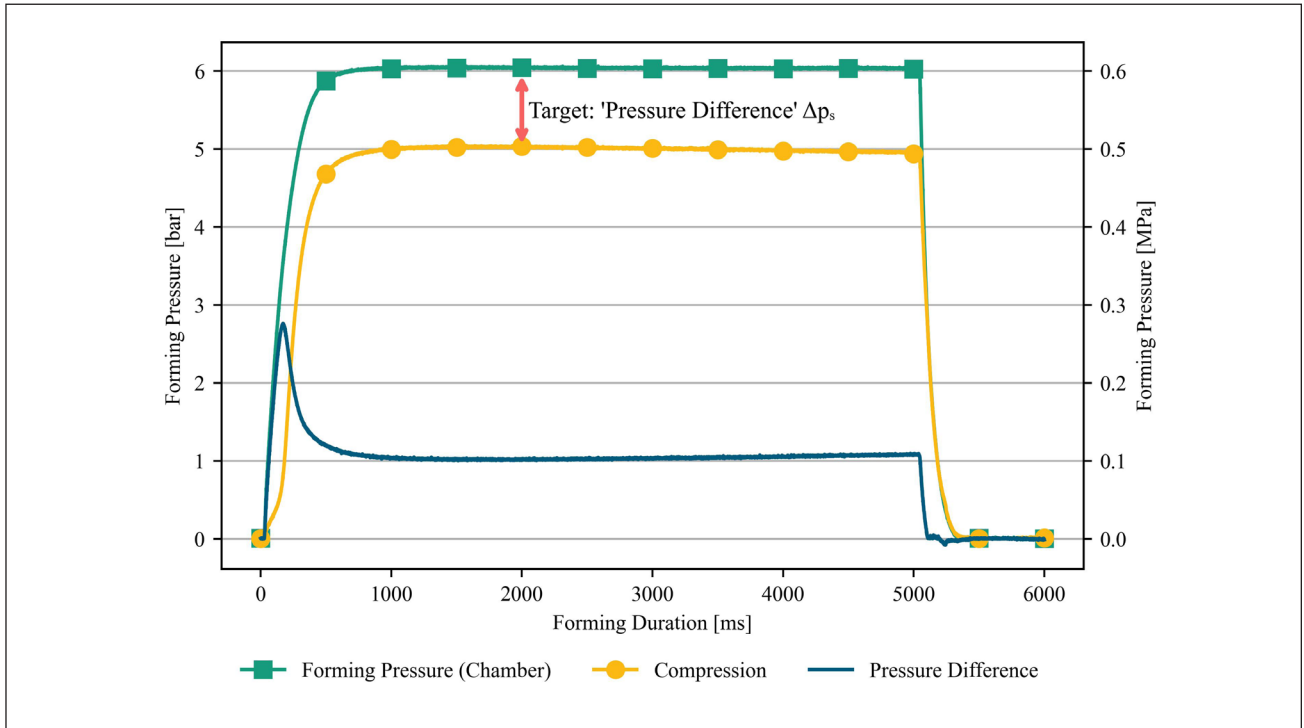
Current methods typically allow only basic comparisons of material properties under idealized, static conditions, limiting their use to preliminary exclusion criteria. As a result, assessing material suitability for specific machines and formats often depends on time-intensive trial-and-error. Simulations are also constrained by the difficulty of replicating real machine conditions. In light of rising regulatory demands, cost pressures, and the need to qualify recycled materials, efficient inline benchmarking is gaining importance.

## METHODS AND MATERIALS

### *In-situ Thermoforming Characterization (ITC method)*

The test setup that we want to introduce in this study is called the In-Situ Thermoforming Characterization (ITC) method and is designed to be integrable into any thermoforming system that operates with positive pressure. It allows for determining the material behavior after heating directly in the forming station and therefore evaluating correlations between the in-machine forming behavior and actual forming results. The process involves measuring the controlled forming pressure in the pressure chamber, as well as the compression pressure below the heated sheet material, in a specially designed mold that does not have vent holes (**Fig. 1**).

The conical bottom shape enables directional shaping into a dome shape. However, the lack of vent openings means that the compressed air generates a back pressure



**2. Exemplary time series of the variables mold pressure, compression pressure, and calculated pressure difference. The scales on the two y-axes have the same meaning and refer to the same data in the units bar and MPa.**

during the forming process that prevents the material from being fully formed into the lower cavity. As counterpressure and material stress oppose the forming force, the resulting pressure difference is assumed to reflect the sheet's temperature-dependent stress-strain behavior. Sensor data is recorded as a time series (**Fig. 2**) from which pressure difference characteristics are derived. This study focuses specifically on the static pressure difference ( $\Delta p_s$ ) measured after 2000 ms of forming time.

The underlying concept is that materials that exhibit similar behavior — i.e., time series of pressure difference in the ITC method — can be formed into equivalent geometries with comparable shape accuracy using the same tools. As wall thickness distribution is an important quality criterion in thermoforming, it is discussed later in this study.

The scope of this study is to introduce the method and its setup and give an example of how to use it to determine process windows of different materials for a specific machine configuration. Further work is needed to evaluate and proof the usability of this approach for other use-cases, especially in industrial environments and different machine configurations.

### Experimental setup

A physical test setup was integrated into the test station for thermoformed packaging, known as “MotiV”, at the Fraunhofer Institute for Process Engineering and Packaging (Fraunhofer IVV) in Dresden, Germany (**Fig. 3**). The mod-

ular design of the test setup enables reproduction of all thermoforming process steps using different technologies. Material heating is possible via radiation or contact methods. The forming unit supports vacuum and pressures up to 0.6 MPa (6 bar) and includes an independently controllable plug-assist holder.

To demonstrate correlations between ITC method outcomes and conventional forming results, a rotationally symmetric cup geometry was selected (30-mm depth, 65-mm opening diameter).

### Experimental design and evaluation procedure

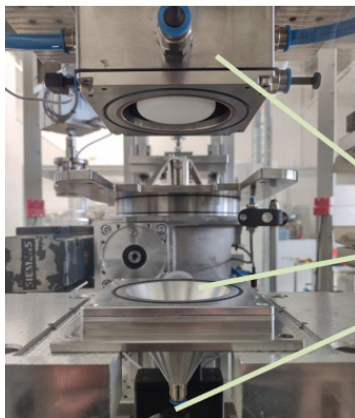
Data collection was conducted using stationary double-sided radiant heating with ceramic elements (maximum 800 W). Radiant element temperature and heating time were varied to analyze forming behavior. After ~1 s transport, the film was formed at 0.6 MPa (6 bar) for 5 s. These parameters applied to both ITC measurements and cup geometry forming tests. **Figure 4** shows 29 test points based on a space-filling design; an area in the lower left was excluded due to insufficient heating. Due to the stochastic distribution of points, this approach effectively maps material behavior across a broad test space.

