Advances in Science and Technology Research Journal

Advances in Science and Technology Research Journal 2024, 18(4), 111–127
https://doi.org/10.12913/22998624/188584
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Received: 2024.03.28
Accepted: 2024.06.03
Published: 2024.06.20

Photogrammetry-Aided Study of the Accuracy and Repeatability of a Modular System for Manufacturing Shelf Ready Packaging

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ABSTRACT

The paper presents an analysis of the influence of the shelf ready packaging (SRP) machine performance parameters on the repeatability of generated cardboard boxes' selected geometric features. As part of the research, two batches of packaging were measured. Each batch contained 100 pieces of packaging, manufactured either at a rate of 15 pcs/min or 20 pcs/min, 50 pcs each. Both batches were measured using Creaform's Academia scanner using VXelements 6.2 software. The results were analyzed using GOM Inspect programming. In the first stage, the geometric repeatability of the products was analyzed on the basis of two selected critical features, which were considered to be the internal length and width of the cardboard packaging. These features are responsible for the proper efficiency of the packaging and the possibility of combining cartons during transportation. The results obtained were subjected to statistical analysis. In the second stage of the research, an analysis of surface deviation maps was carried out against a reference element. Our findings allow it to be concluded that increasing the production output of carton packaging (from 15 to 20 pcs/min) did not negatively affect the dimensional accuracy and repeatability of the process. It was also found that the shortening of packaging production time by increasing productivity had a positive effect on the stability of the manufacturing process of hot-glued SRP packaging.

Keywords: coordinate measuring technique, photogrammetry, shelf ready packaging, repeatability.

INTRODUCTION

In the grocery supply chain, shelf ready packaging (SRP) plays a pivotal role. This is due to the intention to reduce labor costs in the store, resulting from the reduction of time spent by products stacking on shelves, reducing product identification time, etc. [1–5].

SRP packaging can be folded by hand, which creates the possibility of quick and investment-free implementation by the manufacturer of marketed products. However, this is where the advantages of this type of packaging end. Hot-glued packaging is an alternative to the commonly used hand-folded SRP packaging. Its manufacture requires the use of complex machinery, but, as a result, hot-glued packaging is cheaper than hand-folded packaging, resulting in savings [6–8]. In addition, it should be noted that hand-folded bulk packaging is not suitable for automated packaging systems due to the non-rigid nature of its design and shape variability [2]. Thus, it can be concluded that at present the use of hot-glued packaging has become a necessity. Hot-glued SRP packaging, both the different packaging designs and dimensional series, appear to be easy to inventory. Much more difficult is to inventory the market-dominant group of hand-folded packaging, which will be replaced by hot-glued packaging for the reasons mentioned above. As the authors of the paper [3] emphasize, food packaging companies are obliged to carry out activities and provide appropriate conditions to ensure the safety of packaging materials and food contact packaging.

The author of the paper [9] also describes an innovative approach to modern smart packaging in controlling and/or reducing quantitative and qualitative losses during transportation and storage of goods. Since the manufactured packaging throughout the transport and handling chain, are subjected to significant static and dynamic loads, this imposes certain significant requirements on the machinery producing the final product in the form of finished cardboard packaging. As the author of the paper [10] points out, an important issue is the machine's vibrations and acoustic measurements [11] with a complex design and, in addition, with multiple drive units. Increasing the efficiency of automatic packaging machines reduces the duration of the entire process but can affect deformations, i.e. changes in the dimension and shape of the finished package. This can ultimately lead to a break in the transport and handling chain and a deterioration of the quality characteristics of the finished product.

Ensuring the safety of packaging and minimizing losses during transportation and storage of goods pose significant challenges across various industries. Innovative strategies, such as smart packaging, present fresh opportunities to address and mitigate losses throughout the supply chain. Smart packaging leverages advanced technology and environmental monitoring to track the conditions of goods during transport and storage in real time. This enables manufacturers and distributors to receive timely information regarding factors like temperature, humidity, shock, and light exposure, empowering them to swiftly address potential product safety risks. The advent of smart packaging also facilitates monitoring of merchandise consumption levels and expiration dates, enhancing inventory management and waste avoidance [12]. Assessing packaging dimensions and shape is crucial for maintaining high-quality packaging. While traditional quality assessment methods often focus on mechanical strength alone, the utilization of 3D scanners is increasingly prevalent for precise analysis of packaging geometry. This enables detection of even the most minute defects or inconsistencies. A notable challenge for manufacturers and suppliers is the lack of comprehensive guidelines for measuring the geometric characteristics of cardboard packaging and its impact on the supply chain. Therefore, there is a pressing need for research and the development of standards to uniformly evaluate packaging quality and streamline logistics processes. In summary, the adoption of innovative approaches like smart packaging and geometry analysis for packaging safety risk management can significantly enhance the efficiency and safety of the entire supply chain. This, in turn, fosters increased consumer confidence and reduces losses for companies.

Quality requirements for the finished products have necessitated the use of a method to analyze the measurements in terms of geometric shapes and dimensions. In order to obtain these requirements, the designed measuring equipment must quickly collect reference points with the highest possible accuracy in a non-contact manner. A method that meets the requirements is the optical method, which is one of the fastest developing branches of coordinate measuring techniques [13, 14]. Thanks to the development of technology and the increase in the power of computers, the transmission of large-scale data is no longer a problem. Optical technology is now finding more and more applications. It is used in the automotive industry [15, 16], aerospace [17, 18], engineering [19], quality control, and reverse engineering [20]. The optical measurement method allows precise measurements of items featuring intricate geometries, including those crafted from flexible materials like sponges, foams, or plastics [21, 22], as well as those produced via additive technologies [23], and metal components fabricated through wire arc additive manufacturing [24]. Furthermore, there is an emerging potential for extending the application of this technology to smaller scales [25].

Guidelines for the implementation of photogrammetric techniques for testing and inspection in production conditions and new implementations include all the activities related to the preparation of photogrammetric equipment for both manual and automatic (robotic) operation.

It should be mentioned that there are no detailed guidelines in the literature for measuring the geometric characteristics of cardboard packaging. The authors of the paper [26] presented the application of a photogrammetric method for measuring cardboard products in terms of its compressive strength and the formation of deformations during long-term storage and transportation.

In the presented design work, the results of bench tests were used, in which special emphasis was placed on multivariate testing of the performance of the modular SRP system. Independently of the tests performed on the test bench, a research agenda was carried out that included performance evaluation of the prototypes made. The construction work was preceded by drives tests to determine the accuracy and repeatability of positioning of paperboard formats through manipulator and drive modules. Photogrammetric studies of the accuracy and dimensional repeatability of the packaging (trays) presented in this article made it possible to determine the impact of increasing efficiency on the quality parameters of the finished product. Modern measurement systems using optical scanners, in addition to a large number of measuring points, and the lack of need for physical contact with the measured element, also provide speed and repeatability of measurements. Thus, the use of 3D scanning technology is becoming an integral condition for providing manufactured products with the required quality. Furthermore, it eliminates errors in the production preparation process. The organization of the rest of the paper is as follows: section 2 presents functional structure of a modular hot-glued SRP packaging machine. Section 3 describe purpose and scope of the study. Section 4 describe methodology for measuring and analyzing the results obtained. Section 5 presents the experimental analysis and results. Finally, section 6 provides the conclusion.

