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Original scientific paper

Correlation of Geometrical Specifications for Flexible Quality Control in the Manufacturing of Plastic Products

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Abstract: This article presents an analysis to meet the demand for process-optimized applications in industrial plastic production. Since in an injection molding process primarily plastic products are created, which underlie a strict quality control, machine technicians thereby carry out worker operator control in order to ensure even production drawing quality. Thereby injection molding products are qualified among others via component dimensions. Due to the complex accessibility of molded part geometry, these controls underlie high and varying sensor influence. Due to technology advancement and increasingly accurate quality requirements, the demand for process-optimized quality controls is continuously growing. First, the complexity of geometrical quality control from workpieces is presented. Practical and simulative tests to determine the correlation of geometric specifications are examined by means of a variable injection molding process. Finally, the new control dimensions' relevance shall be implemented via appropriate correlation evidence.

Keywords: dimensional dependence; dimensional specifications; plastic part properties; quality predictive; systematic influences

1 INTRODUCTION

Quality is a substantial instrument for the preservation and increase of competitiveness in any manufacturing company. In the long term a company's success depends significantly on the quality of its products in comparison to its competitors. Here, process quality is gaining in importance as economic potentials are primarily desired, which leads to the exhaustion and realization of a cost advantage over competitors [1, 2].

Geometrical specifications in product documentation shall guarantee components' functional requirements beyond their planned service life. Functionally important specifications required for an objective control, are identified and clearly marked on the basis of a variety of specifications [3].

A substantial requirement for a successful production control in any mechanical manufacturing is the geometrical measurement of the essential dimensions [4].

Benchmarks for quality control in manufacturing are those dimensions which are monitored unconditionally. The valuation of the dimension ultimately determines whether manufacturing of the production batch continues or has to be terminated. These cause a temporal delivery decline and therefore economic loss. Despite today's highly accurate and flexible measuring systems, the accessibility of molded part geometry has a significant influence on the valuation of benchmarks. The complexity of the implementation causes a required programmable sensor change, which also results in a significant time exposure and a complex valuation of measurements (outside the specification limits). Fig. 1 shows a possible initial situation, in which the product geometry together with the measuring sensors leads to systematic measurement deviations.

In order to reduce expenditure of time and complexity, function shall be evaluated via the largest sense of proportion as relevant quality control. These are ultimately measurable more flexible and more efficiently. The objective here is to find correlating evidence that function dimensions and (for the control and measurement technology) a simple outer dimension, demonstrate an informative dependence.

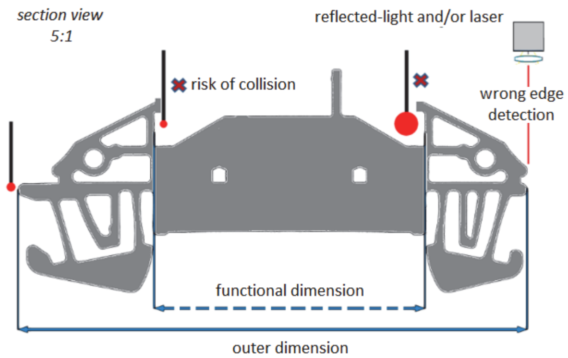

Figure 1 Systematic influences on a measurement object

2 EVIDENCE FOR THE CORRELATION OF DIMENSIONS

The deficits of the manufacturing processes, which are compromised by the influences of the instruments and the material, always result in geometric deviations of the molded part geometry. The engineer determines dimensions for the assurance of the molded part geometry in manufacturing [5].

The molded part dimensions are heavily dependent on different influence variables. In molded injection processes there are instrument-dependent and instrument-independent dimensions. Instrument-dependent dimensions are dimensions within the same instrument part, which are determined through the instrument form. Theoretically, these are always the same. In Practice, a certain dependency of these dimensions on process variables is assumed. Instrument-independent dimensions are dimensions which result from the interaction of different instrument parts, such as the two instrument halves or the slider, which have a relative movement within the instrument. In movable instrument parts, which form the instrument-independent dimensions, the closing has to function exactly and repeat accurately because otherwise the dimension is influenced. These dimensions are hardly variable via the process settings. However, the end position of the slider and the closing force are. How big the influence on the dimension is and how it can be detected, is depicted in Fig. 2. The instrument parts are closed with a closing force of 50 to 200 tons, from which results the evenness and flatness of only a few µm of the parting plane. The consequences of an oversized gap are demonstrated, and the resulting error becomes detectable for a flash formation from 0,01 mm [6].

