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Preliminary Analysis of Image-Based Quality Assessment of Laser-Engraved Graphics

ABSTRACT

This study presents a preliminary image-based method for assessing the quality of laser-engraved graphic elements on colored paperboard. Uncoated, pulp-dyed paperboards in yellow, light blue, and black were engraved with a CO_2 laser at three power settings. The samples were digitized using a flatbed scanner and analyzed in ImageJ with substrate-specific image channels and automatic thresholding. Quality was assessed by measuring the dimensional reproduction of line elements, the area and contour properties of positive and negative geometric shapes, and the uniformity of larger engraved areas. The results showed that engraved lines were consistently wider than their nominal dimensions, with relative deviation rising markedly as nominal line width decreased. The finest lines (0.25 pt) showed the largest dimensional errors and, in several cases, the greatest variability. Positive geometric elements generally increased in area, while lateral expansion of the engraved region could reduce the preserved area of negative elements. Circularity and perimeter measurements revealed contour changes that area measurements alone did not always capture. Surface analysis also showed that the response of normalized non-uniformity to laser power varied by paperboard color. Overall, the findings demonstrate that line-width measurements, shape descriptors, and normalized surface-uniformity parameters provide complementary information and support a multi-parameter approach to objectively evaluating laser-engraving quality on colored paperboard.

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KEY WORDS
Laser engraving, paperboard, image analysis, dimensional accuracy, contour fidelity, surface uniformity

1. Introduction

Cutting is a fundamental print-finishing operation and an essential step in producing bookbinding and packaging products. Mechanical cutting and die-cutting are well-established methods for separating paper and paperboard, while CO_2 laser cutting has emerged as a digitally controlled alternative. Its non-contact operation, programmable tool path, and ability to reproduce complex contours make it especially suitable for prototypes, customized products, and short production runs (Happonen et al., 2015; Pinćjer, Miketić & Tomić, 2022; Pinćjer et al., 2023; Rosnan & Enomae, 2021).

Laser technology in print finishing extends beyond complete substrate separation. By precisely controlling the laser–material interaction, the surface can be modified locally or material removed to a shallow depth without penetrating the full substrate thickness, enabling both marking and engraving. This allows text, symbols, ornaments, and other visual elements to be created directly on the substrate without applying printing ink (Pinćjer, Miketić & Tomić, 2022; Stepanov et al., 2015; Xie et al., 2020). In graphic products, engraved elements may serve identification, visual or combined functions. For machine-readable symbols, successful detection and decoding provide functional criteria for quality assessment (Matuszczyk and Weichert, 2023). Text, logos, and decorative motifs require broader evaluation, including

shape fidelity, fine-detail reproduction, contrast, and edge definition. Tonal relationships and overall visual fidelity are also relevant when assessing ornamental laser engravings (Lungu, Georgescu & Cosereanu, 2025).

The quality of laser engraving has been evaluated using various approaches, depending on the material and the intended function of the processed surface. Some methods focus on surface topography and roughness (Kažukauskas et al., 2024; Sáenz-Nuño et al., 2025), whereas others characterize laser-induced geometric or colorimetric changes (Nguyen-Thi-Ngoc & Dang, 2023; Stepanov et al., 2010, 2011). Although these measurements objectively describe surface texture, feature dimensions or color change, each captures only one aspect of quality and does not directly indicate whether a graphic element has preserved its intended contour, area, and fine details. Digital image processing has been used to quantify grayscale changes and engraving intensity, distinguish defective from defect-free laser-processed surfaces, and segment visible laser-affected regions on paper (Kasim et al., 2025; Rosnan et al., 2022; Zhang et al., 2021). These applications demonstrate the potential of image-based quality assessment, but they address individual indicators rather than the overall quality of engraved graphic elements. Colored paperboards present an additional challenge because their initial color and texture, together with differences in fiber structure, fillers and coatings can affect both the laser–material interaction and the appearance recorded in the image (Pinćjer, Miketić & Tomić, 2022; Stepanov et al., 2010, 2011, 2015). The aim of this study is therefore to propose and test a methodological approach based on the digital analysis of scanned images in ImageJ for quality control of laser-engraved elements on paperboards of different colors. The approach focuses on contour quality, reproduction of small graphic elements, and uniformity of larger engraved areas. It also examines whether these characteristics can be compared consistently across substrates and laser settings.

2. Methods

2.1. Paperboard samples

For this investigation, an uncoated, pulp-dyed paperboard was selected with a basis weight of 220 g/m² (Fa Colore, Fabriano, Italy). The paperboard was made from 100% ECF pulp and dyed throughout to achieve a solid, homogeneous color with high fade resistance. Because of its natural, uniform surface, this paperboard suits a wide range of graphic products, including invitations, greeting cards, menus, brochures, book covers, leaflets, and similar applications. Three paperboard colors were selected for the present investigation: yellow, light blue and black. Their CIELAB color coordinates were previously measured using a Techkon SpectroDens spectrophotometer with white backing, D50 illuminant and a 2° standard observer. Table 1 presents the measured values.