FUNCTIONAL STRUCTURE OF A MODULAR HOT-GLUED SRP PACKAGING MACHINE

Hot-glued SRP packaging machines come as transverse machines, where the longer axis of the package moves transversely to the machine axis, and longitudinal machines. Depending on the design of the packaging, one solution is more advantageous than the other. A machine of this type is built with the following modules:

- the paperboard format buffering module, which can be made as gravity-based with an efficiency of about 150 formats, or driven with an efficiency of about 600 formats, ensures continuous operation of the machine; the buffer can be replenished manually or automatically;
- manipulation module, which is responsible for feeding paperboard formats from the buffer for further processing; a minimum of three different manipulator solutions are envisaged.
- an adhesive application module based on a commercial hot-melt adhesive system;
- three pre-molding modules carrying out the operations of bending, overbending, pressing, etc., carried out using pneumatic and electric drives selected and configured depending on the design of the package to be produced and the required performance;
- the final molding module, the drives of which, depending on the requirements of the packaging design and process, can be implemented pneumatically, by electric asynchronous drives equipped with encoders, or by servo drives.

The whole process integrates the product flow module, which, depending on the needs of the process (packaging design), the variety of packaging formats produced on the machine and the required performance, is implemented pneumatically, by an asynchronous drive with encoder, or by a servo drive. Multi-format machines are equipped with assembly changeover systems. Changeover functions can be performed manually or automatically from the operator panel. In the case of automatic changeovers, the changeover time is limited to tool changeovers because automatic changeovers will be much shorter and will be carried out almost simultaneously. If the tool change is limited only to changing the punch, the changeover time will not exceed 5 minutes, thanks to the use of fast mechanical, electrical, and pneumatic fasteners. Automatic changeovers are carried out using servo drives, so they are a factor in significantly increasing the price of the machine. The quality of the molded package is highly dependent on the process of feeding and moving the paperboard format to the glue application module. While the dynamics of the gluing process under real conditions does not limit the claimed process performance (path application speed ≤ 1 m/s), the accuracy and repeatability of format positioning prior to the gluing operation is affected by the drive used. The module control system meets the requirements of the "Industry 4.0" standard. It is equipped with a communication system, actuators, and sensors to enable efficient data exchange within the system and between other systems. A number of components and solutions have been used to meet the Industry 4.0 standard: an industrial controller supporting several communication protocols, distributed controller expansion modules, an operator panel allowing control and configuration of the system, a router with GSM modem enabling connection to an industrial network and remote access, cabling susceptible to system changes, additional communication standards and actuators with integrated control system and network access, configurable sensors with network access. The requirements of the Industry 4.0 standard must be met while maintaining safety standards. A dedicated processor with "safety" modules using safe inputs, outputs, and communication protocols in conjunction with typical safety devices, switches is responsible for controlling the safety system.

PURPOSE AND SCOPE OF THE STUDY

The main objective of the research was to apply the photogrammetric method to verify the modular SRP-type packaging production system with the innovative modular sequence compensation (MSC) solution, which will enable the improvement of the quality, efficiency, and effectiveness of the product – the existing bulk packaging production system. The research included determining the performance of the prototype packaging machine and the geometric accuracy of the packages. The measurement method used will make it possible to determine the effect of changing the production efficiency of hot-glued SRP cardboard packaging on the accuracy and repeatability of selected geometric features of the finished products. Cardboard packaging of the SRP type was prepared using the FTHT 6 horizontal molding machine designed to produce hot-glued cardboard trays of various formats and dimensions [27]. The following research was carried out to achieve the objectives of the presented research task:

- Scanning of 50 pieces of cartons made at a rate of 15 pcs/min – carton No. 1.
- Scanning of 50 pieces of cartons made at a rate of 20 pcs/min – carton No. 1.
- Scanning of 50 pieces of cartons made at a rate of 15 pcs/min – carton No. 2.
- Scanning of 50 pieces of cartons made at a rate of 20 pcs/min – carton No. 2.

Based on the obtained point clouds, a two-stage analysis of geometric features was carried out. In the first stage, the focus was on evaluating the repeatability of linear dimensions. In the second, one cardboard box was determined for each batch of 50 pieces, which was taken as a reference from which a research model was created. The measurement grids for all 50 cartons measured in the batch were referred to the developed model, obtaining a color map of deviations.

METHODOLOGY FOR MEASURING AND ANALYZING THE RESULTS OBTAINED

Creaform's Academia scanner, with VXelements 6.2 software [28], was used to measure the cartons. It is a portable handheld 3D scanner from Creaform based on white light technology. The device has two built-in cameras, where one of them is responsible for collecting information about the texture of the measured object. At the same time, it allows it to be scanned freely without the use of reference points, since the necessary information (geometric features and natural characteristics of the scanned object), is sufficient information to ensure a seamless orientation of the scanner with respect to the object. In cases where the item to be scanned is not characterized by color or geometric diversity, the positioning system can switch to hybrid mode, i.e. it can support itself simultaneously on geometric points and on reference points. Through the use of white light, the scanner becomes sensitive to reflective objects, which requires the user to properly adjust the object for examination, most often this consists of dulling the surface with spray chalk. In the case of scanning cardboard boxes, such a situation did not occur.

Before the scanning process, the device was properly calibrated in order to eliminate systematic error and thus maintain the specified measurement accuracy of the determined features. The calibration process was carried out on a special calibration plate using the manufacturer's software. The calibration plate is characterized by a certain geometry, and on its surface are plotted referee points with known position coordinates, forming a regular pattern. The plate is placed on a stable surface in a place of uniform illumination to avoid distortions due to external conditions. During the calibration process, the scanner takes a series of measurements of points on the calibration plate, taking into account different measurement distances and the angular orientation of the head relative to the plate. After the scanning process is completed in the software, the data collected by the scanner is analyzed and compared with the actual dimensions and coordinates of the reference points. If there are differences between the measurement results and the reference values, the device automatically makes corrections to the system calibration file. The scanner's internal calibration parameters include the angle between cameras, which can change due to shock or temperature, camera focal distance, optical distortion coefficients or data filtering parameters. After the calibration process is completed, the user is informed of the result of the scanner check. The presented research was carried out in a research laboratory located in the Department of Metrology and Measurement Systems at Poznan University of Technology. The test stand is shown in Figure 1. During measurement, constant environmental conditions prevailed (temperature of 20 °C ± 1 °C), measurements were carried out by one operator in a short period of time. In this way, the influence of internal factors that could negatively affect the measurement result was minimised. An important aspect is to maintain unchanged lighting conditions during measurement. Professional 3D scanners are designed and calibrated to minimize the impact of interfering factors on measurement accuracy. The scanner is equipped with advanced lighting systems to compensate for changes in ambient light. In addition, the professional 3D scanner has adaptive algorithms that automatically adjust scanning parameters to changing lighting conditions, ensuring stability and consistency of measurements. They also have data processing algorithms to detect and correct surface distortions of objects resulting, for example, from reflections, transparency or irregular surface texture. In addition, light angles were adjusted accordingly during scanning to avoid uncontrolled reflections interfering with data collection.

As already mentioned in the introduction, the main objective of the research was to determine the effect of changing the production efficiency of cardboard packaging on the repeatability of selected geometric characteristics. This allows the process to be optimized to increase productivity, as well as determine the limits at which quality problems may arise. Repeatability is the property that readings are close to each other when the same measurand is measured repeatedly under the same reference conditions. The repeatability error is revealed by the scatter of readings and is usually expressed in terms of standard deviation or multiples thereof. The project studied two types of cartons, obtained at two different efficiencies of 15 pcs/min and 20 pcs/min. The cartons were produced using a modular shelf ready packing (SRP) system developed and built by the company PROTiM.

