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Procedia Computer Science 180 (2021) 1024–1033

Procedia Computer Science

www.elsevier.com/locate/procedia

International Conference on Industry 4.0 and Smart Manufacturing

Statistical Process Control of assembly lines in a manufacturing plant: Process Capability assessment

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Abstract

Among the main strategies adopted by companies for enhancing their competitive advantage as well as for improving the internal efficiency is the quality management. Several tools can be involved when dealing with this issue; one of these is the Statistical Process Control, which includes the employment of statistical methods and metrics to monitor and control a process' quality. In this paper, indeed, two statistical metrics are involved for assessing the process capability of a filler machine produced by an Italian company operating in the food context. Specifically, two processes are inspected: the slewing ring-pinion backlash and the handling clamps height check, both showing excellent performances after having carried out the control and provided appropriate adjustments. Results are also compared with those obtained from the Six Sigma theory, another tool involved for quality controls which is in line with principles of lean manufacturing. Moreover, for the second process, a software was implemented for speeding up operations and achieving benefits in terms of time. The reliability of these analysis is confirmed by the application of the ANOVA Gage R&R tool, which allowed to assess the precision of the measurement system involved.

Keywords: Automation; Logistics; Industry 4.0; Food Industry.

1. Introduction

In an increasingly competitive market, one of the main strategies adopted by companies for gaining advantages is to monitor and achieve quality in product and processes [1].

The basic definition of quality refers to one or more desirable characteristics that a product, a service or a process should possess [2] in order to satisfy implicit and explicit customer's requirements. Indeed, the fulcrum is the customer satisfaction: when a consumer receives quality products, in return his loyalty increases, the company's position on the market is maintained or even improved, liability risks are reduced, the brand gets good reputation and, consequently, benefits arise. It follows that, within the industrial context, an appropriate quality control is essential at the process stage to ensure compliances of the final item.

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Peer-review under responsibility of the scientific committee of the International Conference on Industry 4.0 and Smart Manufacturing
10.1016/j.procs.2021.01.353

Among the main tools having this purpose, it is worth mentioning the Statistical Process Control (SPC), which monitors and controls quality by tracking production metrics, and the famous Six Sigma method, which uses five key steps (Define, Measure, Analyze, Improve and Control – DMAIC or Define, Measure, Analyze, Design and Verify - DMADV) to ensure that products meet customers' requirements and have zero defects [3]; specifically, the term Six Sigma refers to a statistically derived performance target of operating with only 3.4 defects per million opportunities (DPMO) [4], which represents a 99.99966% process yield meaning that 99.99966% of output products do not have any defects, and consequently requires significant efforts [5]. For instance, it is worth mentioning studies by [6] as far as a general quality assurance through process improvement, or by [7] who carried out an exhaustive bibliometric analysis concerning the topic of Six Sigma.

The concept of quality is a keyword and a pillar of a particular philosophy of production developed at the beginning of the Third Industrial Revolution [8], namely the well-known *lean manufacturing* (LM). It can be seen as a business strategy implementable through different principles, tools and techniques, which is focused on the elimination of any type of waste (called in this perspective Muda), aiming at supplying the exact quantity of products required by customers, in the right time, with an extremely high level of quality and low cost, thanks to its being *smart* [9]. From the joint union of the LM thinking and one of the abovementioned tools for keeping quality under control, the Lean Six Sigma (LSS) was born, namely a hybrid initiative that combines the Six Sigma's structured problem solving using statistical tools with lean operation's emphasis on flow improvement [10]. Literature in this field is extremely copious and various; for a complete overview and comprehension of the state-of-art, [11] and [12] are recalled. Specifically, in this last paper, its adoption in European organizations is treated.

On the bases of these brief theoretical premises, the aim of this paper is to present two case studies carried out on a company based in the north of Italy, designing and producing food machinery; specifically, an SPC was implemented for a filler machine.

The novelty of the presented paper is threefold: on one side it presents a real and practical implementation of the theoretical process control methodology; second, it provides readers and quality inspectors with real and tangible results and then, on the basis of these outcomes, it precisely describes the design and development of a software tool for improving process capability indices.

The remainder of the paper is as follows: section 2 illustrates material and methods involved, followed by section 3, which deals with the first case study including the measuring system evaluation and the capability process calculation. The second case study, instead, is proposed in section 4, whose structure recalls that of case study 1. Section 5, finally, presents conclusions and future research directions in the light of the obtained results.

2. Material and Methods

The metrics investigated are the process capability indices C_p and C_{pk}, which measure the ability of a process to meet engineering limits [13]. The first index evaluates the performance of the process related to the production specifications, and it is obtained by applying the following formula (1):

$$C_p = \frac{USL-LSL}{6\sigma} \quad (1)$$

Where USL is the Upper Specification Limit of the quality characteristic, LSL the Lower, and σ is the process standard deviation. In case its value is greater than 1.00, the process is capable. Conversely, C_{pk} takes into account the process location, namely whether a process deviates from half of its range of specifications. It is computed as follows (formula 2):

$$C_{pk} = (\frac{USL-\mu}{3\sigma}; \frac{\mu-LSL}{3\sigma}) \quad (2)$$

Where USL and LSL were already defined, and μ is the mean of the process output.