Table 1

CIELAB values of selected paperboard samples

Colour	Code name	L*	a*	b*
Yellow	Giallo	90.08	4.60	86.26
Light blue	Azzurro	59.86	-27.48	-37.18
Black	Nero	24.35	-0.77	-2.59

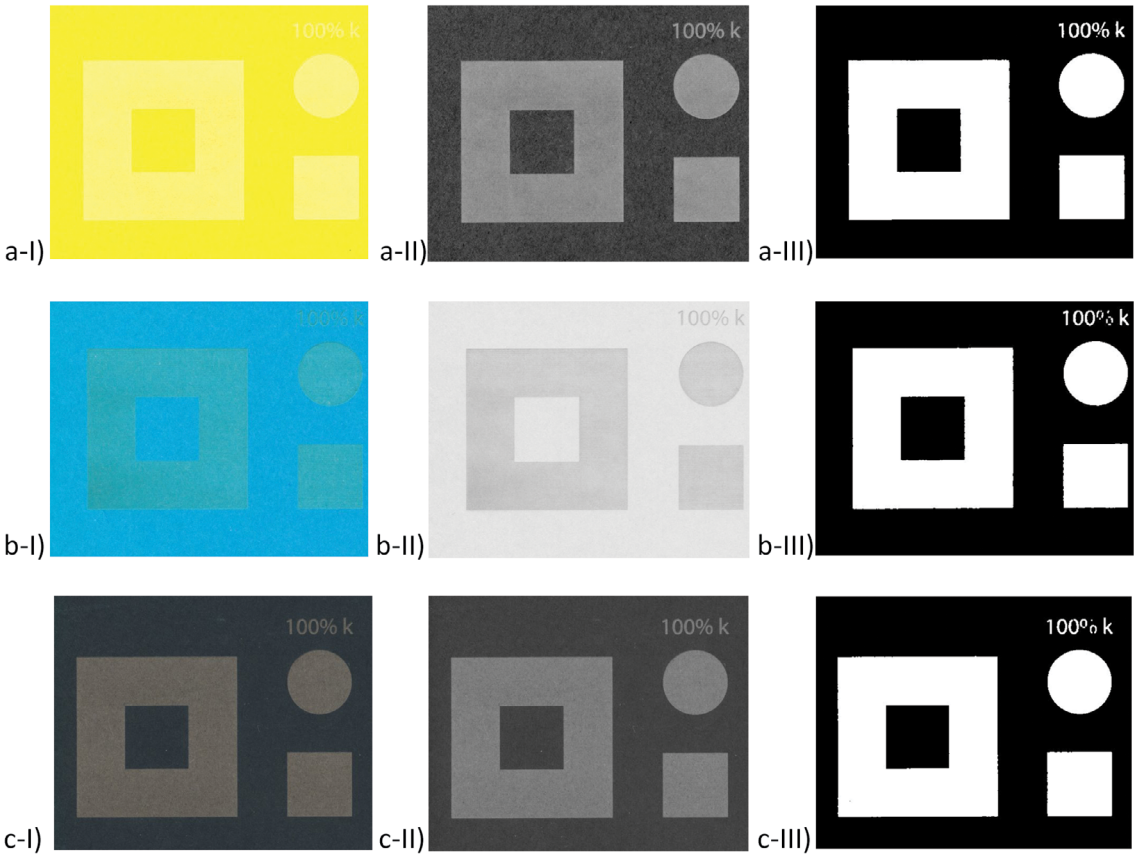
2.2. Laser engraving test elements

The paperboard samples were engraved with a Trotec Speedy 300 CO_2 laser system (Trotec, Marchtrenk, Austria) at three power settings: 55%, 60%, and 65%, designated Laser 1, Laser 2, and Laser 3, respectively. These settings were selected to assess how increasing laser power affects the reproduction of fine graphic elements and the uniformity of larger engraved areas. The laser operated at a wavelength of 10.6 µm, and the engraving speed was set to 30% of the system's maximum speed, as defined in the JobControl software. The laser head's movement in the XY plane was controlled using JobControl software (version 11.1.1).