The analysis of internal dimensions was assumed, so the scan was limited only to the internal surfaces of the cartons. Prior to taking measurements with the 3D scanner, reference points were pasted onto the cardboard placed on a turntable. The reference points were placed randomly with the idea that in each shot the scanner would

Figure 1. Test stand showing Creaform's Academia scanner with the test object

"see" at least three points in common with an earlier shot. An example of the location of reference points for cardboard packaging No. 1 is shown in Figure 2.

For the analysis of accuracy and repeatability, two geometric characteristics of the cartons under consideration were selected (Figure 3): length measured inside the carton – "Dimension A" expressed in millimeters, and width measured inside the carton – "Dimension B" expressed in millimeters. The values of surface deviations from the adopted nominal object were also analyzed.

The various stages of measurement and analysis of the obtained point clouds are presented below in the form of a graphic diagram (Figure 4).

As a result of the measurements, the data obtained in the form of a point cloud, were subjected to further processing and optimization. The point clouds corresponding to the measurement data were subjected to a polygonization process. This consists of building a model in the form of a triangular grid, with vertices located at individual points in the collection. This generated files in STL format and created 3D models of the measured objects. The scanning of each object produces many individual scans, which must be automatically combined using an intelligent algorithm based on surface matching and on a combination of reference points to obtain the most complete model possible [14].

RESULTS

Linear dimension analysis

On the basis of the obtained point cloud from the 3D scanner, after it was cleaned and surface optimization was carried out (mesh errors were dormant), dimensional analysis of the studied objects was carried out in GOM Inspect software.

As already mentioned in the first stage, two dimensions of the tested cartons were analyzed:

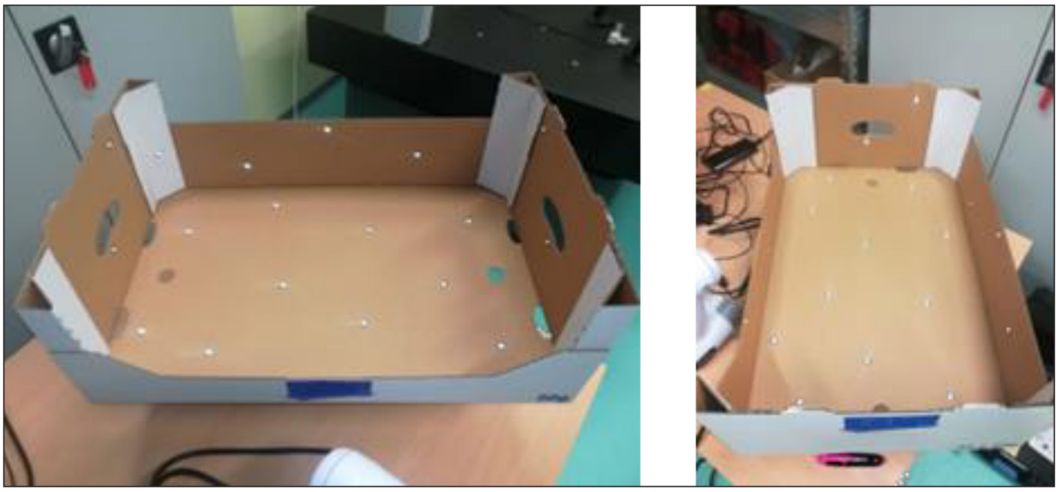

Figure 2. Location of reference points for cardboard packaging No. 1

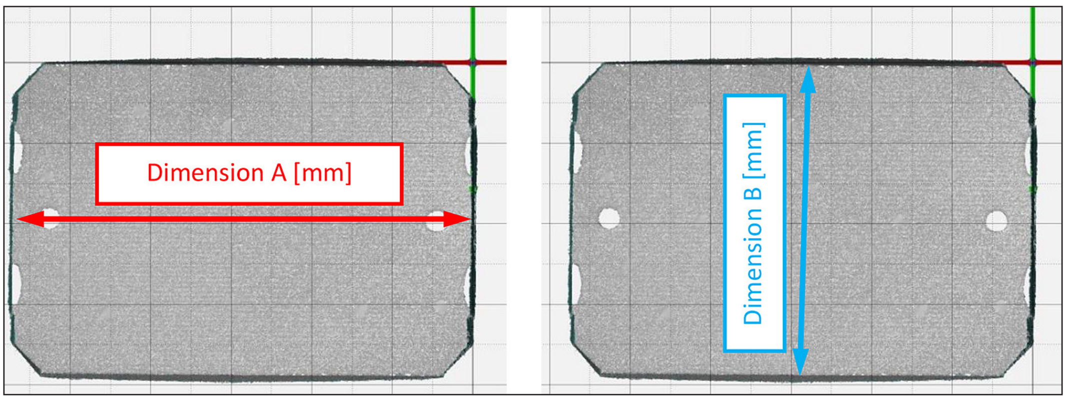

Figure 3. Dimensions analyzed

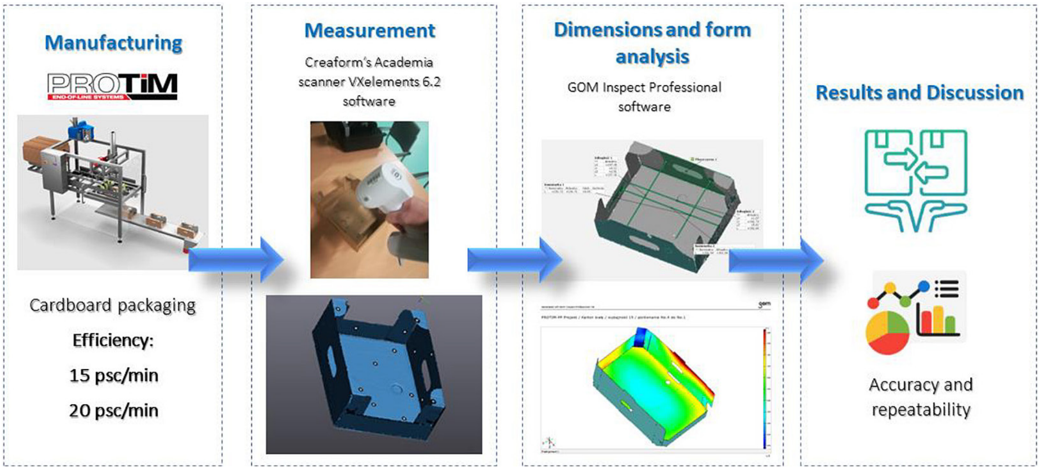

Figure 4. The different stages of analysis of the obtained measurement scans – methodology for measuring

width (dimension B) and length (dimension A). The results obtained were subjected to statistical analysis, which included the determination:

- arithmetic mean,
- medians,
- kurtosis *K*,
- skewness coefficient *A*,
- the maximum MAX and minimum MIN values of a random variable,
- spread *R* = MAX – MIN,
- standard deviation *s*(*x*)
- histogram of the measurement results.

