Geometry Control of Deep Drawn Paperboard Parts by Influencing the Stress-State of Semi-Finished Products

Nicola Jessen ,* Sangeedan Sivanathan, Hana Kim, and Peter Groche

The transition towards sustainable packaging requires reliable forming processes for paperboard, but its anisotropic and hygroscopic nature strongly limits dimensional accuracy in processes such as deep drawing. This study addresses the aforementioned challenge by systematically investigating two complementary strategies: optimizing blank geometry and introducing pretension. A combination of numerical simulations with anisotropic, moisture-dependent plasticity, and experimental validation using a pneumatic press with additively manufactured tools was applied. The base-point method for blank optimization allowed for efficient reduction of flange length deviations and geometric errors by more than 55% in a first iteration and stable convergence within three optimization steps. Pretension strategies, applied either by mechanical pre-stretching or by exploiting hygroexpansion, also reduced anisotropic springback. Hygroexpansion-based pretension proved particularly effective by achieving more homogeneous stress distributions without additional equipment. The results demonstrated that these strategies can reduce springback and increase drawing depth while providing a reproducible approach. Optimized blank geometry ensures a more uniform distribution of blank-holder force, while pretension counteracts anisotropy-induced recovery. Together, these findings provide a pathway toward more accurate and scalable paperboard deep drawing, with relevance for industrial implementation of sustainable three-dimensional packaging.

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INTRODUCTION

In recent years, the demand for sustainable packaging solutions has significantly increased, driven by growing environmental concerns and the need for eco-friendly alternatives. As a result, paper-based materials, including deep-drawn paperboard products, have gained traction in various industries, such as food packaging, electronics and consumer goods (Ibrahim *et al.* 2022). Their ability to form three-dimensional structures enables new application fields compared to conventional folding or winding techniques (Östlund 2017).

However, the inherent anisotropic, inhomogeneous and hygroscopic nature of paperboard presents substantial challenges in achieving the required dimensional accuracy and shape consistency during the deep drawing process (Löwe *et al.* 2017). The fiber alignment generated during the papermaking process causes directional mechanical properties: in machine direction (MD) paperboard typically provides higher tensile strength, but lower strain capacity, while in cross direction (CD) greater elongation but reduced strength is observable (Vishtal and Retulainen 2012). This anisotropy results in directional springback and localized strain variations, complicating the prediction and control of geometrical outcomes (Hauptmann and Majschak 2011). Moreover, the mechanical response of paperboard is strongly influenced by the moisture content, since hydrogen bonding between fibers softens under humid conditions and stiffens when dried (Niini *et al.* 2022).

In deep drawing, a process widely used in sheet metal forming, a flat blank is drawn into a die cavity by a punch while the material flow in the flange is controlled through a blank holder. In comparison to other forming processes for paper-based packaging, such as folding, winding, embossing or pulp casting, deep drawing enables a higher degree of geometrical freedom and produces parts with smoother surfaces (Groche *et al.* 2016). Nonetheless, unlike metals, paperboard cannot undergo significant plastic deformation, and its heterogeneous structure leads to wrinkling, springback, and limited formability. While finite element methods (FEM) are well established in metal forming, their transfer to paperboard is still limited due to the material's distinct anisotropy, inhomogeneity, and moisture- dependent behavior, underlining the need for further research in this field (Jessen *et al.* 2022). Related microstructural and homogenization-based modelling approaches for corrugated board – for example by Garbowski *et al.* (2025) – provide additional theoretical background for constitutive descriptions of fibre materials.

Although significant progress has been made in characterizing the material behavior of paperboard (*e.g.*, anisotropy, moisture sensitivity) and adapting process conditions, several challenges remain unsolved. Most approaches rely heavily on empirical trial-and-error, resulting in high development costs and limited scalability (Vishtal and Retulainen 2012).

Individual strategies, such as temperature or moisture control (Niini *et al.* 2022) or the use of drawing beads (Jessen and Groche 2025), have been studied, but systematic strategies are still scarce. In particular, the influence of anisotropy on directional springback, the interaction with changing blank holder loads, and the potential of pre-tensioning strategies have not been thoroughly addressed.

This study seeks to fill these gaps by looking at two strategies to improve the control over springback and dimensional accuracy in deep-drawn paperboard. Focus is placed on methods that are applicable to deep drawing processes and different paperboard materials, independent of the operator's experience.

To address these challenges, the following study combines experimental investigations and numerical simulations to systematically evaluate strategies to close the gap. The applied methods, experimental setups and numerical modelling approach are described in the next section.