For this study, a simple test form was designed to include line elements, positive and negative geometric shapes, and a larger solid engraved area. Four nominal line widths were used: 1, 0.75, 0.5, and 0.25 pt, corresponding to approximately 0.353, 0.265, 0.176, and 0.088 mm, respectively. Horizontal and vertical lines were included to assess potential directional effects. The geometric test elements comprised circles with a nominal diameter of 10 mm and squares with a nominal side length of 10 mm, each in positive and negative versions. For the positive elements, the area within the shape was engraved. For the negative elements, the surrounding area was engraved while the shape itself remained untreated. This configuration allowed evaluation of laser-modified boundary displacement on both sides of the nominal contour. The large surrounding engraved area was also used to assess engraving uniformity.

2.3. Image acquisition

To maintain fixed imaging geometry and consistent illumination across samples, the engraved paperboard samples were digitized with a Canon CanoScan 5600F flatbed scanner at 1200 spi. Images were acquired in the sRGB color space (IEC 61966-2-1), with automatic brightness, contrast, sharpening, and other image-enhancement functions disabled. All images were saved in TIFF format without lossy compression.



» **Figure 1:** *Representative image-preprocessing workflow for yellow (a), light-blue (b), and black (c) paperboards: original RGB scans (I), selected analysis channels (II), and binary masks obtained using Huang's automatic thresholding method (III)*

Colored paperboards require substrate-specific preprocessing because their original color, texture, and surface structure affect the recorded intensity distribution (Stepanov et al., 2010, 2011, 2015). Accordingly, the RGB channels of each paperboard were examined separately in ImageJ. The blue channel provided the clearest separation between engraved and untreated regions on the yellow paperboard (Figure 1a-II), whereas the red channel was selected for the light-blue and black paperboards (Figure 1b-II and 1c_II). The selected channel images were saved as grayscale, 8-bit TIFF files, while their copies were segmented using Huang's automatic thresholding method to create binary masks for subsequent geometric measurements. The original grayscale images were retained to assess uniformity within larger engraved areas. Channel selection was intended to improve boundary definition and identify spatial variations within the engraved regions. The resulting grayscale values were used solely as image-analysis data and were not interpreted as colorimetric measures of perceived contrast.

2.4. Digital image analysis

Image analysis was performed using ImageJ (version 1.53). Three groups of characteristics were evaluated: line reproduction, geometrical shape reproduction and engraved-surface uniformity.

2.4.1. Line-width measurements

The width of each engraved line was measured manually using a linear region of interest (ROI) positioned perpendicular to the stroke. Vertical measurement ROIs were used for horizontal lines, and horizontal ROIs for vertical lines. For each nominal line width and laser setting, 40 measurements were taken: 20 from horizontal lines and 20 from vertical lines. After spatial calibration, all measurements were recorded in millimeters. The mean line width (w_{mean}), standard deviation (SD), and coefficient of variation (CV) were calculated for each nominal width, line orientation and laser setting.

The line width deviation (Δw) from the nominal line width ($w_{nominal}$) was calculated as (1):

$$\Delta w = w_{mean} - w_{nominal} \qquad (1)$$

while the relative line-width increase was calculated as (2):

$$\Delta w_{relative} = (w_{mean} - w_{nominal}) / w_{nominal} \times 100 \quad (2)$$

Positive values indicate that the engraved line is wider than its nominal width, while negative values indicate that it is narrower. These parameters capture both systematic dimensional deviations and local variability in the reproduced line width.

2.4.2. Geometrical analysis of circles and squares

Positive and negative geometric elements were segmented from the selected image channels and analyzed using ImageJ shape descriptors. The analysis focused on area and perimeter for both circles and squares, while circularity was additionally evaluated for circular elements as an indicator of contour regularity. Measured areas were compared with the corresponding nominal values. The nominal area was 100 mm² for a square with a side length of 10 mm and 78.54 mm² for a circle with a diameter of 10 mm. Relative area deviation was calculated as (3):

$$\Delta A_{relative} = (A_{measured} - A_{nominal}) / A_{nominal} \times 100 \quad (3)$$

Positive and negative elements were evaluated separately. For positive elements, expanding the laser-modified region increases the measured dimensions and area. For negative elements, expanding the engraved surrounding region reduces the dimensions and area of the preserved, untreated shape.

2.4.3. Evaluation of engraved-surface uniformity

Engraved-surface uniformity was evaluated across the entire solid engraved area. Ten square ROIs measuring 5 × 5 mm were placed at predefined positions within the engraved region. The same ROI arrangement was used for all samples. For each ROI, the mean gray value (MGV_i) and the corresponding standard deviation (SD_i) were calculated. A reference mean gray value ($MGV_{reference}$) was obtained from the untreated area of the same paperboard sample.

Because different image channels were selected for the three paperboard colors, raw grayscale variability was normalized relative to the grayscale change caused by engraving. A normalized local nonuniformity index (NU_i) was calculated for each engraved ROI using (4):

$$NU_i = SD_i / | MGV_i - MGV_{reference} | \times 100 \quad (4)$$

For each laser setting the mean normalized nonuniformity and its standard deviation were calculated from the ten ROI values. A higher (NU) value indicates greater local grayscale variation within the engraved area relative to the grayscale difference between the engraved and untreated regions.