We used six materials for the following investigation that are described in the following section. For each material and test point, the ITC method was used to calculate the static pressure difference,  $\Delta p_s$ , which was modeled and visualized in contour plots. The same test points were then used to evaluate the shape accuracy of the actual forming

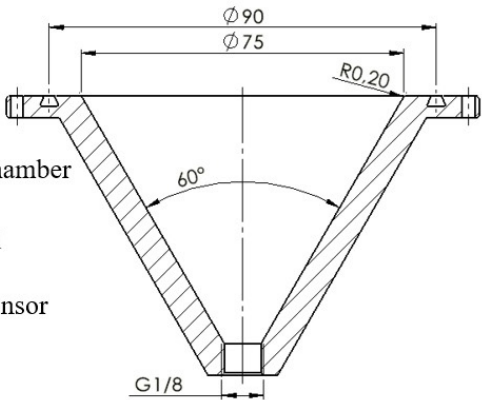
# THERMOFORMING



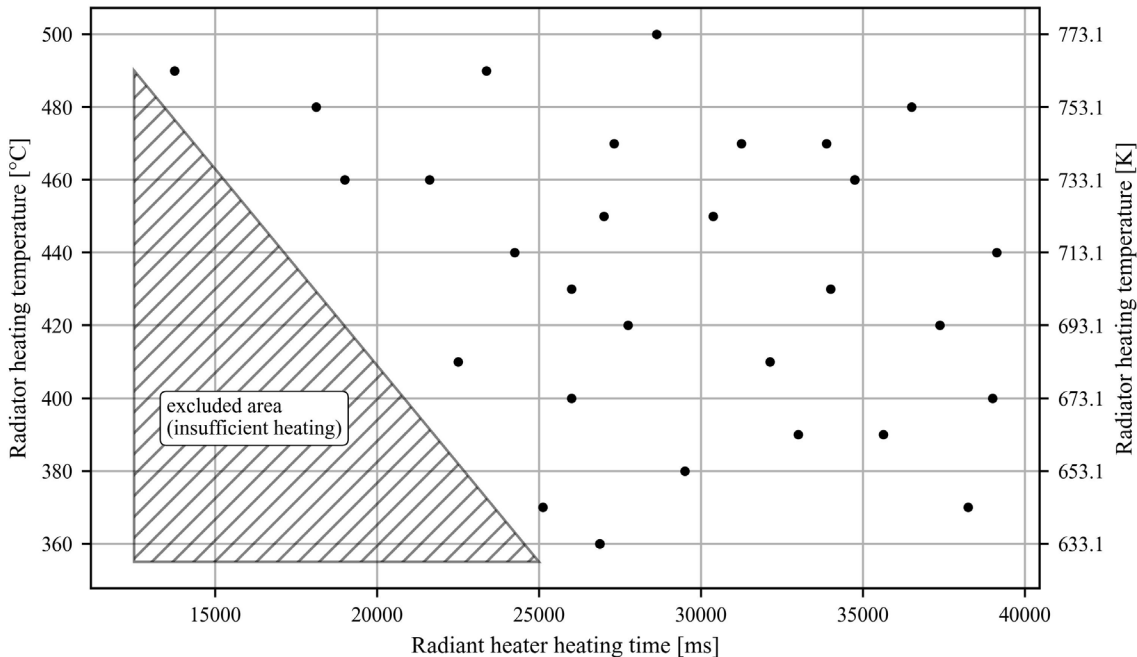
- Circular transport system for the sheet materials (clockwise)
- Radiant Heaters (both sides)
- Conductive Heaters (both sides)
- Forming Station



- pressure chamber
- conic mold
- pressure sensor



3. Test setup at the Fraunhofer IVV Dresden, along with a drawing of the conic mold.



4. Experimental design with the influencing variables heating duration and radiant body temperature. The scales on the two y-axes have the same meaning and refer to the same data in the units °C and K.

|     |                                                                                                                     |
|-----|---------------------------------------------------------------------------------------------------------------------|
| 1   | No molding.                                                                                                         |
| 2   | Low degree of molding; material defects such as brittle fractures possible.                                         |
| 2,3 | Sheet material reaches the bottom of the molded part; no representation of the wall area.                           |
| 2,7 | Wall area is represented; bottom radius is barely determinable.                                                     |
| 3   | Incomplete shaping of the bottom radius; bottom groove indicated but incomplete.                                    |
| 3,3 | Incomplete bottom radius; radius > 3 mm.                                                                            |
| 3,7 | Incomplete bottom radius; radius > 1 mm.                                                                            |
| 4   | Complete shaping of the cup geometry without detectable imprints of vent holes (desired).                           |
| 5   | Complete shaping of the cup geometry with detectable imprints of vent holes.                                        |
| 6   | Material is punctured at the locations of the vent holes; further melting and decomposition effects may be visible. |

#### *1. Ordinal scaling of the shape accuracy for the selected cup geometry.*

results for the selected cup geometry solely for the virgin material “PP-1”. Based on these forming results, molding quality is compared with the observations of the ITC method. Further information about the modeling procedure and model errors can be found in the Appendix.

For our purposes, the molding quality is determined via the complete representation of the cup geometry using ordinal scaling by assigning ascending numerical categories to the observable molding stages. The qualitative observations are categorized according to **Table 1**, and exemplary visualization is shown in **Fig. 5**.