EXPERIMENTAL

Material

The investigated material was a commercial paperboard grade, Trayforma^{TM} by Stora Enso, which is specifically intended for pressed and formed packaging applications. Two different grammages were used in this study: 350 and 190 g/m^2. The board is made up of a multilayer structure with bleached virgin fiber. The outer plies consist of chemical pulp, while the middle layer is a chemi-thermomechanical pulp (Stora Enso). The material was either used at room condition, having a moisture content of about 6% or conditioned at 23 °C and 95% relative humidity based on ISO 187 (1990). The purpose of the latter treatment was to increase the material humidity to 15%, thereby increasing the strain at breakage, resulting in better formability. Trayforma exhibits the typical anisotropic behavior of paperboard, with greater strain in the cross direction (CD) and higher tensile strength in the machine direction (MD), as illustrated in Fig. 1. This anisotropic mechanical response has also been widely reported in the literature (Huttel *et al.* 2011; Vishtal and Retulainen 2012). Figure 1 also demonstrates the critical role that moisture content plays in the mechanical behavior of paperboard, affecting stiffness and elasticity (Pfeiffer and Kolling 2019). Higher humidity leads to breakage of the hydrogen bonds and fiber expansions withing the paperboard, allowing for an increased formability, up to the point of early breakage due to decreased material bonding (Hauptmann *et al.* 2016).

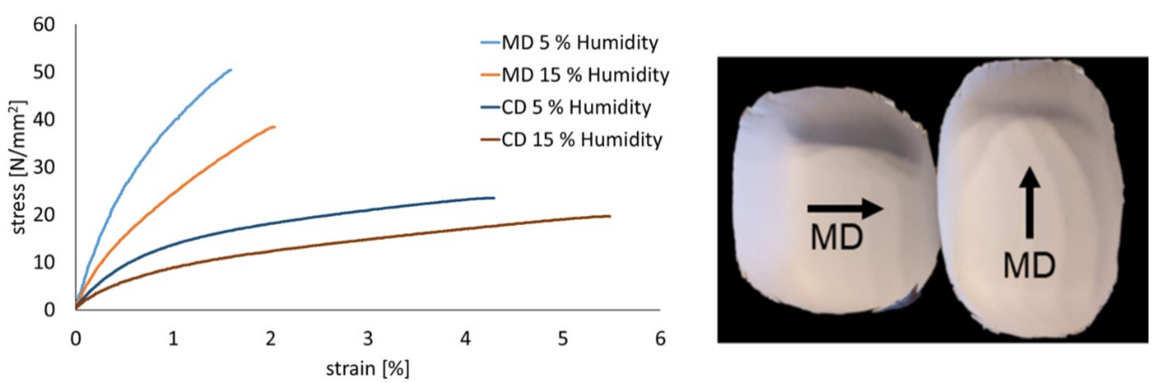

Fig. 1. Humidity dependent stress strain curve (left) and anisotropic springback (right) (Jessen and Groche 2025)

Experimental Setup

The deep drawing experiments were carried out using a press system allowing for flexible, small-scale forming conditions while still being robust. Central to the setup is the typical deep drawing tooling, consisting of a punch, a die, and a blank holder. The process follows three steps: (i) clamping of the paperboard between the die and blank holder under a defined force or force curve, (ii) forming with the punch's downward motion, which draws the blank into the die cavity, and (iii) releasing and removing the formed part after completing the drawing stroke.

All deep drawing was conducted on a pneumatic press equipped with additively manufactured poly(lactic acid) (PLA) tools. This configuration provided high flexibility and rapid tooling adaptations at low cost. Laser cutting was used to prepare the blank geometries, ensuring accurate dimensions and reproducibility. Different blank geometries were tested to study their influence on stress distribution, drawing depth, and springback behavior. Furthermore, blanks were oriented with the long side parallel to the machine direction (MD) or cross direction (CD) to systematically evaluate anisotropy effects.

In addition, a tensile testing machine "Zwick Roell 100" was employed to apply controlled elastic stretching as part of the pretension methodology. After stretching, the pre-tensioned material was bonded to an unstretched carrier layer before being subjected to deep drawing in the pneumatic press. This setup made it possible to quantify the effect of pretension on springback reduction and achievable drawing depth.

Methodological Approaches

To improve the dimensional accuracy and to reduce springback in the deep drawing of paperboard, two complementary methodological approaches were investigated. Both strategies address the stress state in the blank during forming, but from different perspectives: (i) optimization of the blank geometry prior to forming and (ii) application of pretension in the blank.