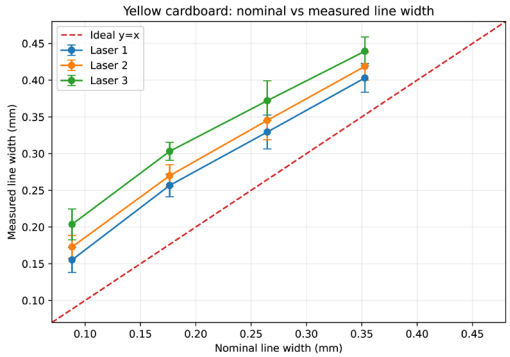
3. Results and discussion

The quality of laser engraving was evaluated through four complementary aspects: dimensional reproduction of line elements, dimensional accuracy of positive and negative geometrical shapes, preservation of shape geometry and uniformity of larger engraved areas. This approach enabled assessment of the influence of laser settings not only on overall dimensional changes, but also on local variability, contour integrity, and surface homogeneity.

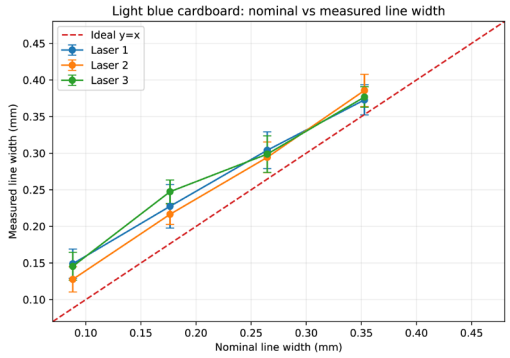
3.1. Reproduction of line elements

The relationship between nominal and measured line width for the three paperboards is presented in Figures 2a–c. In all cases, the measured line width exceeded the nominal value, indicating a systematic widening of the laser-modified region. However, the magnitude of this deviation depended strongly on both the nominal line width and the applied laser setting.

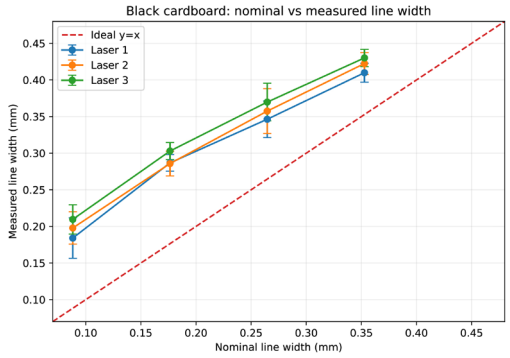
For the yellow paperboard (Figure 2a), line widening increased with laser intensity. The effect was relatively modest for the widest 1 pt (0.353 mm) lines, which measured 14–25% wider than nominal, but became considerably more pronounced as the nominal width decreased. For the finest 0.25 pt (0.088 mm) lines, the relative increase ranged from approximately 76% to more than 130%, depending on the laser setting. A similar relationship between nominal width and relative dimensional error was observed for the black paperboard (Figure 2c). The widest 1 pt (0.353 mm) lines showed a comparatively limited increase, whereas the 0.25 pt (0.088 mm) lines were more than twice as wide as their nominal dimensions under all three laser settings. The increase became progressively greater at higher laser settings, reaching approximately 138% at the highest setting. The light-blue paperboard also exhibited widening of all investigated line elements (Figure 2b). However, unlike the more regular trends observed for the yellow and black samples, the change in measured width with increasing laser setting was not strictly monotonic. Nevertheless, the effect of nominal line width remained evident: the relative dimensional deviation increased substantially as the designed line became thinner. The different response observed for the light-blue paperboard might also be partly affected by its lower grayscale contrast in the selected analysis channel, which could reduce edge visibility and increase uncertainty in the manual positioning of line-width measurements.