#### **Materials**

We selected six polypropylene (PP) materials with a uniform film thickness of 800 µm for our tests. Five were produced under controlled laboratory conditions, including four post-consumer recyclates (PCR), in this case recycled PP (rPP), with 25%, 50%, 75%, and 100% recycled content, designated as PCR-0.25, PCR-0.50, PCR-0.75, and PCR-1.0, respectively. These were blended from PCR-1.0 and a virgin PP granulate used to produce the fifth film, referred to as PP-2. To benchmark against a widely used commercial reference, we included PP-1, a white virgin-grade film. In con-

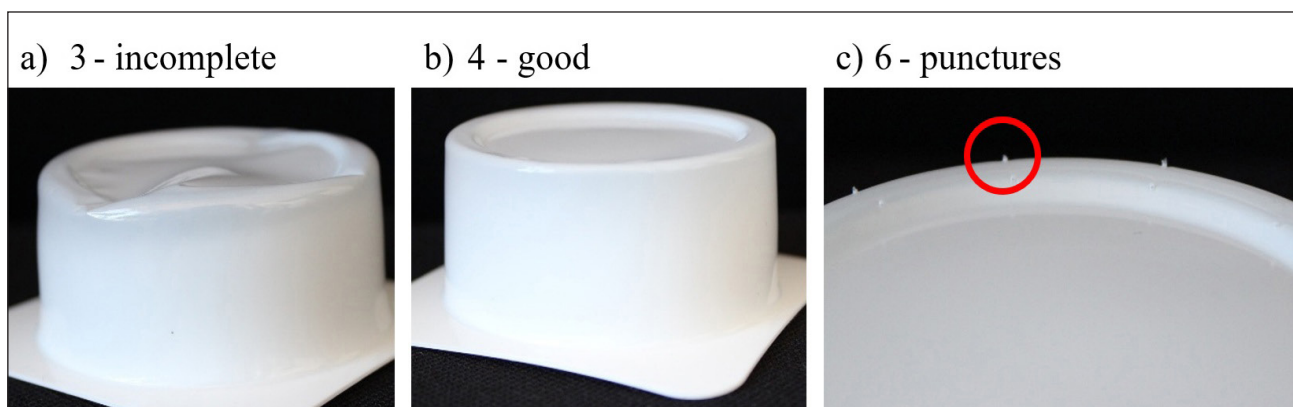
trast, PP-2 is translucent, while the PCR films appear increasingly opaque and greenish with rising recycle content. The PCR material originates from cleaned, unfiltered packaging waste processed via the German dual system, including both thermoformed and injection-molded sources.

The laboratory materials are illustrated in **Fig. 6**.

## **RESULTS AND DISCUSSION**

We define the process window as the set of parameter combinations — such as cycle time and heater settings — that bring the film to the appropriate thermoforming condition and result in high-quality parts. Poor selection of forming parameters (e.g., pressure, plug geometry, plug travel distance, and air cycling) can narrow, shift, or even eliminate this process window, making consistent and reliable production difficult or impossible.

While parameter optimization within the forming station is format-specific, our central hypothesis is that identical pressure differences, independent of the material, lead to comparable forming results under constant forming conditions. This would enable the transfer of an established process window from one material to another.