These indices are both common when dealing with this kind of measures; see for instance [14] or [15], recent studies found in literature.

The values obtained are then compared with those deriving from the Six Sigma theory; more in details table 1 reports the correlations between achieved sigma level, goods conformity percentage, C_{pk} index, PPM (part per million) of defective goods, time wasted for bad production in a month [16].

Table 1. Correlations between sigma level, C_{pk} index, PPM, time wasted

σ	Conformity %	C_{pk}	PPM	Time wasted / 720 h
±1	68.26	0.33	317400	228.5 h
±2	95.46	0.67	45500	32.8 h
±3	99.73	1	2700	1.94 h
±4	99.994	1.33	63	2.74 min
±5	99.99994	1.67	0.57	1.49 min
±6	99.9999998	2	0.002	0.005 s

Before collecting data and start with measurement, a crucial issue is clearly to possess the appropriate instruments, as well as correct methods and trained operators. For validating these instruments, several tools can be involved; one of the most spread, adopted in this case, is the ANOVA gage repeatability and reproducibility (AGRR, also known as ANOVA Gage R&R), which allows to assess the precision of a measurement system. The peculiarity of this method is that of considering the variation due to the instrument as composed by two different variances, respectively inherent to the repeatability and the reproducibility. The step for applying the AGRR are the following: (1) determine an experimental design (e.g. the number of operators, number of parts, number of replicates) according to rule of thumb, budget and availability; (2) measure the parts for each treatment; (3) conduct the ANOVA using the observations; (4) estimate the variance components for each factor and interaction; (5) calculate various performance metrics using the estimates (e.g. C_p or C_{pk}); (6) judge the adequacy precision for the measurement system according to criteria; (7) perform subsequent actions such as improvements of the system according to the results [17]. According to the Automotive Industry Action Group (AIAG) [18], in case Gage R&R < 10% the measurement system is acceptable; if 10% < Gage R&R < 30% the system is conditionally acceptable; not acceptable for remaining values. In this study, Minitab software was implemented for carrying out the ANOVA analysis. Several studies in literature implement this method for validating instruments; see for instance recent works by [19] or [20].

The first case study is related to a quality check which is carried out during the assembly operations of a mechanical machine for the food industry. More in details, this check consists of the measurement of the slewing ring-pinion backlash; it verifies the correct backlash between the teeth of the pinion and the teeth of the slewing ring. The pinion is a toothed wheel connected to the main motor which moves the carousel through the engagement with the teeth of the slewing ring as illustrated in figure 1. A certain backlash between the teeth, according to the design specifications, is important to avoid friction and overheating problems or unexpected forces.

The second analyzed process, instead, refers to another kind of check which is performed during the assembly operations of a mechanical system for handling plastic bottles. Specifically, the clamps check is performed on all the handling clamps connected to the rotation support (namely star), for every clamp the precise height "C" with respect to a fixed reference point is measured as shown in figure 2. The star is made up of several clamps used for sorting bottles and transferring them from one point to another on the machine. In one machine there are several stars rotating and interacting with each other; given the interaction that there must be between the stars and therefore between their clamps, it will be necessary that they are positioned correctly so that the bottle transfer can be carried out correctly.

Fig. 1: Rotating structure.

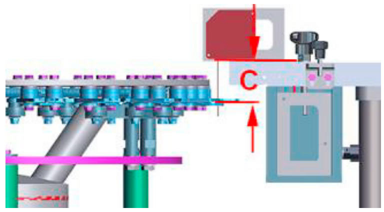

Fig. 2. Clamp height measurement.

3. Case Study 1: slewing ring-pinion backlash check

The correct value of backlash, the minimum and the maximum value are reported in a control sheet, which reports also a very brief description of the operations required to perform the check: the slewing ring tooth must be positioned in perfect tangency with the pinion's tooth. This can be achieved in two different steps. The first is to visually center the pinion tooth with the slewing ring so that the symmetry line of the pinion tooth overlaps with the radius of the slewing ring (they are perfectly aligned centered). Then, the slewing ring must be manually adjusted so that one side of the pinion tooth is in contact with the tooth of the slewing ring, as shown in figure 3.

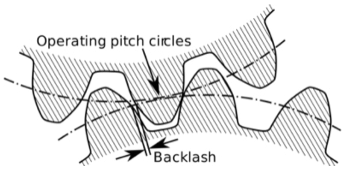

Fig. 3. Contact between the pinion tooth and the tooth of the slewing ring.

At this point, the backlash between the teeth is manually measured by means of a thickness gage having a resolution of 0.05 mm. After the first measurement, according to the abovementioned procedure, the pinion must be rotated 360 degrees so that the backlash between the same tooth of the pinion is checked again and measured with respect to different tooth of the slewing ring. The procedure is repeated five times.

3.1. Measuring system validation

Minitab software, used to perform ANOVA analysis of the measurement values and compute the Gage R&R, returned the outcomes reported in table 2.