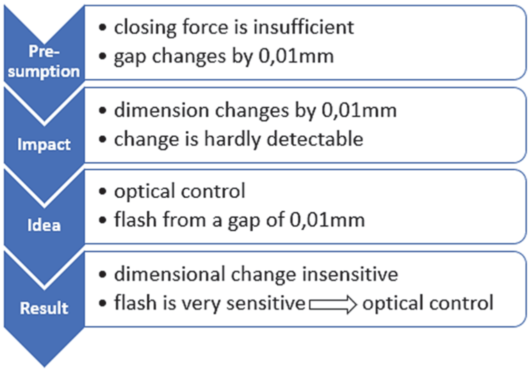

Figure 2 Error detection in instrument-independent dimensions

The correlation is a mutual connection of two conditions, requirements, dimensions or properties. In statistics, correlation is utilized for the description of an interaction between two properties. It is especially important whether the properties are levelled equally or unequally. Correlation also describes how, for example, outer dimensions are connected with inner dimensions. If the connection of the variables is nonlinear, the correlation coefficient (r) will not describe the factual connection [7].

$$r=\frac{\sum_{i=1}^{n}\left(x_i-\overline{x}\right)\cdot\left(y_i-\overline{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i-\overline{x}\right)^2}\cdot\sqrt{\sum_{i=1}^{n}\left(y_i-\overline{y}\right)^2}} \tag{1}$$

- x_i measurements of the outer dimension
- $\overline{x}$ mean value of x_i
- y_i measurements of the inner dimension
- $\overline{y}$ mean value of y_i
- r versus 1; measurements have a connection. x and y increase
- r near 0; connection is not visible
- r versus −1; measurements oppose each other x increases and y decreases und vice versa.

The following Fig. 3 demonstrates correlating dimensions of a molded part geometry with a functional requirement (inner dimension) and an alternative outer dimension.

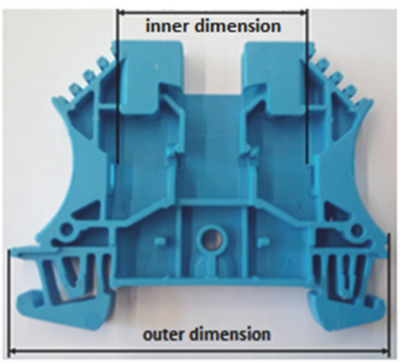

Figure 3 Dimensions of a PA66 plastic part

The inner dimension confirms the accuracy of fit of a metallic counterpart and thus becomes a functional requirement, while the outer dimension holds for the flushness of several strung together parts and maximally plays a role for the visual appearance of a control cabinet. The introduced molded part geometry is randomly verified in the following surveys.

2.1 Distortion of the Correlation Coefficient

The properties of the random sample have an enormous influence on the correlation coefficient with the result that it can be substantially decreased or increased. Outliers of the random sample thereby have the biggest influence on the correlation coefficient. Outliers are values which deviate by 1,5 times of the standard variance from the mean value. Fig. 4 shows a point cloud with a lower value than the correlation coefficient (r) (blue dashed line). In the same figure there is a red line which describes a higher correlation value. This increased correlation coefficient is obtained through a single outlier (upper right) [7].

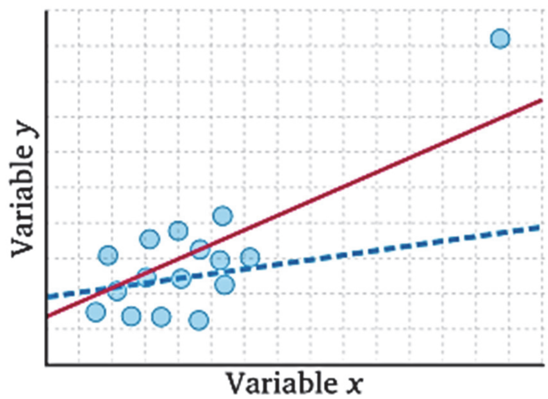

Figure 4 Distortion of the correlation coefficient [8]