Blank Geometry Optimization

The geometry of the blank has a decisive influence on the stress distribution during deep drawing (Hammami *et al.* 2009). Conventional approaches in paperboard forming often rely on iterative, experience-based adjustment of pre-cuts, which is both time-consuming and operator-dependent. Non-optimized blanks typically lead to locally varying flange lengths, which in turn result in non-uniform blank holder pressures. This non-uniform load distribution causes certain areas to undergo excessive stretching while others remain less loaded, thereby contributing to anisotropy-driven springback (Huang and Nygårds 2010). Consequently, blank optimization is an essential prerequisite for improving dimensional accuracy. In this study, two strategies were compared:

1. In the iterative approach, blank shapes are corrected step by step based on flange length deviations. After each forming cycle, the operator measures the remaining flange at three points along each edge and compares the values to the target flange length. The resulting deviations are then added to or subtracted from the corresponding blank edge length for the subsequent iteration.
2. The base-point method is a more systematic approach originally developed for sheet metal forming (Gharehchahi *et al.* 2021). This method relies on a defined reference point within the blank and calculates corrections to the blank contour by minimizing the distance between the formed and the target geometry.

The base-point method has the advantage of being independent of the operator's experience and has the potential to converge faster towards optimized geometries. The following research study investigates the applicability of this method for paperboard.

Pretension Strategy

Even with optimized blank geometries, the inherent anisotropy of paperboard leads to different directional springback, particularly in comparision between MD and CD. This effect cannot be compensated by the blank geometry alone, as the tensions in the deep drawn part as well as in the wrinkles are directional as well. Targeted prestressing has been shown to increase the maximum load before failure of hybrid sheet metals (Husmann and Groche 2021). Introducing pretension into the material may be a way to directly influence the internal stress state of paperboard prior to forming, thereby reducing elastic recovery and balancing anisotropy.

A second strategy addresses this directional springback, especially along the machine direction (MD). To counteract this effect, a pretension concept was developed, aiming to introduce additional tensile stress in MD prior to forming. Two complementary approaches were investigated:

1. Mechanical pre-stretching – Paperboard strips were elastically stretched in the MD, using a tensile testing machine and subsequently bonded to a non-stretched blank. This

composite was then subjected to the deep drawing process. By introducing tensile stresses before forming, the material enters the process in a preloaded state, which is expected to reduce elastic recovery and thereby springback.

2. Hygroexpansion-based pretensioning – Taking advantage of the hygroscopic nature of paperboard, specimens were selectively conditioned to higher humidity levels, resulting in fiber swelling and expansion. By bonding the expanded material to a stable reference layer and subsequently drying, internal stresses are "locked in" due to restrained shrinkage. During deep drawing, these stresses act as an inherent pretension, analogous to the mechanical pre-stretching approach.

Both methods aim to exploit pretension as a countermeasure against anisotropy-driven springback. Furthermore, their influence on achievable drawing depth and wrinkle formation was systematically evaluated in combination with numerical simulation and experimental testing.

Numerical Simulation

The deep drawing process was simulated using Abaqus/Explicit 2021 with solid 3D elements C3D8R. These software items offer a favorable compromise between computational efficiency and the ability to capture the through-thickness deformation and bending-dominated regions that occur in paperboard forming. In addition to geometric symmetries, mass scaling was applied to reduce computation time. The scaling factor was selected so that the stable time increment remained above the critical lower limit, beyond which artificial dynamic effects would influence the results. The material behavior of the paperboard was represented by an anisotropic, moisture-dependent plasticity model, incorporating the following key aspects:

- Elastic properties: Directional stiffness values were used for MD and CD, based on tensile testing at standard climate. Literature values for Poisson's ratios, Young's moduli, and shear moduli were adopted where experimental data were unavailable (Post *et al.* 2012; Jessen *et al.* 2022).
- Yield behavior: The Hill yield criterion was implemented to capture the orthotropic nature of paperboard. Yield stress and plastic strain data were derived from tensile tests at varying humidity levels to reflect hygroscopic effects (Groche *et al.* 2012).
- Damage model: The ductile damage is formulated by the fracture strain and strain rate, with failure defined by a displacement-at-failure criterion of 0.6, in line with previous studies on paperboard forming, which were verified against tensile test data (Jessen *et al.* 2022).
- Moisture influence: Material data sets were generated for two constant humidity states (≈6% and ≈15% moisture content) based on tensile and bulge tests, allowing simulations to represent the softening and increased strain-at-fracture observed under humid conditions. (Jessen *et al.* 2022). During experimental deep drawing, the humidity changes are less than 1%, allowing for the assumption of constant humidity in the simulations.

The simulation outputs included stress and strain distributions, draw-in behavior, and overall geometry of the drawn parts. Due to element limitations, wrinkling could not be resolved in detail; however, the initiation regions of wrinkles were qualitatively identified.