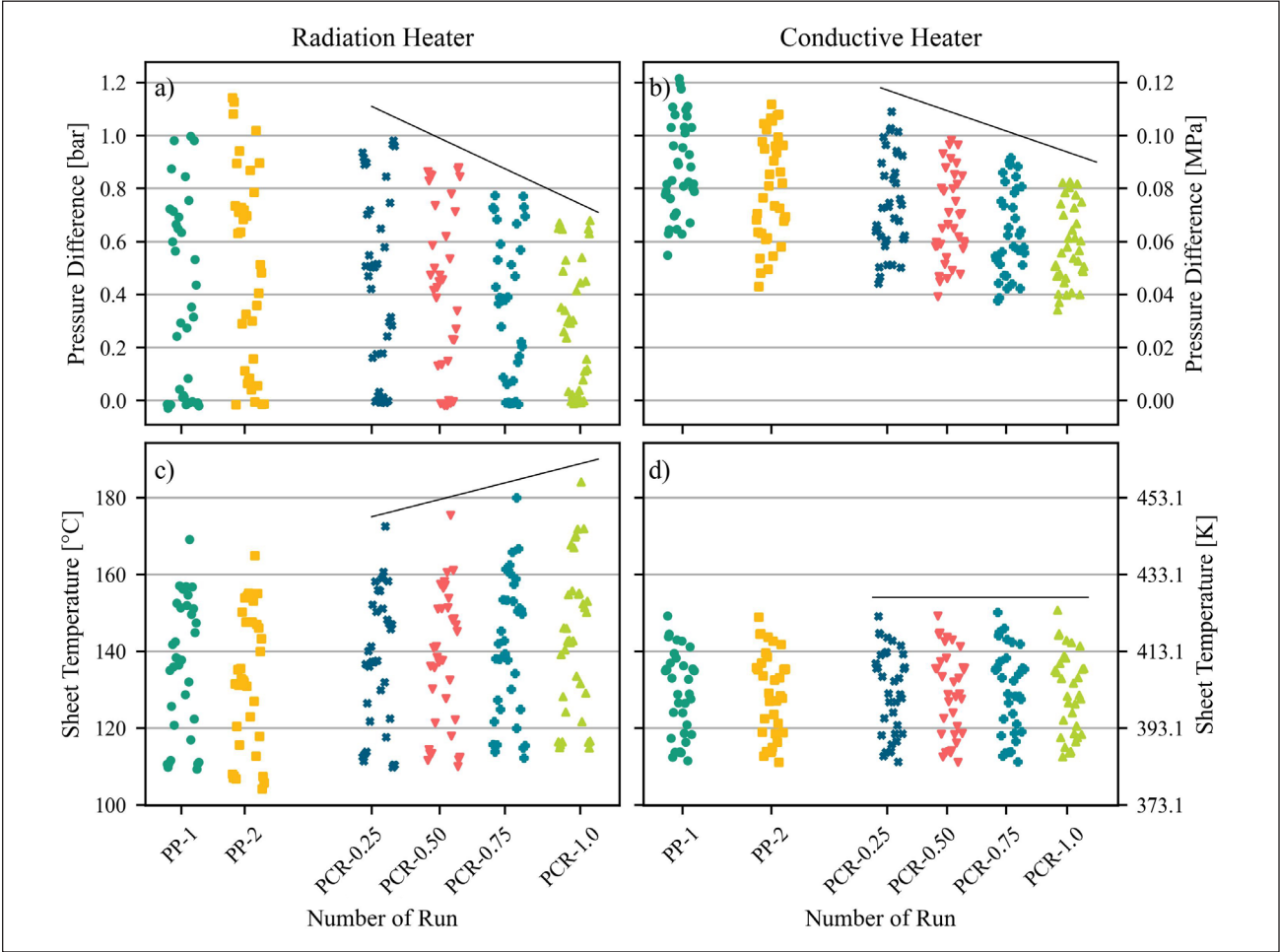


**5. Exemplary visualization for different molding stages according to ordinal scaling.**

# THERMOFORMING



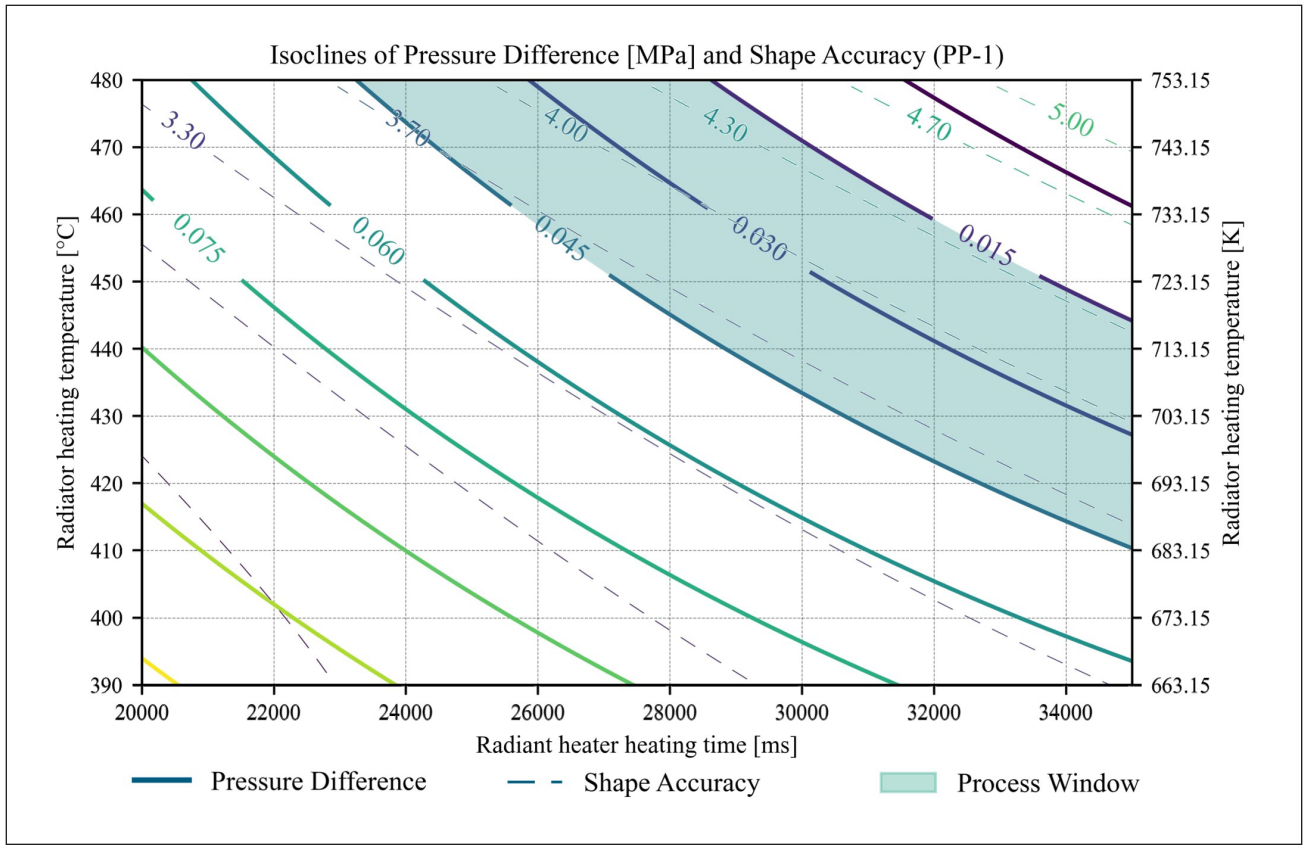
6. Laboratory materials used (PP-1 not shown).



7. Response-vs.-run plot for all tested materials and identical settings. The scales on the four y-axes have the same meaning and refer to the same data in the unit bar and unit MPa, respectively, °C and K.

For our investigations of the forming behavior, we selected heating parameters using the space-filling design described in the Experimental Design and Evaluation Procedure section. Since radiative heating is influenced by the material's emission coefficient, which depends on surface and color, the same settings do not ensure uniform heating

across materials. In **Fig. 7**, we compare the measured static pressure difference  $\Delta p_s$  and film temperature across the test runs. We observe that the maximum  $\Delta p_s$ , and thus the material's resistance to deformation according to the hypothesis of the method, decreases with increasing recyclate content (Fig. 7a), while the maximum temperature rises



**8. Comparison pressure difference and shape accuracy of the molded part without using a plug assist and estimation of the process window. The scales on the two y-axes have the same meaning and refer to the same data in the units °C and K.**

(Fig. 7c), likely due to changes in optical appearance. To decouple these effects, we conducted tests using conductive heating with a similar amount and structure of test points, allowing temperature control independent of emission properties (Fig. 7d). The trend of decreasing  $\Delta p_s$  with higher rPP content persisted (Fig. 7c), confirming the influence of recyclate proportion.

In the following, we will outline the scenario of a material substitution and discuss the respective steps using the proposed ITC method. In this example, PP-1 is the starting material to be replaced by PCR-1.0 for molding the cup geometry presented.