2.2 Simulative Approach

With the GOM-Inspect 3D-Software, which is examined and certified by NIST and PTB, amongst others, parts are measured [9]. The correlation of dimension can be simulated here. Thereto, the file from the CAD-model (Computer Aided Design) and a scanned net of the part are uploaded into the software. Subsequently, the dimensions, for which the correlation shall be simulated, can be selected. For scaling, a new value is determined for the inner dimension. For example, the dimension of the upper tolerance limit, as here, the function of the molded part geometry is theoretically not yet violated. Then it is divided by the previously determined dimension (actual dimension), to then obtain the factor with which the part shall be rescaled. Subsequently, the axes (X, Y, Z) are rescaled linearly with this factor. The software allows to optimally lap the files in order to see where these differ the most. The color-coded Fig. 5 and Fig. 6 demonstrate where there is too much or not enough material in comparison to the CAD-model.

The inner dimension of the original plastic part is 30,657 mm. This dimension is extended to 30,672 mm. The factor, by which the plastic part is rescaled is $1{,}00048\overline{9}$. The outer dimension of the plastic part increases by the same factor, from 59,940 mm to 59,969 mm. The simulation shows that there is a connection between the dimensions. This means that when the inner dimension increases or decreases, the outer dimension changes as well. Thereby, from an absolute point of view, the outer dimension increases faster, because it is much larger than the inner dimension. Here, the connection between the dimensions is 100%, as the dimensions are recalculated through the scaling, which is the same for all dimensions.

Nevertheless, a limited linear increase due to influences such as the setup of the instrument geometry (including molded part dimensions with stages and fixed cores), is to be expected here [13]. Therefore, this theoretical result is not significant and has to be considered an assumption.

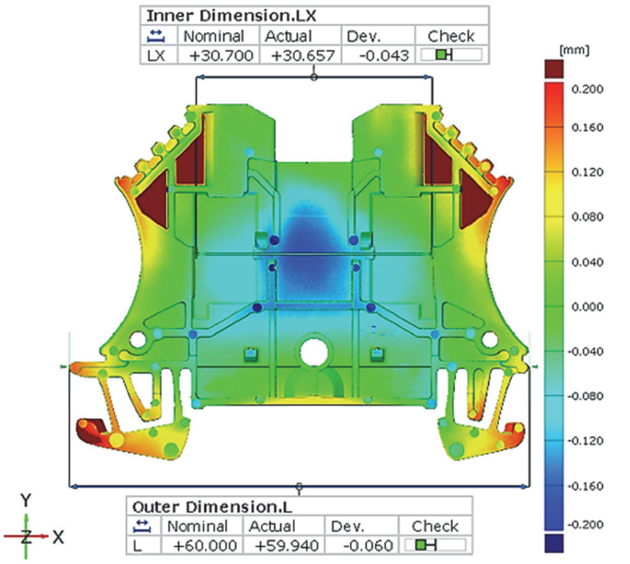

Figure 5 Original condition of a PA66 plastic part in color-coded comparison

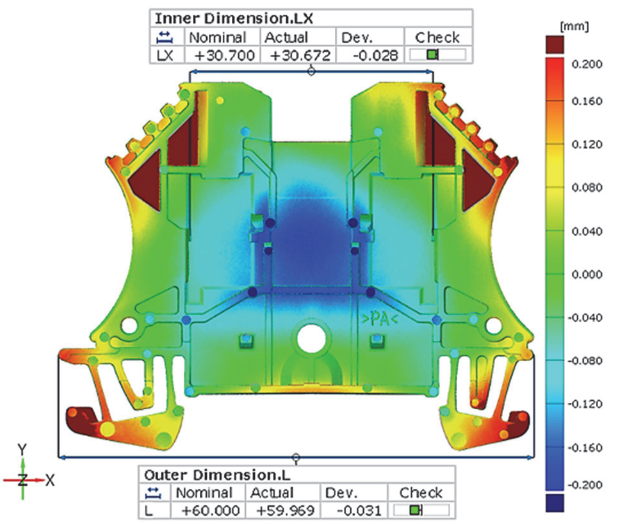

Figure 6 Scaled condition of a PA66 plastic part in color-coded comparison

2.3 Experimental Setup

In order to confirm the theory, an experiment is conducted, which proves the correlation of the dimensions in practice. Thereto, three differently sized plastic part variants (classified into validation groups) are manufactured. The size of the part variant is influenced via cooling times of different length during the manufacturing process. All other machine parameters remain constant.