The numerical predictions were systematically compared against laser scanning measurements to validate the model and assess its predictive capability. The comparison is based on the remaining flange length rather than the springback, as the springback simulation does not yet provide sufficiently precise results regarding the wrinkle cohesion and friction.

Measurements

To evaluate the forming behavior and the effectiveness of the applied optimization strategies, both geometrical and mechanical measurements were conducted. The focus was placed on quantifying springback, dimensional accuracy, and structural stability of the deep-drawn specimens.

Geometrical characterization was carried out using a high-resolution 3D laser scanning system (Hexagon Absolute Arm with integrated scanner). The system provides full-field surface data of the formed parts, enabling a precise comparison between different blank geometries, material conditions, and pretensioning strategies. A cross-sectional analysis of the scanned geometries was performed using the Inspire software, which allowed for the evaluation of flange length, drawing depth, and wall angles. For fast and robust verification of characteristic dimensions, caliper gauges were additionally employed. Springback evaluation was based on deviations between the measured geometries and the target dimensions at a nominal drawing depth of 40 mm. The relative displacement between opposite side walls was calculated as an indicator for anisotropic springback. This approach allowed for a quantitative comparison of different forming conditions and optimization methods.

Additionally, all experimental results were validated numerically, correlating experimental measurements with finite element simulations. The Abaqus 2021 models reproduced local strain and stress distributions and provided complementary insights into draw-in behavior and geometry changes. The combination of experimental and numerical measurements enabled a comprehensive assessment of the process and accuracy of the applied material models.

Mechanical stability testing was conducted to evaluate the load-bearing capacity of the formed components. Compressive loads were applied using a Zwick universal testing machine, and force–displacement curves were recorded. From these data, stiffness, deformation behavior, and failure resistance were determined, providing a benchmark for the functional performance of the deep-drawn paperboard structures.

Together, these measurement methods provided a robust framework for analyzing the effectiveness of blank geometry optimization and pretension strategies in improving the dimensional accuracy and structural integrity of deep-drawn paperboard products.

RESULTS AND DISCUSSION

Blank Geometry Optimization

The blank geometry showed a decisive influence on the stress distribution and, consequently, on dimensional accuracy during deep drawing. Two approaches were evaluated: iterative, experience-based optimization and the systematic base-point method.

While the iterative approach achieved minor improvements, error distributions remained inconsistent between MD and CD. Moreover, the operator's subjective selection of the three measurement points introduced variability, leading to non-uniform compensation and limited convergence. After three iterations, no substantial further improvements were observed. For complex geometries with varying radii, the definition of the edge itself becomes the first challenge and relies on subjective operator decisions, thereby reducing inter-operator comparability and reproducibility.

In contrast, the base-point method offered an easy-to-use, systematic, and reproducible correction strategy for numerical simulations. The goal geometry, as well as the initial blank geometry must be determined. Additionally, a so-called "base point" must be selected. It is recommended to choose a central point on the same initial probe plane as the base point, as all other points are moved towards or away from the base point to optimize the geometry, and a central point results in fewer iterations (Gharehchahi *et al.* 2021).

Afterwards, the deep drawing process was simulated numerically. Between each point of the deep drawn geometry ($\vec{X}_{i,p}^{n}$) and the nearest point of the goal geometry the distance is calculated. The initial point ($\vec{X}_{i,p}^{0}$) is then moved along $\widehat{UV}$ to determine the new blank geometry (Fig. 2).

$$\vec{X}_{i,p+1}^{0} = \vec{X}_{i,p}^{0} \pm \xi e_{i,p}\widehat{UV} \qquad (1)$$

The unit vector $\widehat{UV}$ is defined as follows,

$$\widehat{UV} = \frac{\overrightarrow{BP} - \vec{X}_{i,p}^{0}}{\left|\overrightarrow{BP} - \vec{X}_{i,p}^{0}\right|} \qquad (2)$$

where ξ is used as a stabilizing factor and initially set to 0.6 for metals. As paperboard is less elastic, it is corrected to 0.7 for the application in the deep drawing. This method rapidly converged towards optimized blank shapes independent of the initial guess.