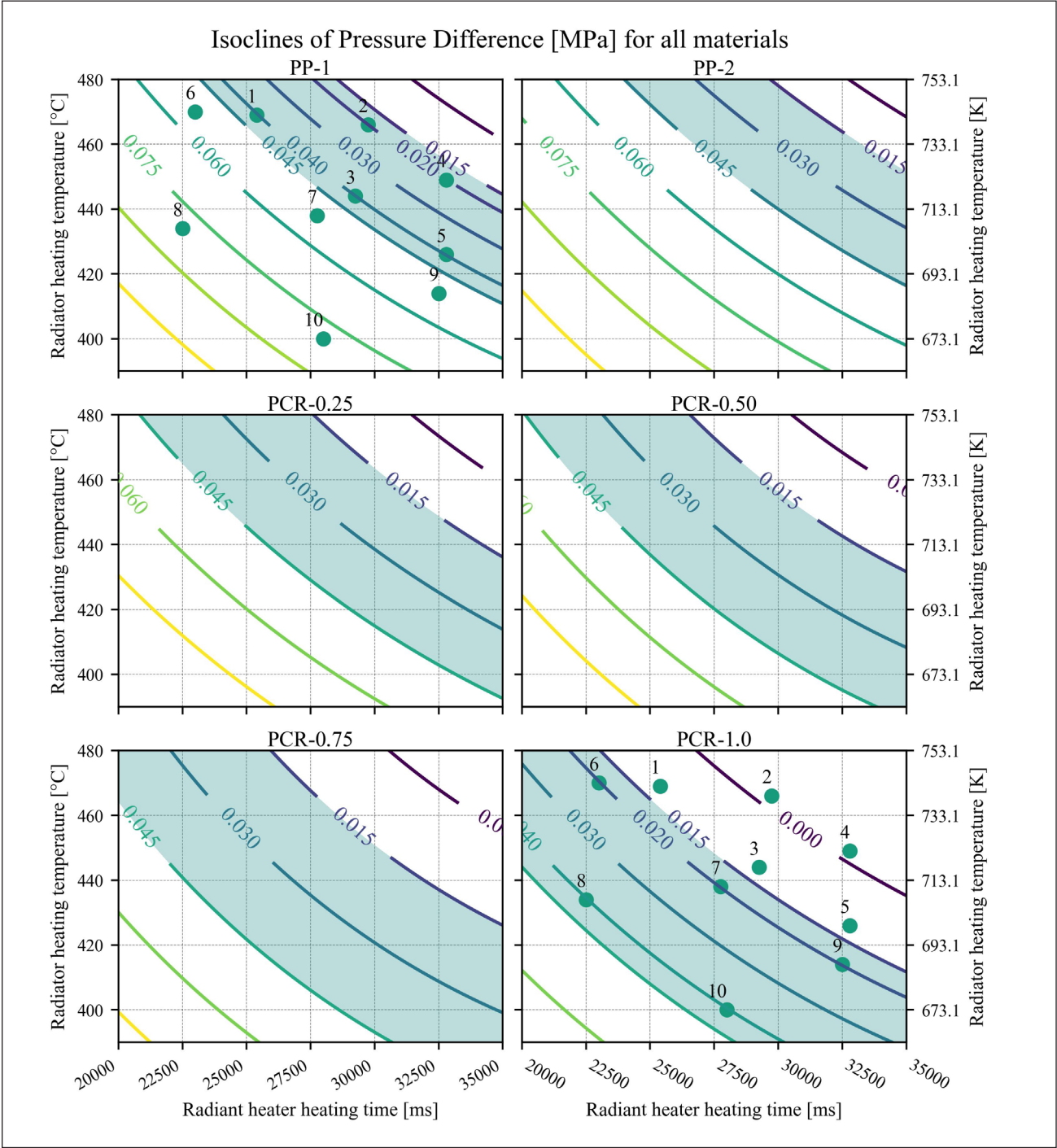
First, we model the relationship between heating duration, radiator temperature, and the target variable  $\Delta p_s$  for each material. To evaluate the process window, we compare  $\Delta p_s$  with forming quality. For this, we produced the cup geometry from PP-1 — initially without plug assist — at the same test points and assessed shape accuracy as defined in Table 1. **Figure 8** shows the resulting contour plots for PP-1. Both target variables were modeled using quadratic support vector regression. Our aim is to define the  $\Delta p_s$  range that corresponds to the desired shape accuracy of 4.0 (highlighted).

The desired shape accuracy of 4.0, including the transition areas 3.7 and 4.3, can be approximated using the iso-

clines of pressure difference at 0.015 and 0.045 MPa (0.15 and 0.45 bar). In this range, quality-compliant molded parts are expected for all reference materials. The nearly parallel alignment of the isoclines further indicates a correlation between shape accuracy and  $\Delta p_s$ , supporting its use as a cross-material indicator for defining the process window.

**Figure 9** presents the contour plots and process windows for all six materials. The highlighted windows for PP-2 and the PCR materials are projections based on empirical results with PP-1. As expected, all materials exhibit qualitatively similar  $\Delta p_s$  behavior in relation to the two setting parameters. However, with increasing recyclate content, the predicted process window shifts toward lower temperature and heating durations. A widening of the window is also observed. Literature reports lower melting points and higher elongation at break for rPP with increasing recyclate share, accompanied by reduced tensile strength [8], which may explain the broader window at lower temperatures, though we cannot confirm this experimentally within this study.

We tested the hypothesis that equal  $\Delta p_s$  values result in comparable shape accuracy by conducting selected test points for PP-1 and PCR-1.0. For PP-1, points 2 and 4 lie on the 0.02 MPa (0.2 bar) isocline, and points 1, 3, and 5 lie on the 0.04 MPa (0.4 bar) isocline — each associated with qual-



9. Contour diagrams for the target pressure difference and process windows of the materials. The scales on the two y-axes have the same meaning and refer to the same data in the units °C and K.

ity level 4.0. The same applies to PCR-1.0 at points 6, 7, and 9 (0.02 MPa) and points 8 and 10 (0.04 MPa). Corresponding process settings and quality evaluations are listed in **Table II**.

The validation results largely confirm our expectations, though some test points near the lower process window limit were rated at shape level 3.7. As seen in Fig. 8, this rating intersects the 0.045 MPa (0.45 bar) isocline, suggest-

ing the  $\Delta p_s$  threshold should be refined to more accurately define the process window. While an ordinal logistic regression could model the correlation between  $\Delta p_s$  and shape accuracy more precisely, this would require a broader data set across shaping stages. Nevertheless, for practical estimations with limited data, the method demonstrates sufficient accuracy. **Figure 10** illustrates the forming results for selected points 2, 7, and 8 as examples.

| No. | Heating Time, s | Radiator Heating Temperature, °C | Shape Accuracy PP-1 (expected) | Shape Accuracy PCR 1.0 (expected) |
|-----|-----------------|----------------------------------|--------------------------------|-----------------------------------|
| 1   | 25.40           | 469 (742.15 K)                   | 3.7 (= 4.0)                    | 4.0 (> 4.0)                       |
| 2   | 29.75           | 466 (739.15 K)                   | 4.0 (= 4.0)                    | 6.0 (> 4.0)                       |
| 3   | 29.25           | 444 (717.15 K)                   | 4.0 (= 4.0)                    | 4.0 (> 4.0)                       |
| 4   | 32.80           | 449 (722.15 K)                   | 4.0 (= 4.0)                    | 6.0 (> 4.0)                       |
| 5   | 32.80           | 426 (699.15 K)                   | 3.7 (= 4.0)                    | 4.0 (> 4.0)                       |
| 6   | 23.00           | 470 (743.15 K)                   | 3.7 (< 4.0)                    | 4.0 (= 4.0)                       |
| 7   | 27.70           | 438 (711.15 K)                   | 3.7 (< 4.0)                    | 4.0 (= 4.0)                       |
| 8   | 22.50           | 434 (707.15 K)                   | 3.0 (< 4.0)                    | 3.7 (= 4.0)                       |
| 9   | 32.50           | 414 (687.15 K)                   | 3.7 (< 4.0)                    | 4.0 (= 4.0)                       |
| 10  | 28.00           | 400 (673.15 K)                   | 3.0 (< 4.0)                    | 3.7 (= 4.0)                       |