The primary measure of inaccuracy is the standard uncertainty *u*(*x*), expressed in the form of standard deviation *s*(*x*) and expanded uncertainty *u*(*x*) understood as quantities that define the interval around the measurement result [29]. They include a large, dependent on the adopted confidence level, part of the distribution of values that can be reasonably attributed to the measured quantity [29, 30]. The report uses the type A method (statistical method) to analyze measurement uncertainty. The adopted method of estimating measurement uncertainty is realized by measuring the same element *n* times, in the same position, with the same equipment and under the same repeatability conditions. The standard uncertainty *u*(*x*) is determined by the experimental standard deviation *s*(*x*):

$$u(x) = s(x) = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}} \tag{1}$$

where: $\bar{x}$ - arithmetic mean value calculated from the formula:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

where: x_i – the next measurement result, *n* – the number of measurements (*n* = 50).

The standard uncertainty of the measurement thus determined can be assigned to each observation $x_1,\dots,x_n$ taken separately. It is possible to reduce the value of the standard uncertainty by determining the average value of a series of measurements. Then the uncertainty is calculated according to the formula:

$$u(\bar{x}) = s(\bar{x}) = \frac{s(x)}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n(n-1)}} \tag{3}$$

In the above case, the uncertainty is o times smaller than the standard uncertainty of a single measurement. The expanded uncertainty *U*(*x*) is understood as the value defining the interval around the measurement result. It is obtained by multiplying the standard uncertainty by the appropriate expansion factor:

$$U(x) = k \cdot u(x) \tag{4}$$

where: *U*(*x*) – expanded uncertainty, *u*(*x*) – standard uncertainty, *k* – coefficient of expansion depending on the adopted confidence level.

For calculations, *k* = 1.960 is most often taken, which corresponds to the quantile of the normal distribution $u_{\alpha,n}$ at the confidence level *P* = 95%. When the number of repetitions is less than 30, the expansion factor takes the value of the quantile of the Student's distribution. For example, for a confidence level of *P* = 95%, the quantile of the Student's distribution is $t_{\alpha,n}$ = 2.262. Statistical parameters were determined in a series of 50 repetitions (*n* = 50). The skewness of *A* was determined from the equation:

$$A = \frac{n}{(n-1)(n-2)}\sum_{i=1}^{n}\left(\frac{x_i-\bar{x}}{\sigma}\right)^3 \tag{5}$$

The Equation was used to determine *K* kurtosis:

$$K = \left\{\frac{n(n+1)}{(n-1)(n-2)(n-3)}\sum_{i=1}^{n}\left(\frac{x_i-\bar{x}}{\sigma}\right)^4\right\} - \frac{3(n-1)^2}{(n-2)(n-3)} \quad (6)$$

Table 1 and 2 summarizes the compiled statistical results of measuring cardboard packaging No. 1 and No. 2. For a normal distribution, the kurtosis statistic equals zero. A positive kurtosis suggests a higher occurrence of extreme outliers compared to a normal distribution, while a negative kurtosis suggests fewer positive outliers than in a normal distribution. A skewness coefficient exceeding 0 indicates a right-skewed (positive skew) distribution, while a coefficient below 0 indicates a left-skewed (negative skew) distribution. For cardboard packaging No. 1 (Table 1), the values of kurtosis and skewness for an efficiency of 20 psc/min took on a positive value for both the dimensions A and B considered. For a efficiency of 15 psc/min for dimension A, skewness and kurtosis took on a negative value, amounting to -0.21 and -0.14, respectively. For cardboard package No. 2 (Table 2), the value of skewness was negative for dimension B for the 15 psc/min and 20 psc/min efficiency, amounting to -0.48 and -0.55, respectively. Kurtosis took on a negative value for dimensions A and B at 20 psc/min and dimension A for the efficiency of 15 psc/min. Figures 5 and 6 show the obtained histograms for the different measured geometric features and the different efficiency obtained with the modular SRP packaging system. All obtained distributions of measurement results showed convergence to a normal distribution. None of the results crossed the control lines, so none of the results were subject to excessive error. Comparative comparison of the values of the spread (Figure 7) of the length dimension and the width dimension for the first carton showed that in the case of length, increasing the output reduced the spread of the results, and so for 15 pcs/min the average value of the spread was 3.19 mm, while for

Table 1. Statistical parameters of the measurement results – cardboard packaging No. 1

Parameter	Efficiency 15 pcs/min		Efficiency 20 pcs/min	
	Dimension A [mm]	Dimension B [mm]	Dimension A [mm]	Dimension B [mm]
$\bar{x}$	577.16	386.80	577.74	387.91
MAX	578.51	389.32	579.25	391.24
MIN	575.32	384.28	576.53	385.58
R	3.19	5.040	2.72	5.66
mediana	577.08	386.92	577.73	387.93
s(*x*)	0.70	1.16	0.52	1.18
A	-0.21	0.08	0.24	0.59
K	-0.14	-0.61	0.80	0.73
$u_{0.95}$	0.10	0.16	0.07	0.17
$U_{0.95}$	0.20	0.32	0.14	0.33

Table 2. Statistical parameters of the measurement results – cardboard packaging No. 2

Parameter	Efficiency 15 pcs/min		Efficiency 20 pcs/min	
	Dimension A [mm]	Dimension B [mm]	Dimension A [mm]	Dimension B [mm]
$\bar{x}$	578.94	384.42	578.43	384.31
MAX	581.00	386.15	580.53	385.60
MIN	577.00	382.01	576.55	382.49
R	4.00	4.14	3.98	3.11
mediana	578.77	384.55	578.28	384.36
s(*x*)	0.97	0.85	0.99	0.73
A	0.26	-0.48	0.16	-0.55
K	-0.62	0.27	-0.86	-0.06
$u_{0,95}$	0.14	0.12	0.14	0.10
$U_{0,95}$	0.27	0.24	0.28	0.20

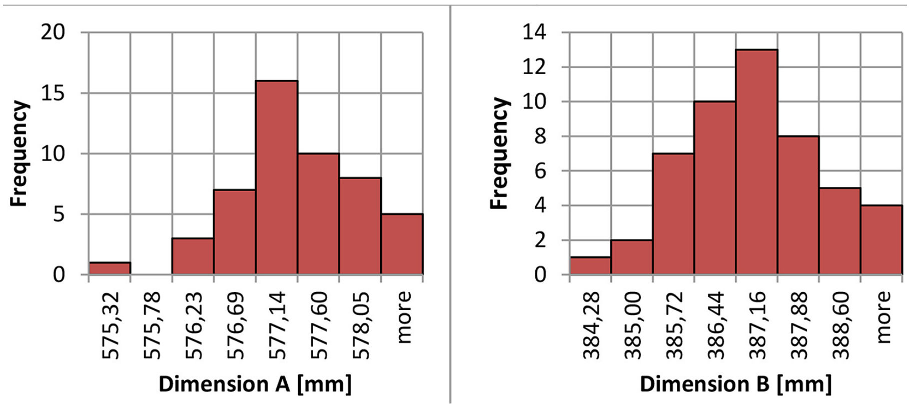

Figure 5. Histogram of dimension A [mm] (left side); dimension B [mm] (right side) – efficiency 15 pcs/min (cardboard packaging No. 1)