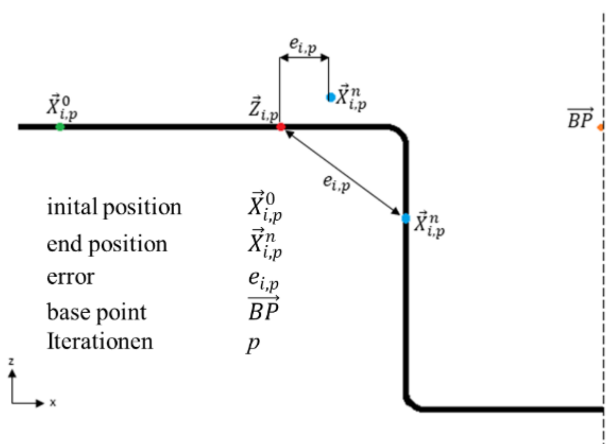

Fig. 2. Demonstration of the base point method using a 2D cross-sectional image of a deep-drawn geometry

Quantitatively, the base-point method reduced the average geometrical error by more than 55% after the first iteration. After three iterations, a stable improvement was achieved, with negligible changes in subsequent steps. The maximum drawing depth was increased by 1.06% from 49 mm to 52 mm for the rectangular geometry and from 25 mm to 30 mm for the complex geometry due to the optimized blank geometry. The optimized blanks enabled higher drawing depths and more uniform flange lengths compared to the experience-based procedure.

Figure 3 depicts the difference between the two methods, based on the optimized blank geometry and the remaining flange length from the simulation. The base point method shows results that are closer to the goal geometry. The experience-based method, by just correcting the blank geometry based on the operator's subjective visual evaluation of the previous iteration, results in inhomogeneous errors. This leads to the geometry being too short in MD, while being too long in CD. Comparing the blank geometries after each iteration, the base point method results in a more complex geometry, which would not be intuitive to find experience-based. In view of these results, and their subsequent experimental confirmation, along with the replicability of the base point method independent of the operator, all subsequent research is to be conducted using the base point method.

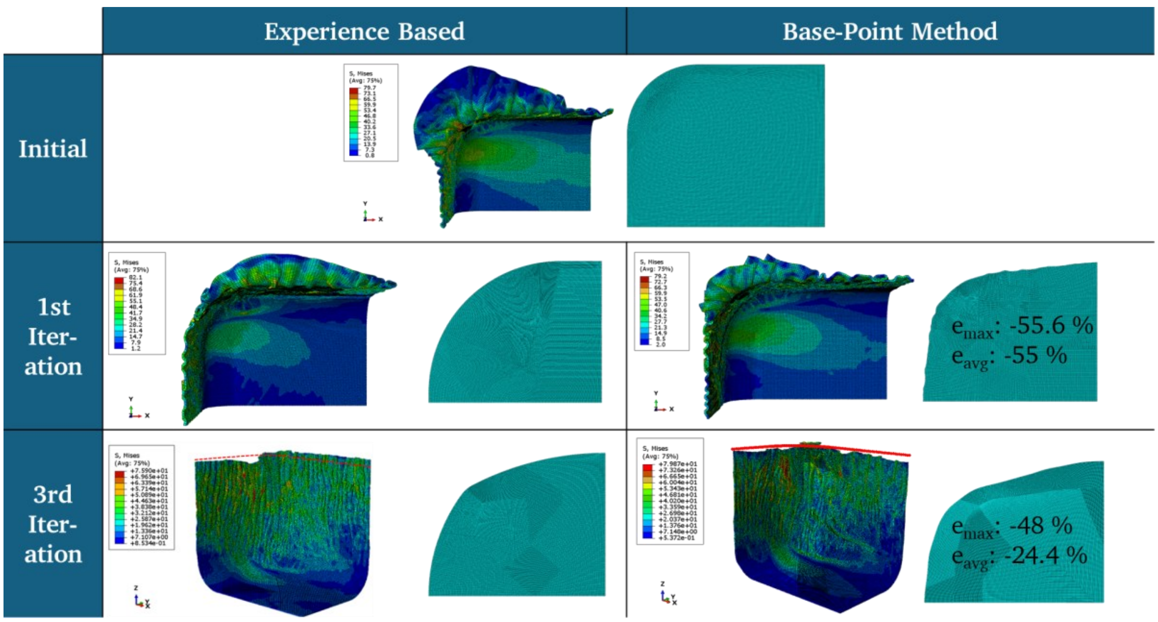

Fig. 3. Comparison between the 1st and the 3rd iteration for the experience-based method and the base point method, quarter deep drawn model (left), quarter optimized geometry (right), values for error change compared to the previous iteration for the base-point method

The influence of fiber orientation was analyzed by aligning MD parallel versus orthogonal to the long side of the part. As shown in Fig. 4, different optimized blank cutting geometries resulted depending on orientation. With MD along the long edge, higher stiffness limited flange deformation, while CD alignment allowed greater elongation, but led to increased wrinkling. Across both orientations, the base-point method yielded consistent improvements, whereas the iterative approach showed more inhomogeneous results, with blanks too short in MD but too long in CD.