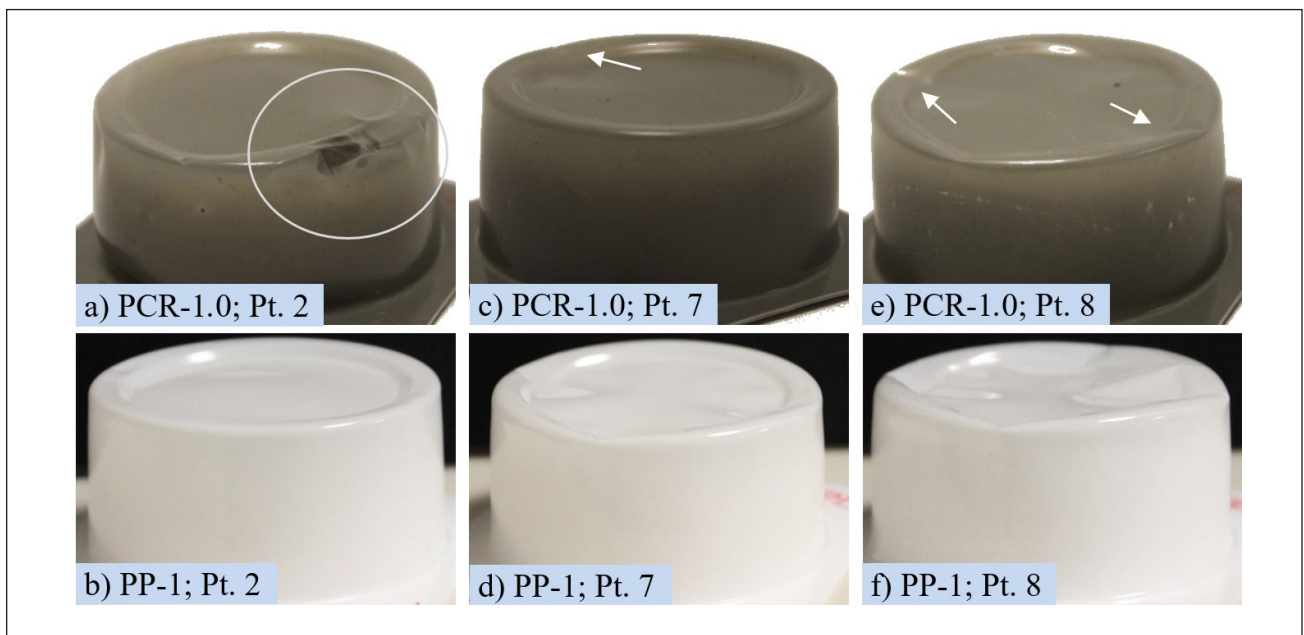
## II. Settings for validation points and quality ratings.

Figure 10c and Fig. 10e show isolated areas on the molded parts with PCR material where the material bends in the bottom radius. This bending results from unfavorable material distribution in that area and associated static instability, which is irrelevant for evaluating shape accuracy.

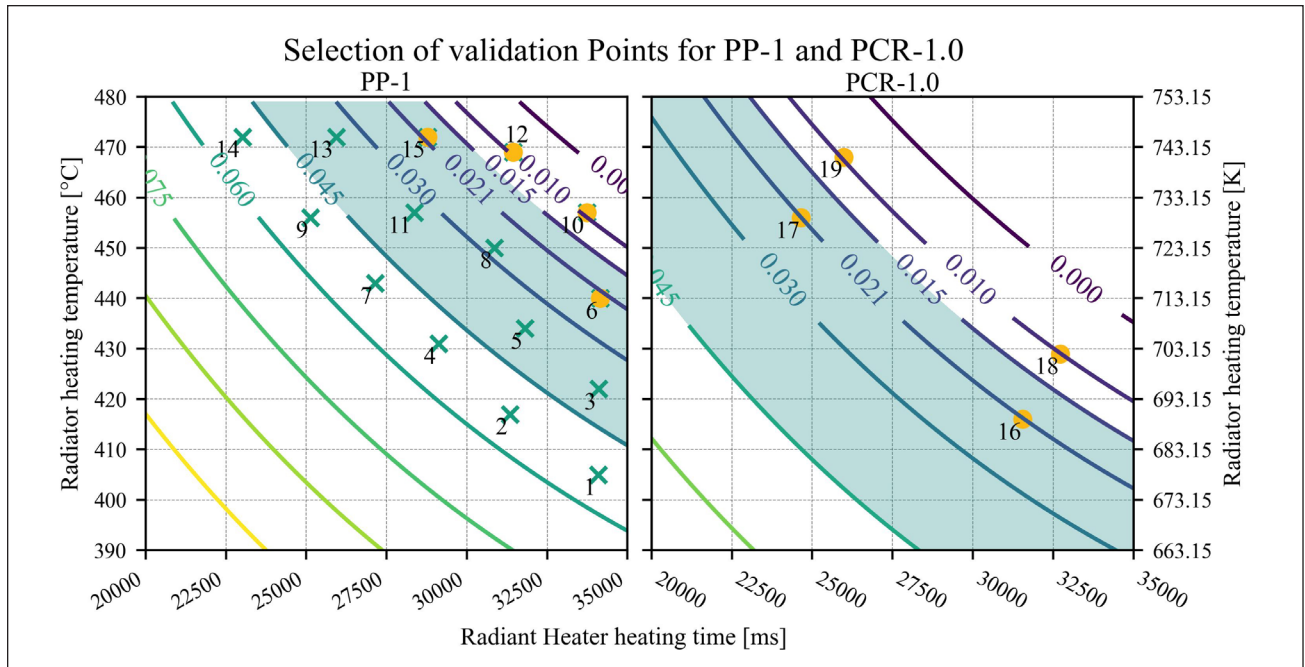
Plug-assisted thermoforming is commonly used to improve wall thickness distribution. Shape accuracy can be assessed using the same criteria as in Table I. Due to surface cooling and friction on the plug assist, the wall thickness in the bottom area typically increases. This leads to the expectation that longer heating times and higher temperatures are necessary to achieve the same shape accuracy as

with non-plug-assisted thermoforming, resulting in a shift of the process window. Validation with PP-1 shows that the isocline at 0.021 MPa (0.21 bar) marks the onset of quality-compliant molding (level 4.0). **Figure 11** compares the tested pattern for PP-1 (left) with the earlier process window without plug assist. Only test points 6, 10, 12, and 15 (upper right quadrant) yielded acceptable results with significantly improved wall thickness. For PCR-1.0, points 16 to 19 (right) were selected along the same isoclines (0.021 and 0.01 MPa), corresponding to the PP-1 points.