(a)



(b)

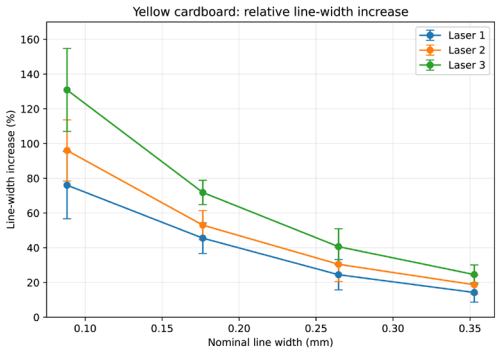


(c)

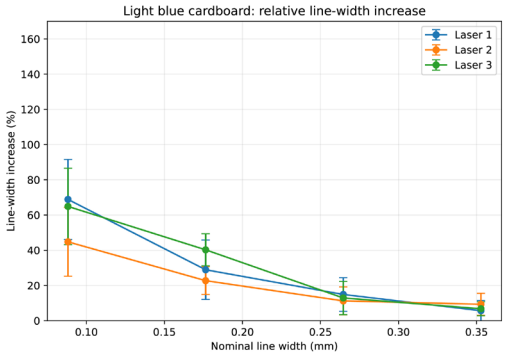
» **Figure 2:** *Line width reproduction - nominal versus measured line width for yellow (a), light-blue (b) and black (c) paperboards, respectively. Error bars represent ±1 SD*

The relative increase in line width for all three paperboards is shown in Figures 3a–c. These results further underscore the engraving process's increasing sensitivity as the nominal line width decreases. Although the relative dimensional change remained relatively small for the widest elements, it increased substantially for the finest lines, particularly at a nominal width of 0.25 pt.

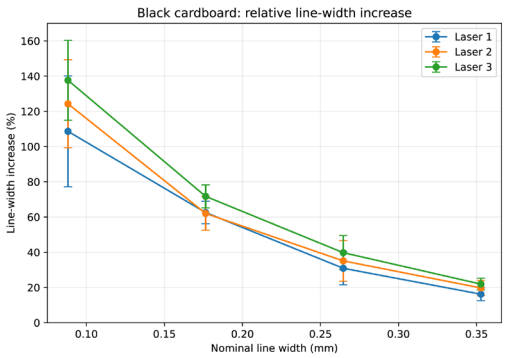
The error bars in Figures 2a–c and 3a–c represent ±1 standard deviation, providing additional information about the local repeatability of line reproduction. For the wider 1 pt lines, coefficients of variation were generally low, indicating relatively consistent reproduction along the measured segments. Relative variability tended to increase as nominal width decreased. This was especially evident for the 0.25 pt elements, where CV values reached approximately 9–15%, depending on the paperboard and laser settings.



(a)



(b)



(c)

» **Figure 3:** *Relative line-width increase for yellow (a), light-blue (b) and black (c) paperboards, respectively. Error bars represent ±1 SD*

Analyzing dimensional deviation alongside CV is important because the two parameters describe different aspects of reproduction quality. A line may show a substantial systematic increase in width while maintaining a relatively low CV, indicating consistent widening along the engraved element. Conversely, a high CV indicates greater local variation in line width and, consequently, lower dimensional uniformity. The pronounced relative error observed for the finest lines can be explained by the lateral extension of the laser-modified zone beyond the nominal graphic boundary. Even a small

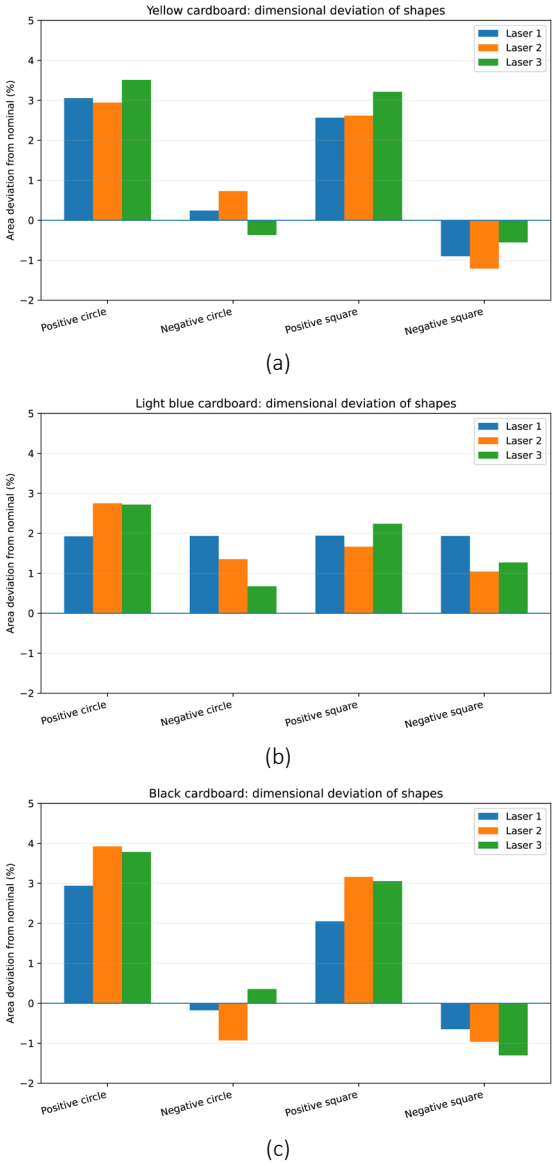
absolute lateral expansion accounts for only a minor fraction of a wide element but becomes a substantial proportion of the nominal dimension when very thin elements are engraved. Therefore, the smallest nominal line widths are inherently more sensitive to the characteristics of the laser–material interaction.