- validation group *S* = small with a cycle period of 6,4 seconds
- validation group *N* = normal with a cycle period of 7,9 seconds
- validation group *L* = large with a cycle period of 9,1 seconds

While validation group *S* has been manufactured with the fastest cycle period, validation group *L* is produced with the slowest cycle period in order to avoid the still coarse and identifiable influences. The chosen validation group *N* thus forms the still possible to determine mean value of the validation groups. After manufacturing, the parts of the individual validation groups are measured. Thereby, each respective largest outer dimension of the part and the functional inner dimensions are determined. The internal dimension has a draft angle and thus no distinct optically detectable edge can be identified. For the assurance of the inner dimension, it is finally switched to a highly precise Werth multi sensor measuring machine (with passed measurement system analysis). The obtainable length measurement tolerances are beneath 0,3 µm [10].

The mean value of the validation groups indicates that, with increasing cooling time, both dimensions increase, which suggests a connection between the validation groups.

2.4 Correlation Evidence

The validation groups are shown in Fig. 7. In this Figure, the outer dimension is compared to the inner dimension, so that an optical connection of these dimensions becomes identifiable.

Thereby the inner dimension is to be observed vertically and the outer dimension horizontally. The individual validation groups are clearly distinguishable on the basis of their varying cooling time. The blue line shows the correlation coefficient around which the measurements are spread.

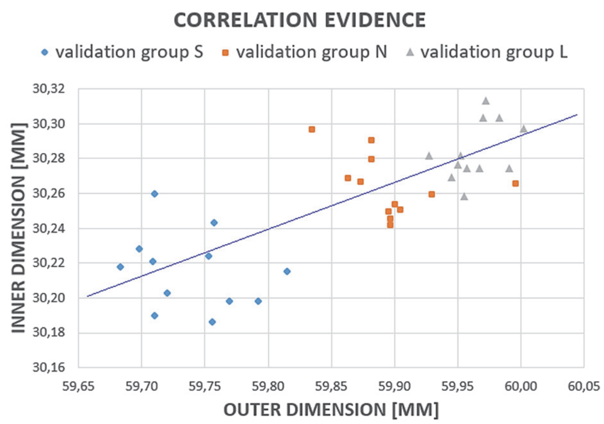

Figure 7 Correlation coefficient

The calculated positive correlation coefficient in Fig. 7 is r = 0,77. The result may be considered as relatively large, at the least as very moderate [11, 12]. The correlation coefficient shows that there is a connection between outer dimension and functional inner dimension in practice.

Consequently, reliable conclusions about the inner dimension can be drawn from the outer dimension.

3 PREDICTABILITY OF DIMENSIONS

The validation groups are shown in Fig. 8, in which the left vertical axis for the outer dimension and the right axis for the inner dimension are depicted. The blue bars show the outer dimension for the small validation groups (*S*), the orange bars for the normal validation groups (*N*) and the grey bars for the large validation groups (*L*). The lines show the inner dimension of the individual validation groups. Thereby, the color is the same as for the outer dimension.

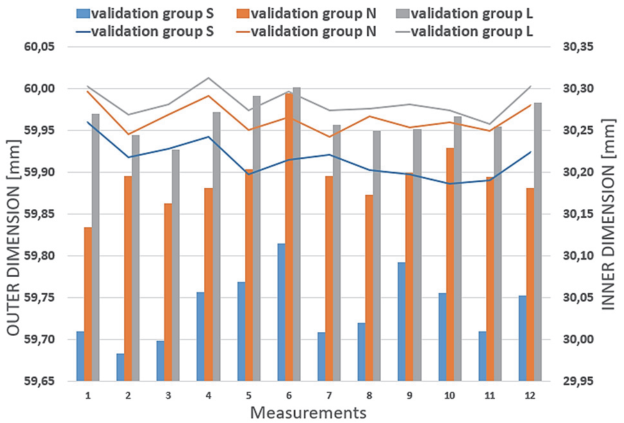

Figure 8 Comparison of outer dimensions to inner dimensions

From an absolute point of view the figure clearly shows that the outer dimension increases faster than the inner dimension. This is amongst others due to the outer dimension, which is nearly twice as big as the inner dimension. Additionally, aggravated growth and impaired shrinkage both occur for the inner dimension of the molded form part, as the form part dimensions are fixed within the instrument geometry via stages and cores [13].