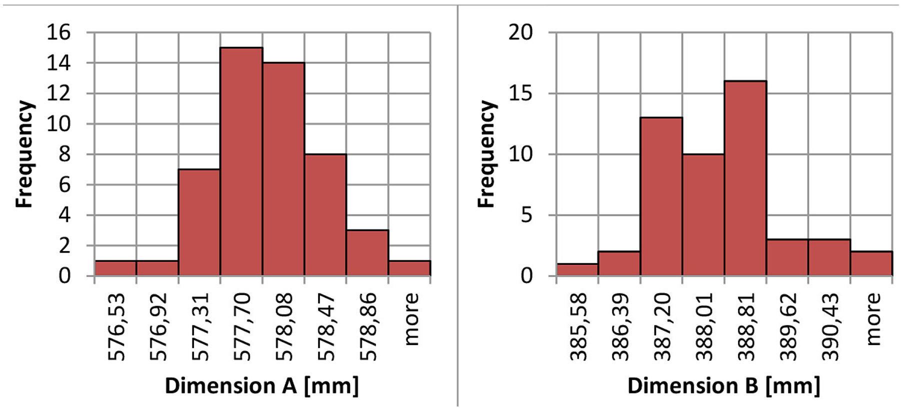

Figure 6. Histogram of dimension A [mm] (left side); dimension B [mm] (right side) – efficiency 20 pcs/min (cardboard packaging No. 1)

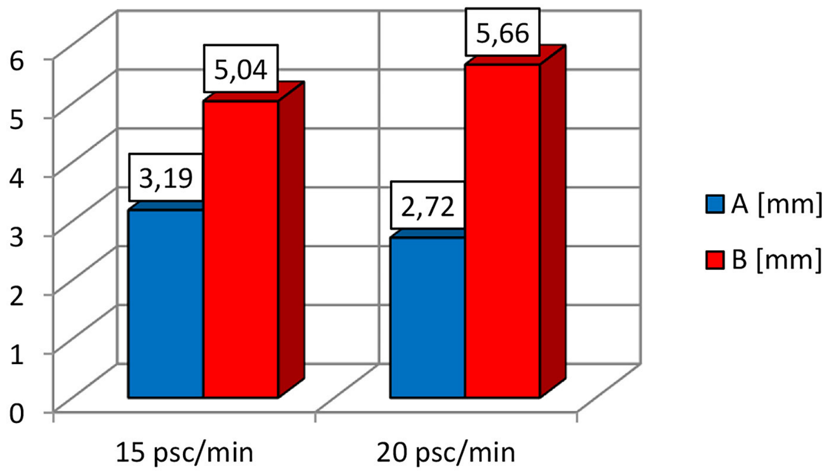

Figure 7. Comparison of the values of dimension A and dimension B divergence in relation to performance for the considered cardboard packaging No. 1

the output of 20 pcs/min it was 2.72 mm. In contrast, for the width dimension, the average value of the spread increased slightly from a value of 5.04 mm to 5.66 mm. A similar trend was noted for the comparison of standard deviation values (Figure 8). Also for the length value, the average value of the standard deviation with increased yield decreased from 0.70 mm to 0.52 mm, while

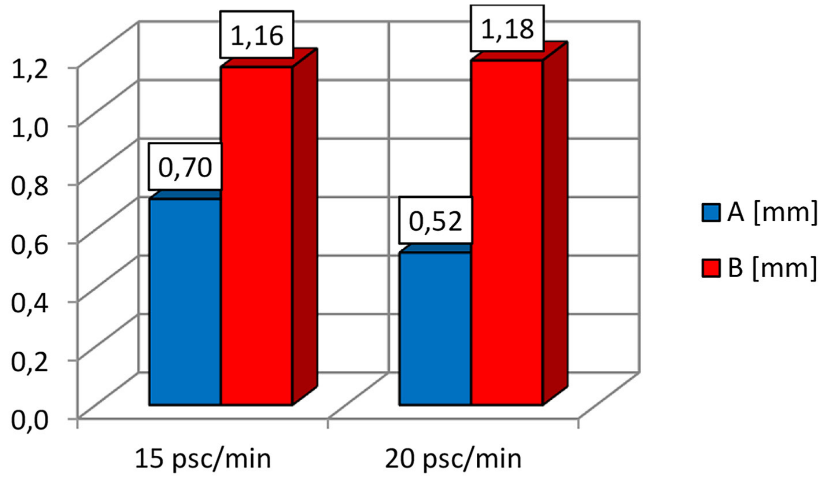

Figure 8. Comparison of the standard deviation values of dimension A and dimension B depending on the performance for the considered cardboard packaging No. 1

for the width dimension it increased slightly from 1.16 mm to 1.18 mm. Figures 9 and 10 show the obtained histograms for each measured geometric feature. As in the case of package one, the obtained results showed convergence to a normal distribution.

In the case of the second package, analyzing the values of the gap (Figure 11) of the measured characteristics, for both the length and width dimensions, the value of the gap decreased with increased performance. For the length dimension, the gap decreased from 4.00 mm to 3.98 mm, while for the width dimension it decreased from 4.14 mm to 3.11 mm. An identical situation occurs in the case of comparative analysis of standard deviation values (Figure 12). In this case, too, the mean value of the deviation decreased with increased efficiency. The change in the standard deviation values and scatter of the results was influenced by the design and construction of the cardboard packaging selected for analysis.

Analysis of surface deviation maps

In the second stage of the analysis, 1 carton was determined for each batch of 50 pieces, which was taken as a reference from which a research model was created. The measurement grids for all 50 cartons measured in the batch were referred to the developed model. When the element adopted as the model was compared with the corresponding grid, the deviations indicated zero values, which confirmed the correctness of the matching of the elements and the developed procedures.

Color deviation maps showing the differences between the base model and the next tested packaging were determined for cardboard packaging 1 and 2 made at 15 pcs/min and 20 pcs/min. In addition, analyses were performed in the cross-section located in the center of the package in two perpendicular directions (corresponding to the X and Y axes). For these cross sections, the distribution of deviations was determined, and the distribution of maximum and minimum deviation values was analyzed (Figure 13). In addition, control points were determined on each of the eight walls (4 main walls and 4 angled walls that are reinforcements), for which numerical deviation values were determined (Figure 14). Tables 3 and 4 show the numerical values with statistical analysis of the results obtained for the adopted control points. Table 3 deals with the deviation values obtained for the first type of carton packaging, and Table 4 for the second type of packaging. For simplicity, the following description of the individual columns of the tables was adopted:

1. Maximum value of negative deviation - cross-section in the Y-plane.
2. Maximum value of positive deviation - cross-section in the Y-plane.
3. Maximum value of negative deviation - cross-section in plane X.
4. Maximum value of positive deviation - cross-section in plane X
5. Deviation value - point 8.
6. Deviation value - point 7.
7. Deviation value - point 6.
8. Deviation value - point 5.
9. Deviation value - point 4.