The plug-assisted tests confirm that identical  $\Delta p_s$  values result in comparable shape accuracy for both materials.



10. Exemplary comparison of the forming results at points 2 (left), 7 (center), and 8 (right) for material PCR-1.0 (top) and PP-1 (bottom).



**11. Point selection for plug assisted tests for PP-1 (left) and PCR-1.0 (right) with isoclines of  $\Delta p_s$  (MPa). The scales on the two y-axes have the same meaning and refer to the same data in the units °C and K.**

Wall thickness distribution was evaluated optically using the ATOS Q stereo camera system (Carl Zeiss GOM GmbH; Braunschweig, Germany) with an MV170 lens. Forming pressure (0.6 MPa), activation time, plug assist depth (28 mm), and geometry were kept constant across tests. The qualitative wall thickness distribution of a molded part depends to a large extent on the desired geometry of the part, the forming parameters, and the geometry of the plug assist used. In this case, the settings result in a thicker bottom area (points 0–24 mm), a thinner area in the lower bead area (points 24–36 mm), a local peak in the lower lateral surface (points 34–38 mm), and a thinner area in the middle of the lateral surface of the cup (points 38–54 mm). The range of 54–67 mm marks the entry area of the cup opening. **Figure 12** compares thickness distributions for PP-1 and PCR-1.0 at 0.021 MPa (left) and 0.01 MPa (right) isoclines, showing individual test results ( $n=3$ ) and corresponding averages for both materials.

Both diagrams exhibit the same qualitative behavior, independent of material or test point. However, Fig. 12a and Fig. 12b reveal quantitative differences: higher temperatures or lower pressure differences lead to reduced wall thickness at the base and increased thickness in the outer region that are consistent with constant mass and volume. In Fig. 12a, PP-1 points 6 and 15 yield nearly identical thickness profiles, indicating similar material behavior at comparable  $\Delta p_s$  values. The PCR shows similar reproducibility but with ~100  $\mu\text{m}$  greater base thickness and a thinner lateral wall compared to PP-1 material, despite identical predicted pressure differences.

One possible explanation is the limited prediction ac-

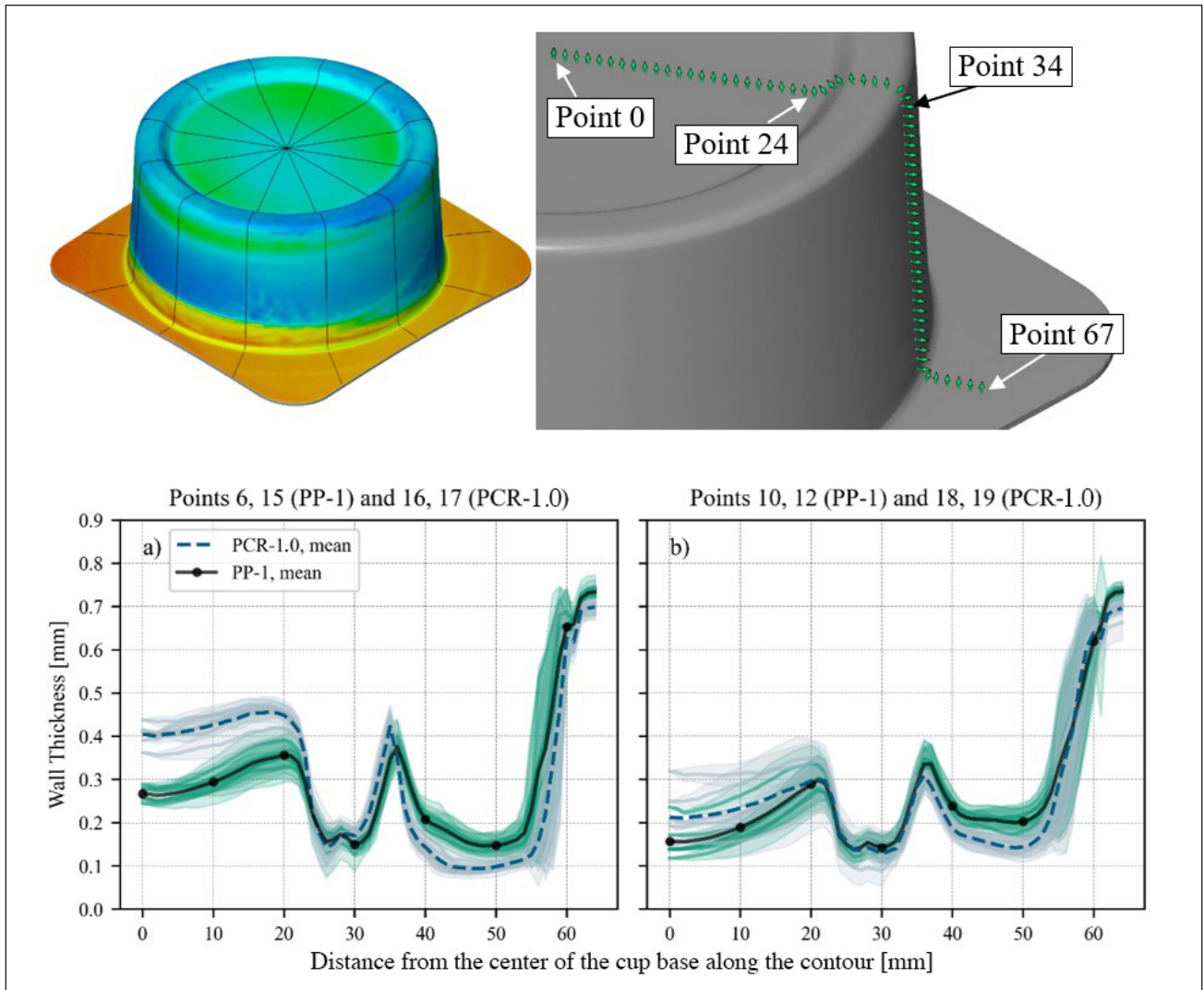
curacy and potential model errors, which may have led to selecting comparison points with only seemingly identical pressure differences. Another contributing factor could be differing heat transfer conditions between the heated film and the punch, possibly causing faster cooling in the PCR material. Additionally, specific material properties may not be fully captured by the current modeling approach, which could further explain the observed deviations.