3.1 Shrinkage Evidence

In order to determine the shrinkage of the dimensions, the measured dimensions are compared to the tool dimensions on the product [14]. The defaults for the tool dimensions (*TD*) are 60,93mm for the outer dimension and 30,70mm for the inner dimension. Based on the material data sheets, a shrinkage (*S*) of the molded form part of 1,55% is anticipated. Accordingly, an outer dimension (*O*) of 59,99 mm and an inner dimension of 30,22 mm should result for the part.

$$O = TD * (1 - S) \approx 59{,}99\,\text{mm} \tag{2}$$

This shrinkage (S_x) is recalculated with the recorded measurements in order to check whether this shrinkage reflects reality. Example calculation for a cycle period of 6,4 seconds. M_x stands for measurement value. ΔS describes the difference between the mean values of the shrinkages $\bar{S}_{\text{outerdimension}}$ and $\bar{S}_{\text{innerdimension}}$.

$$S_{\text{outerdimension}} = \left(1 - \frac{M_{\text{outerdimension}}}{TD_{\text{outerdimension}}}\right) * 100\% \tag{3}$$
$$S_{\text{outerdimension}} = 2{,}00\ \%$$

$$S_{\text{innerdimension}} = \left(1 - \frac{M_{\text{innerdimension}}}{TD_{\text{innerdimension}}}\right) * 100\% \tag{4}$$
$$S_{\text{innerdimension}} = 1{,}43\ \%$$

$$\bar{S}_{\text{outerdimension}} = \frac{\sum_i^n S_{\text{outerdimension}}}{n} \tag{5}$$
$$\bar{S}_{\text{outerdimension}} = 1{,}95\%$$

$$\bar{S}_{\text{innerdimension}} = \frac{\sum_i^n S_{\text{innerdimension}}}{n} \tag{6}$$
$$\bar{S}_{\text{innerdimension}} = 1{,}58\%$$

$$\Delta S = \left(1 - \frac{\bar{S}_{\text{innerdimension}}}{\bar{S}_{\text{outerdimension}}}\right) * 100\% \tag{7}$$
$$\Delta S = 19{,}21\%$$

These calculations were performed for all measurements, in order to check whether the shrinkages and the shrinkage differences are constant. Fig. 9 shows how the shrinkage difference performs over cycle period.

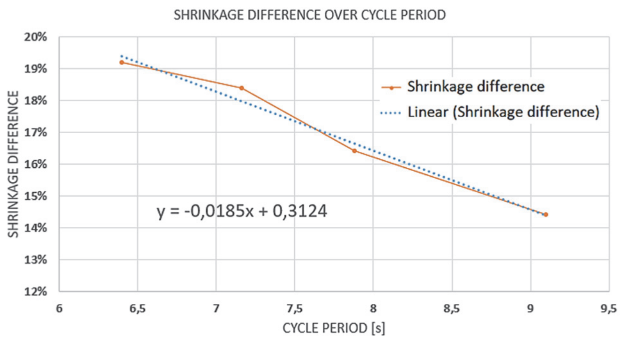

Figure 9 Shrinkage difference over cycle period

The above figure shows an almost linear shrinkage difference (orange line) over the different cycle periods. The balance line (blue line) forms a linear connection of the calculated shrinkage differences. The following formula describes the line:

$$Y = -0{,}0185 \cdot x + 0{,}3124 \tag{8}$$

The shrinkage difference decreases with increasing cycle period. The reason for this is that the outer dimension shrinkage decreases faster than the inner dimension shrinkage with increasing cooling time. Based on the realization that the shrinkage is linear, the inner dimension can be predicted with the help of the above formula. Therefore, the largest outer dimension of molded injection geometry is required.