Springback was evaluated using laser scanning and cross-sectional analysis. Optimized blanks exhibited reduced anisotropic springback: the average wall angle deviation decreased compared to non-optimized blanks. This improvement is attributed to a more homogeneous blank-holder pressure distribution. Irregular flange lengths in non-optimized blanks resulted in locally increased blank-holder pressures, leading to strain localization and amplified springback in specific regions. With optimized blanks, flange uniformity balanced the force distribution, resulting in improved geometrical accuracy and reduced anisotropy.

Overall, the base-point method proved to be not only more efficient, but also more robust. It eliminated operator dependency and converged to reproducible geometries. It also enabled the definition of target flange lengths in specific areas, further improving dimensional control.

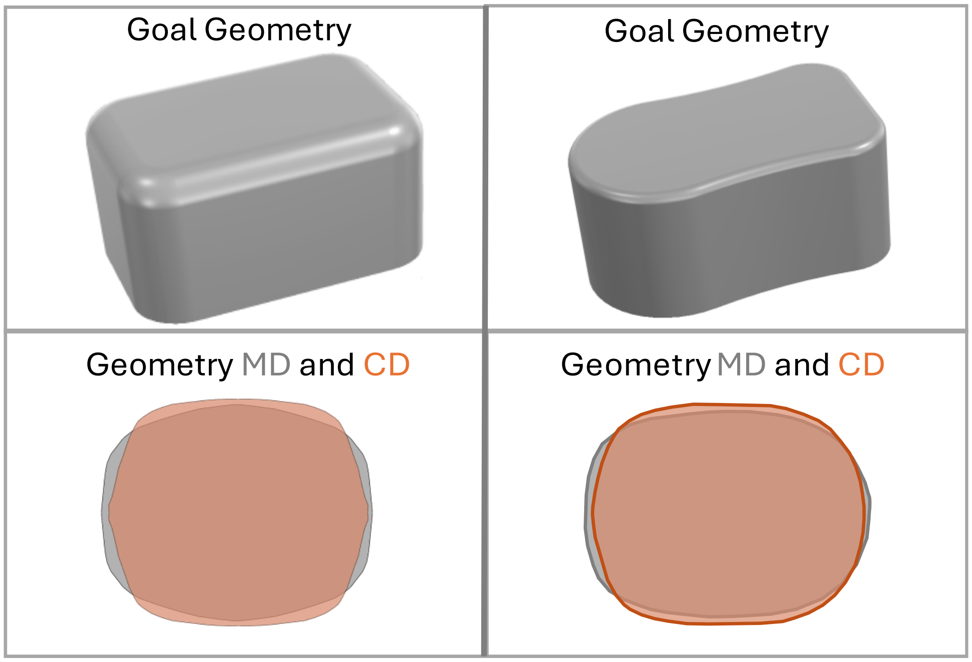

Fig. 4. Optimized blank geometries for MD *vs*. CD parallel to the long edge

Although the base-point method proved advantageous, its performance is naturally limited by paperboard-specific effects such as inhomogeneity, moisture sensitivity, and local wrinkling. Nonetheless, the method consistently improves flange uniformity despite these material constraints.

Pretension Strategy

The second approach to improve dimensional accuracy, addressed anisotropy-induced springback by introducing pretension in MD before or during forming. For the two researched variants, the PVAc dispersion adhesive Jowacoll® 103.30 was used for bonding. It is classified as water-resistant according to EN 204: D3, exhibits low emissions, and does not chemically alter the paperboard. However, the water content of the dispersion may temporarily affect the moisture content of the substrate.

Mechanical pre-stretching

Paperboard strips were elastically stretched in MD up to 2.16% strain, as this was found to be the elastic maximum, using a tensile testing machine. The uniformity of the stretching is dependent on the papers individual inhomogenities. While still stretched, they were bonded to unstretched blanks. Following the relaxation phase, the blanks exhibited pretension in the direction of the strip, as evidenced by the blank curvature. The pretension remained stable over the researched 10-day period. After deep drawing of those blanks, laser measurements were used to measure the changes in deviation from the expected geometry due to springback.

Figure 5 shows an example in which the material is prestressed in MD, parallel to the short side of the deep drawn product, as indicated by the arrow. After the deep drawing, the product was measured in MD. The diagram shows a reference without an additional strip in black, in yellow probes that contain an additional, but not pre-stretched strip and in blue compounds containing a strip that was pre-stretched at its elasticity limit of 2.16%. The improvement in springback based geometry deviations was measured at 8% relative to the reference. The observed scatter is mainly attributed to unavoidable variations in wrinkle formation but may also result from minor adhesive-induced changes in moisture content. These factors locally alter stiffness and stress distribution, which explains the variability in the quantitative results. The graph in the bottom left of Fig. 5 shows the contour changes as measured in the laser scan, demonstrating how the pre-stretching reduces the springback, as can also be seen in the relative displacement in the diagram.