Figure 12b shows similar mean wall thickness distributions for both materials. However, larger deviations in reproducibility are observed for both materials, which could point to initial material degradation due to high thermal exposure. The suitability of using  $\Delta p_s$  as a target variable along with other time-series features remains under investigation.

## CONCLUSION

Our investigations show that the proposed In-Situ Thermoforming Characterization (ITC) method strongly correlates with forming results under identical forming settings, both in terms of shape accuracy and wall thickness distribution — with and without plug assist. The data and results presented in our study suggest that the method enables a quantitative, practical comparison of material behavior during forming. Furthermore, it allowed the transfer of empirical data based on a specific material and format to support process optimization and material substitution with competing or innovative materials.

Cross-system or cross-machine validation could not be addressed in this study. Future research will focus on transferring process windows across different thermoforming setups and integrating the method into material models for



**12. Wall thickness distribution for different heating settings of identical pressure differences for the materials PP-1 and PCR-1.0.**

machine-specific, simulation-based optimization. This will also support better utilization and transfer of results and insights gained from test setups to industrial environments, such as packaging production lines.

We also demonstrated the general process suitability of post-consumer recyclates for thermoforming using a cup geometry as an example. Further studies on long-term performance (e.g., in logistics or barrier properties) aim to support the broader implementation of a circular economy in the packaging sector. **TJ**

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APPENDIX

Notes on modeling

For modeling, support vector regression (SVR) is conducted using the input variables “Radiant Heater Heating Time” and “Radiator Heating Temperature” to predict the target variables “Pressure Difference” and “Shape Accuracy” (PP-1 only). The database consists of measured data points for each material or target variable, following the space-filling design shown in Fig. 4. Previous screening with PP-1 allowed us to exclude some lower-range parameter combinations that would result in insufficient moldability, balancing the training data across trials. Before training the SVR models with the data obtained, input, and target variables are scaled to a range of [0,1] using minimum-maximum scaling to avoid distortions from differing orders of magnitude. A quadratic consideration of the influencing variables is also performed using a linear kernel for the SVR model. This approach aims to provide a precise representation of the heating process without risking overfitting. The following code can be used to reproduce the model structure:

```
from sklearn.preprocessing import Polynomial-
Features, MinMaxScaler
from sklearn.pipeline import make_pipeline
from sklearn.svm import SVR

model = make_pipeline(
    PolynomialFeatures(degree=2,
        include_bias=False),
    MinMaxScaler(),
    SVR(kernel='linear',
        C=10,
        epsilon=0.01)
)
```

Due to the limited number of data sets per material, model accuracy — aside from additional validation tests in the Results and Discussion section — is assessed using leave-one-out cross-validation. This method evaluates the mean absolute model error (MAE), standard deviation (SD), and standard error (SE) by iteratively removing one data point, training the model on the remaining data, and testing it against the excluded point. Evaluation is conducted in the original scaling, with results for each material and target variable listed in **Table A1**. When using a classic regression model for the target variable shape accuracy, it is important to note that evaluation levels are not equidistant and have a qualitative nature due to ordinal scaling. Ordinal logistic regression could enhance model results if a larger, more widely distributed database is available. In this study, we consider the model quality of the quadratic SVR sufficient, as the MAE plus the standard deviation corresponds to an intermediate level (x.3, x.7) and does not indicate a gross model error.

Based on model errors, we find that the models predicting pressure difference yield comparable values at an acceptable level across all metrics. Compared to the observed range of the target value “pressure difference” of approximately 1 bar, the mean MAE across all models is about 3% of this range.

| Prediction Model                                                                                                          | Unit         | MAE              | SD (MAE)         | SE (MAE)          |
|---------------------------------------------------------------------------------------------------------------------------|--------------|------------------|------------------|-------------------|
| Shape accuracy (PP-1)                                                                                                     | -            | 0.228            | 0.169            | 0.031             |
| Pressure difference (PP-1)                                                                                                | bar<br>(MPa) | 0.030<br>(0.003) | 0.045<br>(0.005) | 0.008<br>(0.0008) |
| Pressure difference (PP-2)                                                                                                | bar<br>(MPa) | 0.028<br>(0.003) | 0.033<br>(0.003) | 0.006<br>(0.0006) |
| Pressure difference (PCR-0.25)                                                                                            | bar<br>(MPa) | 0.036<br>(0.004) | 0.036<br>(0.004) | 0.006<br>(0.0006) |
| Pressure difference (PCR-0.50)                                                                                            | bar<br>(MPa) | 0.037<br>(0.004) | 0.034<br>(0.003) | 0.006<br>(0.0006) |
| Pressure difference (PCR-0.75)                                                                                            | bar<br>(MPa) | 0.032<br>(0.003) | 0.032<br>(0.003) | 0.005<br>(0.0005) |
| Pressure difference (PCR-1.0)                                                                                             | bar<br>(MPa) | 0.028<br>(0.003) | 0.040<br>(0.004) | 0.007<br>(0.0007) |
| PP: polypropylene; PCR: post-consumer recycle; MAE: mean absolute model error; SD: standard deviation; SE: standard error |              |                  |                  |                   |

A1. Results of the model evaluation for each model (material and targets).

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We chose this topic for study because we develop machine-specific, yet format-independent, methods to efficiently assess thermoforming process windows across diverse materials. Beyond this study's practical value, the method sparked insightful discussions with project partners on evaluating diverse recycled materials and their processability. The simple structure of the ITC method presented here allows easy machine integration and aims to support both scientific analysis and practical tasks like commissioning and material changes in industry. Future projects will focus on analyzing time series of pressure differences for potential correlations with part quality and on further improving machine integration of the proposed ITC method.



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