3.2 Validation

During validation it is tested whether the simulation sufficiently accurately matches reality [15]. In order to be able to perform a validation, new measurements are required. Therefore, two variants are taken from the molded injection machine for each two different function cycles. Two variants with a cycle period of 7,18 seconds and two with a cycle period of 8,00 seconds. Only the cooling time varies, all other setting parameter are constant. Subsequently, the variants are measured again. The cycle period of 7,18 seconds was chosen deliberately, because here the biggest difference between balance line (blue line) and calculated shrinkage differences (orange line) can be observed. Consequently, here too the biggest deviation between measurement result and simulation result is expected.

Outliers within the measurement series were deleted, due to the significance [7]. For this reason and due to the representative informative value, different numbers of measurement results are included in Fig. 10 and 11. Deviations of the simulation to the measurements result from the dispersion of the measurements. The inner dimension is plotted on the vertical axis, the measured parts are plotted on the horizontal axis. The blue bars show the measured inner dimension and the orange bars show the calculated inner dimension.

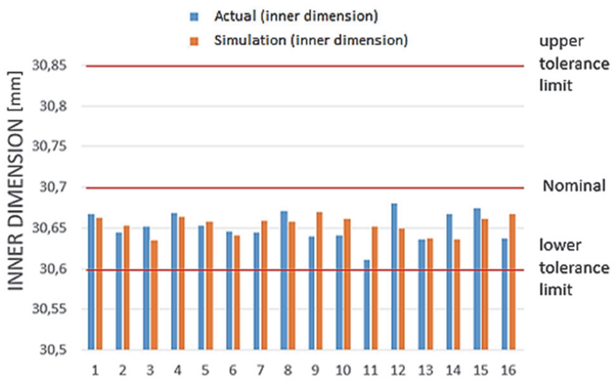

Figure 10 Presentation of validation results at 7,18 seconds cycle period

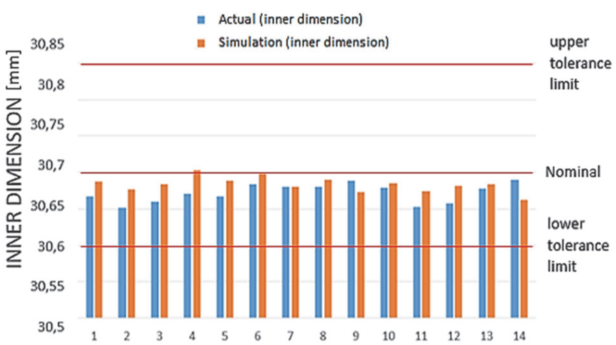

Figure 11 Presentation of validation results at 8,00 seconds cycle period

The dispersion of the measurements from Fig. 10 is within the range of 30,61 mm to 30,67 mm opposed by a dispersion of the calculated results of 30,64 mm to 30,68 mm. The dispersion of the measurements from Fig. 11 is within the range of 30,65 mm to 30,69 mm opposed by a dispersion of the calculated results of 30,66 mm to 30,70 mm. Tendentially, the calculated inner dimension is slightly bigger than the measured dimension. The dispersion of the simulation results shows that calculation via the outer dimension is less prone to variation. This is a positive sign, as the process reliability is increased. The empirically presented approach demonstrates that the assumption of an efficient and flexible outer dimension can be ensured during manufacturing.

4 CONCLUSION

The correlation of geometrical specifications for efficient and flexible quality control in the manufacturing of molded injection parts was primarily examined. Therefore, experiments were conducted, which examine the vibration variances between an outer dimension and its respective functional inner dimension considering the varying cooling times. Thereof a linear connection and a positive correlation of the two factors could be concluded. With the help of this observation, the inner dimension can be estimated approximately via outer dimension and cycle period. The result was confirmed through validation with different cycle periods. Further experiments also showed that the outer and inner dimension shrink to a varying degree during manufacturing. With this knowledge, engineers can construct their instruments more precisely with the objective of manufacturing the molded parts' dimensions closer to the reference value.

The real shrinkages can only be calculated approximately, because research showed that shrinkage in direction of flow and shrinkage transversely to direction of flow turn out considerably different [1, 16, 17].

This research can be applied to many other plastic products with complicated instrument geometry, in order to conclude the functional inner dimension from the outer dimension. In this way, examination efforts can be accelerated, easily automated and reduced significantly in current manufacturing. This, of course, increases efficiency and the economic orientation in an industrial environment. With regard to industry 4.0, the potential to plausibly network the multitude of generated data.

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