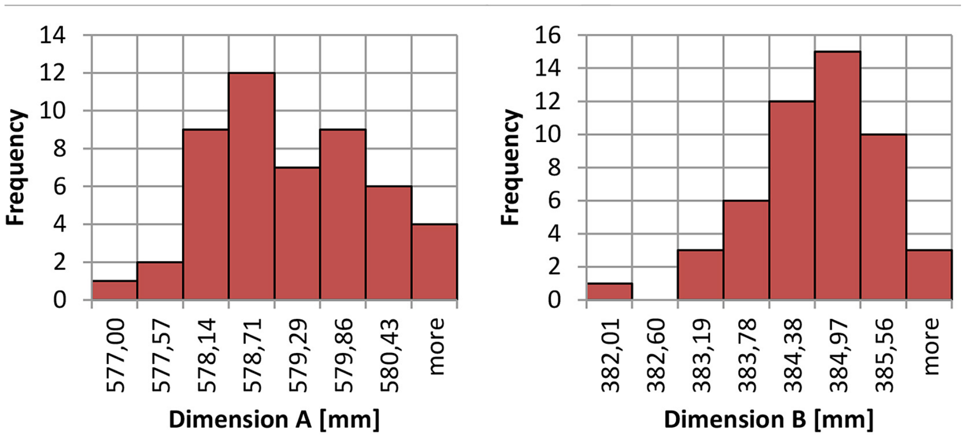

Figure 9. Histogram of dimension A [mm] (left side); dimension B [mm] (right side) – efficiency 15 pcs/min (cardboard packaging No. 2)

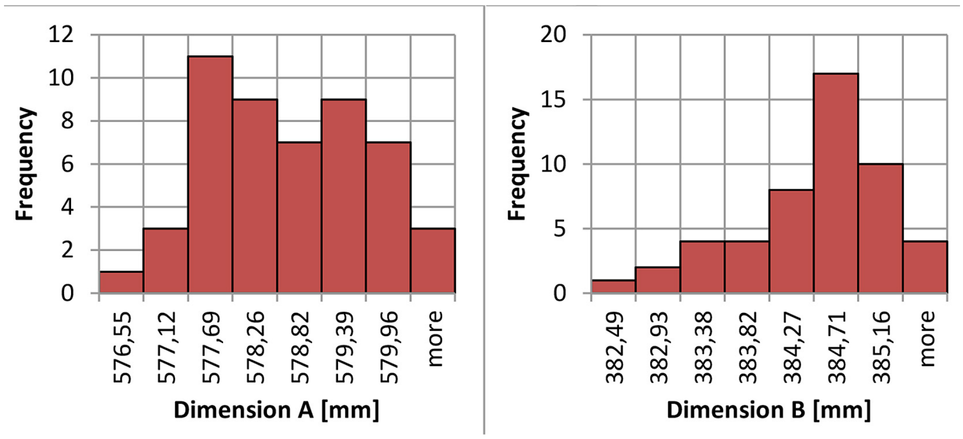

Figure 10. Histogram of dimension A [mm] (left side); dimension B [mm] (right side) – efficiency 15 pcs/min (cardboard packaging No. 1)

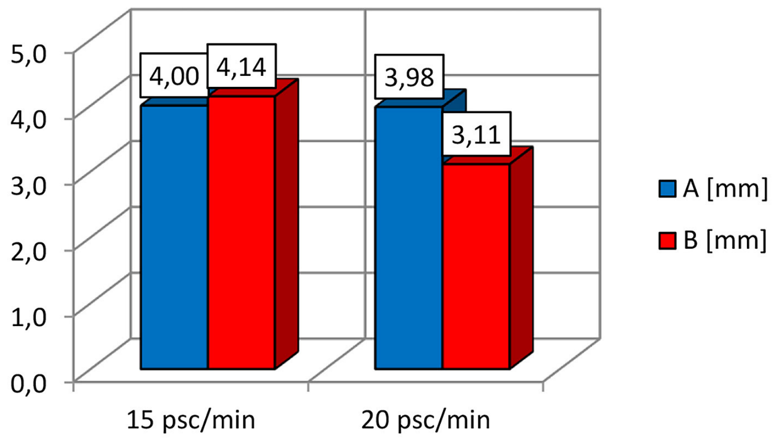

Figure 11. Comparison of the values of dimension A and dimension B divergence in relation to performance for the cardboard packaging No. 2

10. Deviation value - point 3.
11. Deviation value - point 2.
12. Deviation value - point 1.

Analysing the presented results of geometric deviations at designated points showed no clear trend. The change in efficiency did not

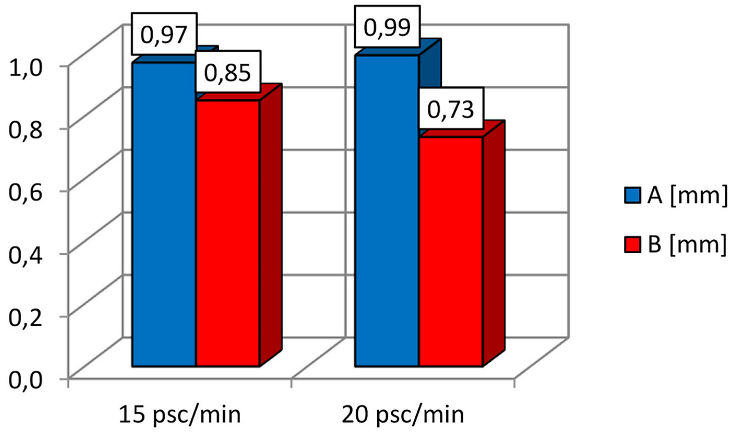

Figure 12. Comparison of the standard deviation values of dimension A and dimension B depending on the performance for the cardboard packaging No. 1

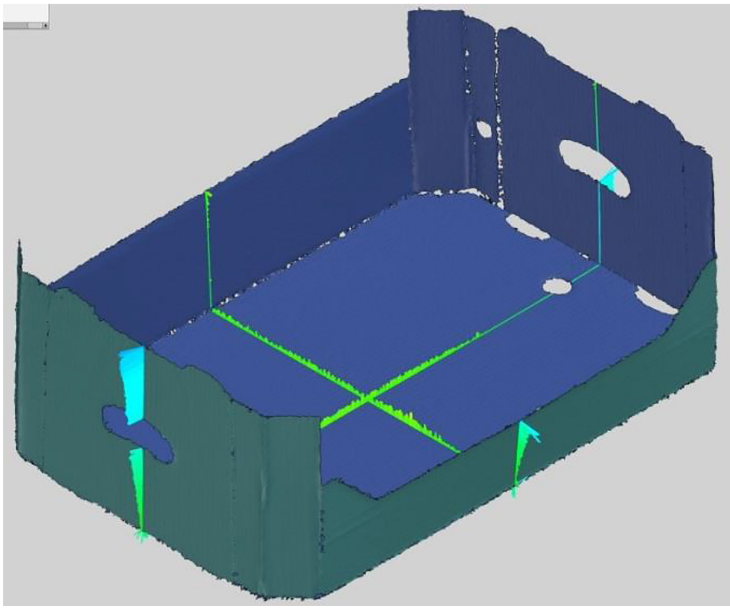

Figure 13. Location of measuring sections

Table 3. Results of geometric deviation measurements – cardboard packaging No. 1

Efficiency 15 pcs/min												
	1	2	3	4	5	6	7	8	9	10	11	12
$\bar{x}$	-2.49	1.49	2.13	-4.26	-0.01	0.34	-0.18	-0.55	-0.24	-0.76	-0.26	0.11
MAX	-1.25	4.25	5.00	-2.69	3.06	2.29	0.42	1.27	1.23	0.45	0.76	1.24
MIN	-3.92	0.53	0.65	-4.99	-2.35	-0.63	-0.58	-2.19	-1.73	-2.08	-0.97	-1.29
R	2.67	3.72	4.35	2.30	5.41	2.92	1.00	3.46	2.96	2.53	1.73	2.53
s(*x*)	0.74	0.76	1.07	0.56	0.86	0.67	0.26	0.79	0.63	0.69	0.42	0.59
Efficiency 20 pcs/min												
	1	2	3	4	5	6	7	8	9	10	11	12
$\bar{x}$	-2.07	3.30	3.60	-2.62	-0.51	-0.17	-0.52	0.73	-0.19	-0.10	0.07	0.18
MAX	-1.07	4.92	4.87	-0.87	0.56	1.27	0.03	2.29	0.71	1.21	0.85	1.22
MIN	-3.87	1.21	1.67	-4.62	-2.95	-1.63	-0.99	-1.02	-0.90	-1.09	-0.71	-0.95
R	2.80	3.71	3.20	3.75	3.51	2.90	1.02	3.31	1.61	2.30	1.56	2.17
s(*x*)	0.56	0.90	0.88	1.05	0.72	0.69	0.23	0.84	0.43	0.54	0.39	0.54