This finding aligns with Lei et al. (2020), who demonstrated that laser engraving quality on paper depends on both laser intensity and the preset width of the engraved marks. A comparable effect of increased energy input on the lateral dimensions of laser-treated zones has also been reported for other lignocellulosic materials, where higher laser power resulted in increased kerf width (Štefančin et al., 2026). The present results therefore confirm that nominal element width should be considered alongside laser parameters when evaluating the reproducibility of fine graphic details.

3.2. Dimensional reproduction of geometrical shapes

The relative area deviation of positive and negative circles and squares for the three paperboards is presented in Figures 4a–c. The results indicate that the dimensional response of each geometric element depended on whether the analyzed shape represented the engraved region itself or an unengraved area enclosed by engraving.

For the yellow paperboard (Figure 4a), positive circles and squares generally exhibited areas larger than their nominal dimensions. The increase was relatively small compared with that observed for the finest line elements, typically remaining within a few percent of the nominal area. Negative elements remained closer to their nominal dimensions, with the negative square showing a slight reduction in area. A similar behavior was observed for the light-blue paperboard (Figure 4b), while positive elements generally exhibited a positive area deviation, whereas the dimensional response of the negative elements was smaller and less regular. In particular, the negative circle showed a tendency toward decreasing area as the laser setting increased. For the black paperboard (Figure 4c), positive circles and squares again showed areas larger than the corresponding nominal values. In contrast, the negative square exhibited a gradual reduction in area with increasing laser treatment, while the negative circle remained comparatively close to its nominal size. Overall, positive circles and squares generally exhibited areas larger than their nominal dimensions. The increase was relatively small compared with that observed for the finest line elements, typically remaining within a few percent of the nominal area. Nevertheless, the direction of the deviation was consistent with the widening observed for the line structures. The behavior of negative elements was different in geometrical terms. Since the region surrounding the shape was engraved, lateral extension of



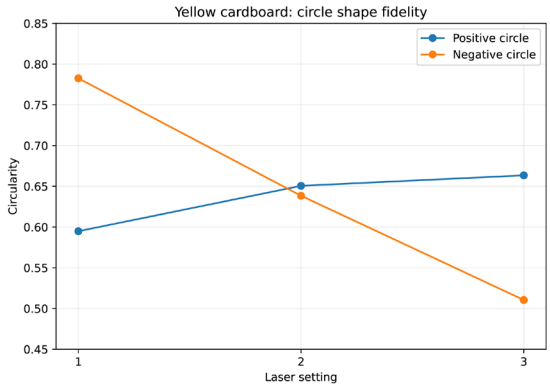
» **Figure 4:** *Relative area deviation of positive and negative circles and squares for yellow (a), light-blue (b), and black (c) paperboards*

the laser-modified area occurred towards the interior of the unengraved element. Consequently, the preserved negative area tended to decrease. This effect was particularly evident for some of the negative square elements, where increasing laser treatment was accompanied by a gradual reduction in measured area. Positive and negative elements should therefore not be interpreted as showing different physical responses to laser treatment. Both behaviors arise from the same lateral expansion of the laser-affected region. The apparent difference results solely from the position of the analyzed contour: outward expansion increases the area of a positive engraving, while inward expansion reduces the remaining area of a negative element. The area measurements further indicate that the dimensional effect observed for isolated lines also extends to more complex closed geometries. However, the relatively small changes in total

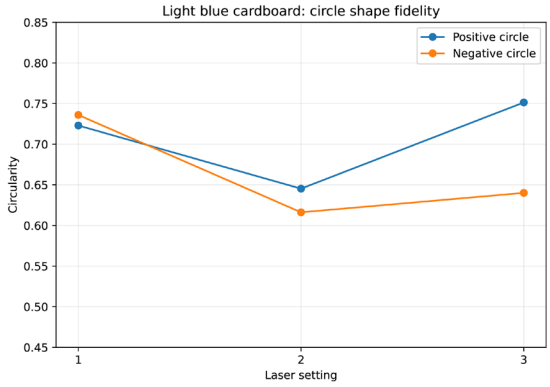
area compared with the more pronounced variations in some contour descriptors demonstrate that area alone is not sufficient to characterize reproduction quality.