The results of this method show that pre-stretching in MD was more efficient, which was to be expected, as the springback in MD was more severe and the pre-stretching resulted in an in-plane-compression of the probe along the strips. But pre-stretching in MD also resulted in an increased springback in CD of up to 2%. Although not ideal, the overall springback anisotropy was reduced, resulting in a more balanced geometry.

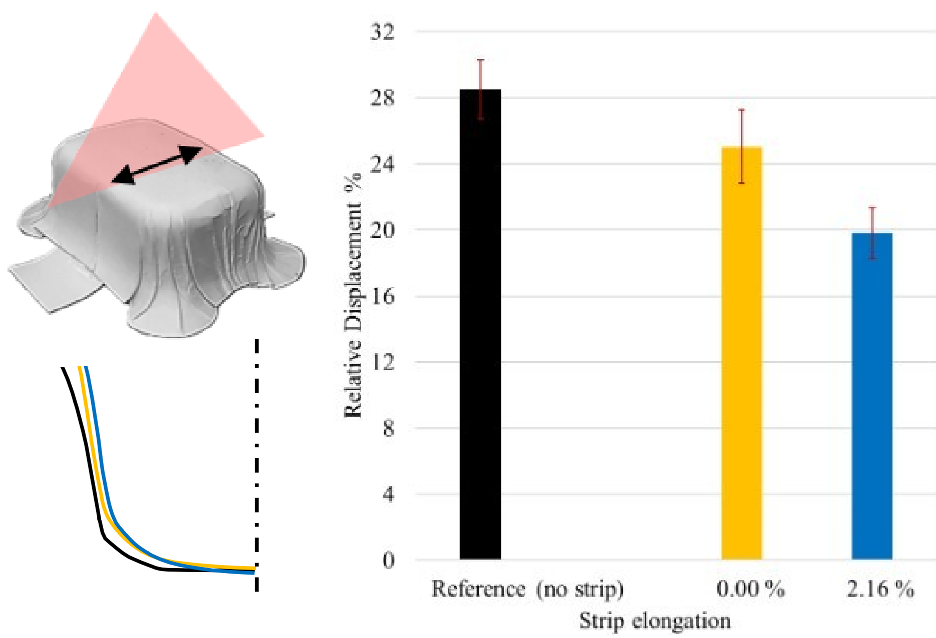

Fig. 5. Measurement of pre-tension results

Compressive load testing further indicated increased stability, with force–displacement curves suggesting higher energy absorption compared to non-pre-stretched references. Nevertheless, strong scatter due to wrinkle formation prevented reliable statistical quantification. To further analyze the strain and stress in the probe, the pre-stretching was simulated numerically.

Figure 6 contains an image of the pre-stretched blank before deep drawing, as well as a comparison of plastic elongation for three different compound variants: the reference compound, the compound without pre-stretching, and the compound with a pre-stretched strip (2.16%).

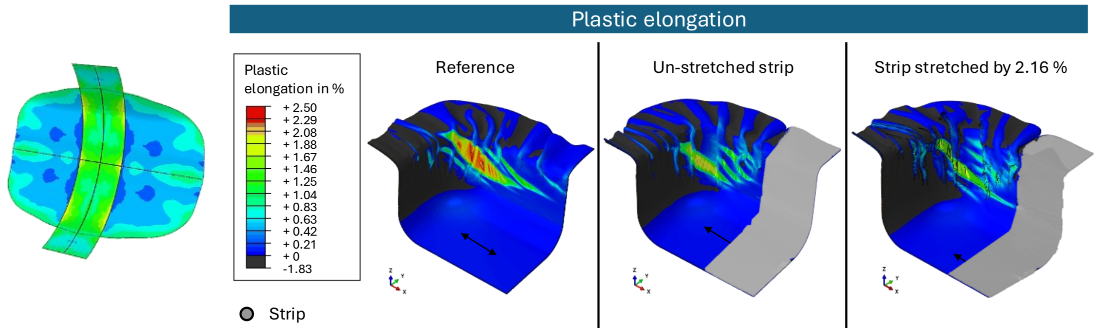

Fig. 6. Pre-stretched blank and plastic elongation after deep drawing of different compound variants

The plastic elongation was already reduced by just adding the strip, without any pre-stretching, due to the added material. But it was also apparent that the stretching reduced the plastic elongation further. The qualitative measurements of increased stability may be a result of the reduced plastic elongation, as the material is nearer to its load limit due to the plastic elongation.

Hygroexpansion-based pretensioning

The second approach utilized the hygroscopic nature of paperboard. Specimens were conditioned at 15% moisture content, resulting in fiber swelling and expansion, and then bonded to blanks at standard climate (~6% moisture). Upon drying, restrained shrinkage induced tensile stresses, analogous to mechanical pre-stretching.