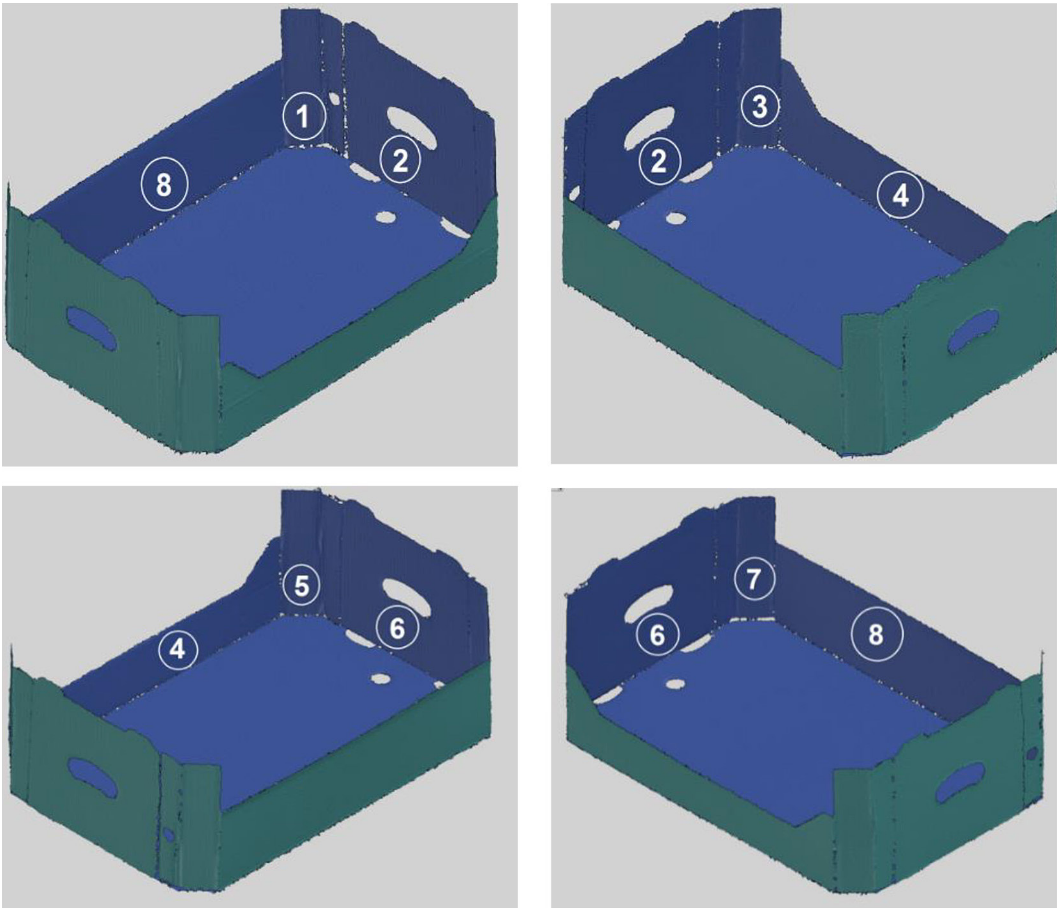

Figure 14. Location of checkpoints

Table 4. Results of geometric deviation measurements – cardboard packaging No. 2

Efficiency 15 psc/min												
	1	2	3	4	5	6	7	8	9	10	11	12
$\bar{x}$	-1.56	2.90	3.12	-1.13	1.07	-0.44	0.83	-1.36	0.56	0.11	0.08	1.22
MAX	-0.31	4.96	5.00	-0.35	4.53	2.21	1.82	1.65	2.96	1.47	0.58	2.48
MIN	-4.94	0.69	1.24	-2.95	-2.85	-2.46	-0.01	-3.61	-1.23	-1.87	-0.27	-0.79
R	4.63	4.27	3.76	2.60	7.38	4.67	1.83	5.26	4.19	3.34	0.85	3.27
s(*x*)	0.92	1.09	1.32	0.59	1.35	1.34	0.53	1.39	0.90	0.68	0.22	0.66
Efficiency 20 psc/min												
	1	2	3	4	5	6	7	8	9	10	11	12
$\bar{x}$	-3.83	2.30	3.46	-1.64	1.80	0.23	-0.87	0.27	2.45	-1.03	0.20	-0.96
MAX	-1.85	4.71	5.00	-0.46	4.17	2.98	0.23	3.15	4.46	0.05	0.83	0.88
MIN	-4.83	0.95	1.75	-3.34	-0.35	-1.31	-2.51	-1.52	-0.40	-2.19	-0.27	-2.43
R	2.98	3.76	3.25	2.88	4.52	4.29	2.74	4.67	4.86	2.24	1.10	3.31
s(*x*)	0.67	0.85	1.01	0.59	1.09	0.86	0.62	0.90	0.87	0.58	0.30	0.60

clearly change the values of the geometric deviations. The average values changed in value and sign depending on the efficiency. In the case of cardboard packaging No. 1, the highest average deviation value of -4.26 mm was recorded at a throughput of 15 psc/min (point 4). Six measurement points recorded larger deviation values for the 15 psc/min yield and six recorded smaller values, indicating that there was no effect of the change in efficiency. In the case of cardboard packaging No. 2, only in three cases the geometric deviation value was exceeded for the 15 psc/min capacity. This was observed for points 2, 6 and 8. In the case of cardboard packaging No 2, an increase in efficiency resulted in increased geometric deviations for the nine measurement points considered. Figure 15 shows an example of a comparative summary of the distribution of the maximum value of positive cross-sectional deviation in the Y-plane for cardboard packaging No. 1, depending on the analyzed efficiency.Based on the analysis of the values of the range *R* and standard deviation *s*(*x*) (Tables 3 and 4) of the measurement points considered, it can be concluded that increasing the yield does not negatively affect the values of geometric deviations of the analyzed cardboard packaging. Both for the case of cardboard packaging No. 1 (Figure 16) and for cardboard packaging

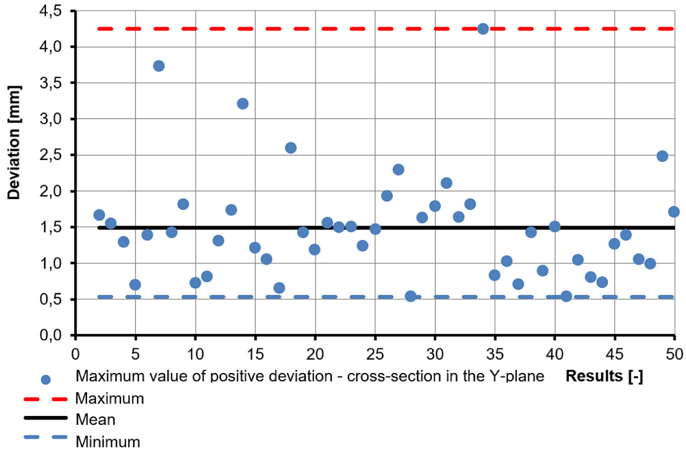

Figure 15. Example of a comparative summary of the distribution of the maximum value of positive cross-sectional deviation in the Y-plane for cardboard packaging No. 1