3.3. Preservation of shape geometry

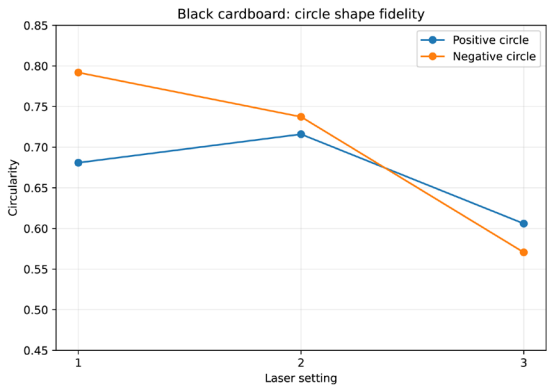
Circularity was used to assess how well the circular geometry was preserved. The results for the yellow, light-blue, and black paperboards are shown in Figures 5a–c, respectively. Unlike area, which mainly reflects an element's overall size, circularity is strongly affected by contour irregularities because it depends on perimeter.



(a)



(b)



(c)

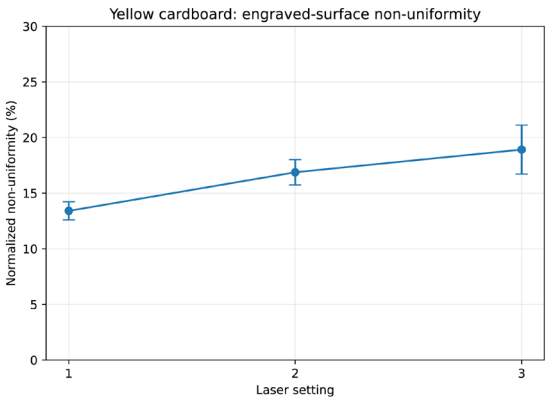
» **Figure 5:** *Circularity of positive and negative circular elements for yellow (a), light-blue (b), and black (c) paperboards*

For the yellow paperboard (Figure 5a), the positive circle's circularity increased slightly with laser setting, whereas the negative circle's circularity decreased markedly. This suggests that the negative element's contour became progressively less regular despite relatively limited changes in its total area. For the light-blue paperboard (Figure 5b), changes in circularity were less monotonic. Both positive and negative circles varied across the three laser settings, indicating that contour response was not governed solely by increasing laser intensity. For the black paperboard (Figure 5c), the positive circle showed its highest circularity at the intermediate laser setting, whereas the negative circle's circularity decreased markedly with increasing laser treatment.

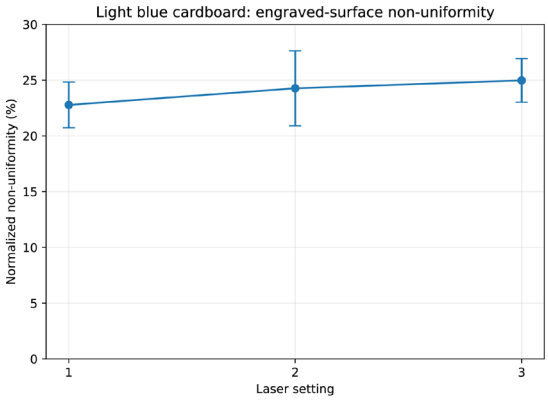
The results show that relatively small changes in measured area can be accompanied by much larger changes in circularity. This was particularly evident for several negative circular elements, where the area remained close to the nominal value while circularity decreased with increasing laser treatment. This behavior indicates that stronger laser treatment may affect the local contour without necessarily producing an equivalent change in total element area. Local protrusions, recesses, fiber removal and boundary irregularities increase the measured perimeter and consequently reduce circularity. For example, the negative circles on both the yellow and black paperboards showed a marked reduction in circularity as the laser setting increased, whereas their total areas changed considerably less. The results therefore demonstrate the importance of separating dimensional accuracy from contour fidelity. The same interpretation is supported by perimeter measurements of the square elements. In some cases, the measured perimeter increased despite only minor changes in total area, suggesting that the contour became geometrically more complex rather than simply larger or smaller. This behavior is consistent with the heterogeneous nature of paper-based materials. Schechtel et al. (2016) demonstrated that laser processing of paper is influenced by both the composition of the paper matrix and the inherent cellulose fibers. Local differences in fiber arrangement and material composition may therefore result in non-uniform material removal along the engraved boundary, contributing to contour irregularity. Accordingly, area, perimeter, and circularity should be viewed as complementary parameters. Area indicates overall changes in size, whereas perimeter and circularity are more sensitive to local changes in boundary quality.