While testing the shrinkage, 350 g/m² paperboard strips showed relative length reductions of 0.27% (MD) and 0.67% (CD) (Table 1). For 190 g/m², smaller contractions were observed, consistent with the lower thickness. The tensions due to shrinkage were measured by clamping the paper strips in the tensile testing machine at 205 mm and measuring the forces while the paper strips dried meanwhile not allowing for movement.

Thickness, Direction of Trayforma Paperstrip	Relative length reduction (%)	Average increase in tension (N/mm^2)
350 µm, MD	0.267	2.20
190 µm, MD	0.187	2.11
350 µm, CD	0.669	1.86
190 µm, CD	0.793	1.50

Applied to deep drawing, pretension by hygroexpansion achieved superior results compared to mechanical pre-stretching. Springback reduction in MD was more pronounced, while CD springback increases were less significant. When strips were applied to the inner wall during forming, improvements were maximized, which was likely due to more homogeneous stress introduction. Importantly, this method required no additional equipment and could be integrated in-line. To do so, the deep drawing process was stopped after 75% of the drawing depth was achieved and the punch was retrieved. A humid strip was attached to the deep drawn product along MD, while the probe remained in the drawing die. The strip was then left to dry, which achieved the tensile stress in the preformed geometry. As it was left in the die, no springback occurred at this point. After drying, the deep drawing process for the compound was finished. This process achieved even better results, due to the already made forming progress. The process reduced the relative displacement by about 4% more than the mechanical pre-stressing did.

However, complete anisotropy compensation was not achieved. The limiting factor was the relatively small moisture gradient between bonded layers, as the bonding glue, Jowacoll® 103.30, introduced additional moisture and partially equalized humidity differences. Stability improvements were visible but could not be quantified reliably due to scatter.

It is not possible to quantify the remaining tension by removing the strip afterwards in a non-destructive manner. To verify the remaining tension qualitatively, it was necessary to observe the springback, when tension is removed from the strip, while still being glued to the formed part. To achieve this, half of a strip was cut 15 times across its width, approximately 50% of its thickness, 12 weeks after forming.

Although this process is not reproducible, an increase in springback was observed immediately in every case, strongly suggesting that the strip holds tension even after three months.

Comparative Assessment

Both strategies proved effective in reducing anisotropy-induced springback and improving dimensional accuracy through different mechanisms. The base-point method primarily improved flange uniformity, which balanced blank-holder forces and reduced localized strain concentrations. Pretension strategies, in contrast, directly modified the stress state of the blank, reducing elastic recovery and evening out anisotropic effects.

Mechanical pre-stretching demonstrated feasibility, but introduced additional layers and altered forming gap conditions, limiting its applicability. Hygroexpansion-based pretension offered a more elegant and potentially industrially viable route, though further work is needed to control moisture gradients and shorten production times, when used in-line.

In summary, blank geometry optimization *via* the base-point method provided a reliable and automatable foundation for improving deep-drawn paperboard products. Pretension strategies offered additional potential, particularly through hygroexpansion, and could complement geometry optimization in a combined approach.

Outlook

While the presented strategies demonstrated clear potential for improving the dimensional accuracy of deep-drawn paperboard, several challenges remain. First, the current numerical models cannot yet capture wrinkling and the complex interaction between anisotropy, hygroexpansion, and springback perfectly. Advancing constitutive models, particularly regarding humidity-dependent behavior and interlayer bonding, will be crucial for a higher predictive accuracy. Second, the reproducibility of pretensioning methods requires further validation under industrial conditions, especially with respect to continuous processing and accelerated drying techniques. Finally, integrating blank geometry optimization with in-line pretension strategies offers a promising pathway towards automated process control, which should be addressed in future work.

CONCLUSIONS

1. Blank geometry strongly influences the forming process, as flange irregularities lead to non-uniform blank-holder forces, localized strain, and anisotropic springback.

2. The base-point method significantly reduced geometric error (> 55% after the first iteration) and provided reproducible results independent of operator experience, outperforming iterative approaches.
3. Optimized blank geometries increased achievable drawing depth and improved wall angle consistency, thereby reducing anisotropy-driven springback.
4. Mechanical pre-stretching in MD reduced springback but introduced side effects such as increased CD springback and altered wrinkle distribution.
5. Hygroexpansion-based pretension proved more effective, providing homogeneous and more uniform stress states and stronger overall reduction of anisotropic springback, though limited by achievable humidity gradients.
6. Numerical simulations supported the experimental findings, but wrinkle development and springback prediction remain insufficiently captured, highlighting the need for improved material models.

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