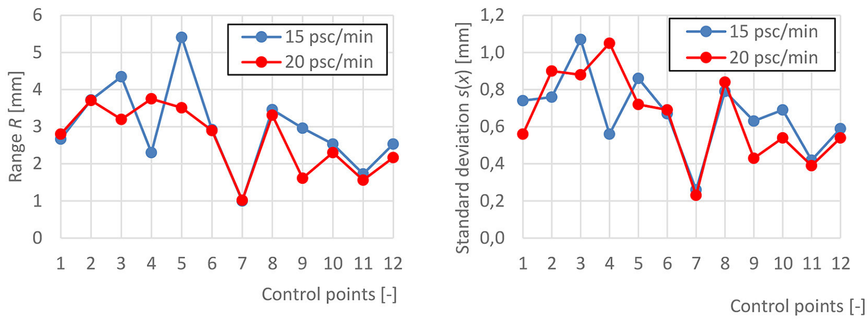

Figure 16. Distribution of range R (left side) and standard deviation s(x) (right side) values for cardboard packaging No. 1 obtained for the adopted control points

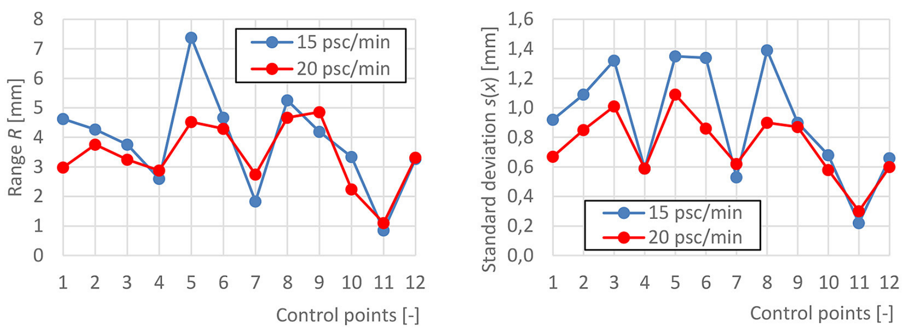

Figure 17. Distribution of range R (left side) and standard deviation s(x) (right side) values for cardboard packaging No. 2 obtained for the adopted control points

No. 2 (Figure 17), the values of range R and standard deviation $s(x)$ had smaller values for a productivity of 20 pcs/min.

CONCLUSIONS

Shelf-ready packaging is commonly used in the retail industry to enhance the efficiency of supply chain processes and improve the overall consumer shopping experience. It is a strategy that benefits both manufacturers and retailers by reducing costs and enhancing product visibility.

The main objective of the research was to determine the effect of changing the production rate of cardboard boxes on the repeatability of selected geometric characteristics. In the project, 50 pieces of each of two types of cartons were scanned, obtained with two different efficiencies of 15 pcs/min and 20 pcs/min, which corresponds to an increase in productivity of about 33%. Two geometric characteristics of the cartons under consideration were selected for repeatability analysis: length measured inside the carton, expressed in millimeters, and width measured inside the carton, expressed in millimeters. All obtained distributions of measurement results for both types of cartons revealed convergence to a normal distribution, as shown by the corresponding histograms. None of the results crossed the control lines. Consequently, they entailed no excessive error. Comparison of the spread values of the length dimension and the width dimension for the first carton demonstrated that, in the case of length, increasing the output reduced the spread of the results, and, therefore, for the rate of 15 pcs/min the average value of the spread was 3.19 mm, while for the output of 20 pcs/min it was 2.72 mm. In contrast, for the width dimension, the average value of the spread increased slightly from a value of 5.04 mm to 5.66 mm. A similar trend was recorded for the set of standard deviation values. Also for the length value, the average value of the standard deviation with the increase in yield decreased from 0.70 mm to 0.52 mm, while for the width dimension it increased slightly from 1.16 mm to 1.18 mm. The observed tendency may have stemmed from the design of the tested carton. The walls defining the length had additional reinforcements, so that the carton in a given section possessed greater rigidity. In the case of carton two, analyzing the values of the stretch of the measured characteristics, for both the length and width dimensions, the value of the stretch decreased with increasing efficiency. For the length dimension, the gap decreased from 4.00 mm to 3.98 mm. At the same time, for the width dimension it decreased from 4.14 mm to 3.11 mm. An identical situation occurs in the comparative analysis of the standard deviation values. In this case, too, the average value of the deviation decreased with increased efficiency. As in the case of the first carton, the results obtained, and the noted trend, were influenced by the carton design. The second carton had a different design from the first. In summary, the increase in carton production efficiency did not negatively affect dimensional accuracy and repeatability.

Using 3D scanners has several limitations that can affect their accuracy, efficiency, and applicability in various contexts. The resolution of 3D scanners determines the level of detail they can capture. Lower-resolution scanners may struggle to capture fine details accurately, leading to loss of fidelity in the scanned model. Some 3D scanners can be slow, especially when capturing high-resolution scans or scanning large objects. This can make them impractical for certain applications where speed is essential. Objects with intricate geometries or reflective surfaces can pose challenges for 3D scanners. Shiny or transparent surfaces may cause reflections or refractions, leading to inaccuracies in the scanned data. Limited scanning range: Many 3D scanners have a limited scanning range, which means they may not be suitable for scanning large objects or environments without multiple scans and subsequent stitching. External factors such as lighting conditions, temperature variations can affect the performance of 3D scanners, leading to inaccuracies in the scanned data. Raw scan data often requires extensive post-processing to remove noise, align multiple scans, and create a usable 3D model. This process can be time-consuming and may require specialized software and expertise. Despite these limitations, 3D scanners remain valuable tools for various applications, including industrial design, reverse engineering, quality control, medical imaging, and cultural heritage preservation. Advances in technology continue to address many of these limitations, improving the accuracy, speed, and usability of 3D scanning systems.

The measurement data obtained as a result of the accuracy and repeatability tests of card-board packaging confirmed the design assumptions. Increasing the productivity from 15 pcs/min to

20 pcs/min, which corresponds to an increase in productivity by 50% of the initial value, definitely shortened the duration of the production process, while maintaining the required dimensional and shape accuracy and repeatability of the produced cardboard packaging. Achieving the set performance parameters was possible by increasing the punch speed to 1500 mm/s. The reduction in the execution time of the basic functions of the molding machine indicates the fact that the individual sequences of operation of the device have been optimized, which does not negatively affect the accuracy and repeatability of the produced SRP carton packs. Obtaining the required performance parameters requires a detailed analysis of the time waveforms describing the molding machine's cycle of operation starting from taking the carton from the warehouse to feeding it into the stamping area. It should be noted that the design and construction of the carton packages selected for analysis had a significant impact on the change in the value of the standard deviation and the scatter of the results. Carton packages with complex construction (cardboard packaging No. 2) show less susceptibility to mechanical deformation.

In a further stage of research, it is proposed to test the geometry of packaging machines. The tests will assess the positioning (drive position) in the initial (starting) and final positions occupied by the cardboard format (box).

Acknowledgements

This research was funded by The National Centre for Research and Development, grant number POIR.01.01.01-00-0224/17 Modular SRP packaging production system (shelf ready packaging) and the presented research, executed under the subject No. 0614/SBAD/1579, was funded with grants for education allocated by the Ministry of Science and Higher Education in Poland.

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