3.4. Uniformity of the engraved surface

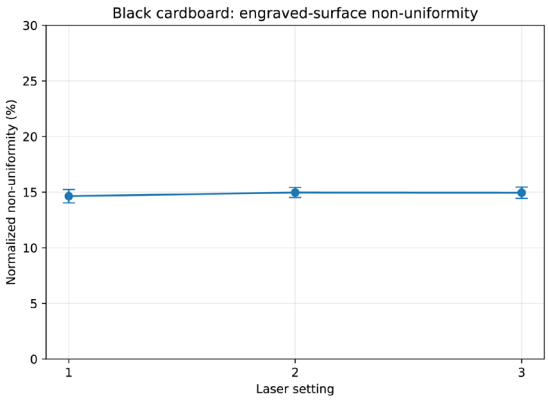
The normalized non-uniformity index was used to characterize local grayscale variation within the larger engraved areas. The results for the three paperboards, expressed as mean normalized non-uniformity ±1 SD, are presented in Figures 6a–c.



(a)



(b)



(c)

» **Figure 6:** *Normalized non-uniformity of engraved surfaces for yellow (a), light-blue (b), and black (c) paperboards. Values represent the mean of ten analyzed ROIs ±1 SD*

For the yellow paperboard (Figure 6a), normalized non-uniformity increased progressively with increasing laser setting, from approximately 13% to 19%. In parallel, the coefficient of variation increased at the highest setting, indicating that the stronger laser treatment was associated not only with greater local tonal variation but also with less consistent surface behavior among the analyzed regions. The light-blue paperboard (Figure 6b) also showed an increase in mean normalized non-uniformity with increasing laser setting, although the magnitude of the change was smaller. The CV varied between the three settings, indicating that spatial variability did not follow a strictly monotonic trend. In contrast, the black paperboard (Figure 6c) exhibited highly similar normalized non-uniformity values under all three laser settings, with mean values close to 15%. The corresponding CV values remained low, approximately 3–4%, indicating relatively stable local surface characteristics throughout the analyzed engraved region. For the light-blue paperboard, the lower grayscale contrast between engraved and untreated regions might also influence the normalized non-uniformity values, since a smaller engraved-to-reference intensity difference increases the sensitivity of the index to local grayscale variations.

These findings demonstrate that surface uniformity does not necessarily respond to laser treatment in the same manner as dimensional reproduction. A laser setting that produces a greater change in line width or contour geometry does not automatically result in a proportionally greater degree of surface non-uniformity. The normalized index is particularly useful in this context because the standard deviation of grayscale values is interpreted relative to the tonal difference between the engraved and unengraved reference areas. Consequently, the parameter describes local variation within the engraved surface rather than its absolute brightness. The use of grayscale variability as an indicator of surface uniformity has methodological parallels in previous image-analysis studies. Kennedy and Niebergall (1997), for example, used standard deviations of optical measurements to assess coating uniformity. The observed variations can also be related to the heterogeneous structure of paperboard. Local differences in fiber distribution, fillers, pigments and surface structure may influence the extent of material removal and thermal modification within the laser-treated area (Schechtel et al., 2016).

4. Conclusions

The results demonstrate that laser engraving quality on colored paperboard cannot be adequately characterized by a single image-analysis parameter. Dimensional accuracy, local repeatability, contour fidelity and surface uniformity describe complementary aspects of engraving quality and may respond differently to changes in laser settings.

Across all investigated paperboards, engraved line widths exceeded their nominal values, indicating consistent lateral expansion of the laser-modified zone. This effect became more pronounced as nominal line width decreased. The largest relative deviations and, in several cases, the highest coefficients of variation occurred in the finest 0.25 pt (0.088 mm) lines, making very thin graphic elements the most critical features for dimensional reproduction. Analysis of positive and

negative geometric elements confirmed that both were affected by the same lateral expansion, although the dimensional impact depended on the location of the analyzed boundary. Positive elements generally increased in area, while expansion of the engraved surroundings could reduce the preserved area of negative elements. Circularity and perimeter offered further insight into contour fidelity, revealing boundary irregularities that were not necessarily evident in total-area changes. The normalized non-uniformity index provided complementary information about spatial variations within larger engraved areas. Its response to increasing laser power varied among the investigated paperboards and did not necessarily align with trends in dimensional reproduction. These findings further underscore the need to assess dimensional and surface-related characteristics separately when evaluating engraving quality.

Overall, combining line-width measurements, shape descriptors, and normalized surface-uniformity analysis offers a useful image-based framework for objectively assessing laser-engraved paperboard. Instead of relying on a single quality indicator, this approach allows different aspects of reproduction quality to be evaluated together and may help define material-specific engraving conditions and minimum reproducible graphic-element dimensions.

Future work should include a broader range of paperboard types and colors, repeat engraving trials independently, and conduct additional analysis of color and visual contrast between engraved and non-engraved areas. In particular, the possible influence of image contrast on edge localization and normalized surface-uniformity measurements should be investigated to distinguish material-related effects from image-analysis sensitivity.

5. Acknowledgments

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