Table 2. Results from the AGRR analysis.

Source	VarComp	%Contribution (of VarComp)	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.0011806	51.52	0.0343592	0.206155	**71.77**
Repeatability	0.0005556	24.24	0.0235702	0.141421	49.24
Reproducibility	0.0006250	27.27	0.0250000	0.150000	52.22
Operators	0.0000648	2.83	0.0080508	0.048305	16.82
Part-To-Part	0.0011111	48.48	0.0333333	0.200000	69.63
Total Variation	0.0022917	100.00	0.0478714	0.287228	100.00

It should be noticed that the Total Gage R&R value (%Study Var) is 71.77%, so the variance of the results obtained according to the described measurement procedure is 71.77% caused by the low repeatability and reproducibility of the measurement process. This is a very poor result, as acceptable values of %Study Var must be less than 30% according to the AIAG standard in order to have a reliable measuring system.

As a consequence, the calculation of the process capability indexes cannot be performed until the measuring system is not improved. Thanks to the observation of two operators performing the measurement, some differences in actions' execution were noticed; thus, as a first step, the measuring method has been standardized as much as possible, performing more training on the operators, explaining them how the measurement should be performed without relying on the spontaneity of the operators. A SOP (Standard Operation Procedure) consisting of clear and simple images was designed, as reported in figure 4.

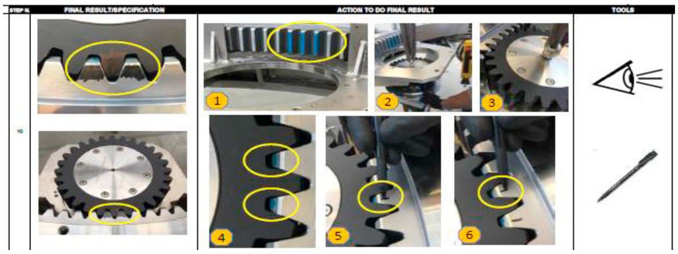

Fig. 4. SOP steps.

After the introduction of the SOP and the training of the operators, a second measurement session was carried out and 30 values were obtained; specifically, these 30 values come from the operations repeated three times by two operators for five different components, according to the same procedure previously described. After data analysis, the following results were obtained (table 3):

Table 3. Results from the AGRR analysis after the SOP and training of operators.

Source	VarComp	%Contribution (of VarComp)	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.0003065	21.69	0.0175075	0.105045	**46.58**
Repeatability	0.0003065	21.69	0.0175075	0.105045	46.58
Reproducibility	0.0000000	0.00	0.0000000	0.000000	0.00
Operators	0.0000000	0.00	0.0000000	0.000000	0.00
Part-To-Part	0.0011063	78.31	0.0332614	0.199569	88.49
Total Variation	0.0014128	100.00	0.0375877	0.225526	100.00

The introduction of SOP methodology in the measurement system has reduced the %Study Var from 71.77% to 46.58%, which is still too high for a reliable measurement system. In order to further lower the value, the main actions that could somehow bring variability have been specifically addressed.

As mentioned above, in order to check the backlash between the pinion tooth and the slewing ring, the pinion tooth must be first perfectly aligned with a radius of the slewing ring. This operation is performed by the operators without the aid of any tool or equipment, relying only on his visual skills and experience. This visual inspection which guide the alignment can lead to a great variability in the measurement.

An alignment jig could improve the process by satisfying the need for positioning and by increasing the accuracy of the centering of the two teeth; in fact, it could indicate the correct position of the tooth in relation to the slewing ring. Since this specific tool was not available on the market, the tool was designed using 3D modeling software and then 3D printed thanks to additive-manufacturing techniques; the model is shown in figure 5.

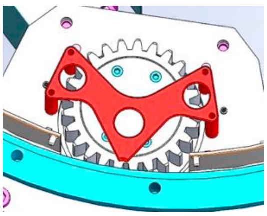

Fig. 5. 3D Model of the alignment tool.

After the introduction of the jig, the SOP was updated with its assembly and positioning instructions; once done, the tooth positioning becomes easier as the jig provide fixed reference points for tooth alignment.

A third measurement campaign was performed with 30 measures and excellent results were obtained as reported by Minitab in table 4.

Table 4. Results from the AGRR analysis after jig introduction.

Source	VarComp	%Contribution (of VarComp)	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.0003065	2.42	0.017508	0.105045	**15.56**
Repeatability	0.0003065	2.42	0.017508	0.105045	15.56
Reproducibility	0.0000000	0.00	0.000000	0.000000	0.00
Operators	0.0000000	0.00	0.000000	0.000000	0.00
Part-To-Part	0.0123563	97.58	0.111159	0.666954	98.78
Total Variation	0.0126628	100.00	0.112529	0.675176	100.00

The %Study Var has dropped to 15.56%, significantly below the threshold of 30% typical of a reliable measuring process. The introduction of the mask has significantly reduced the probability of error caused by the operators. The measuring system can be considered reliable and therefore repeatable and reproducible, allowing the computation of the process capability analysis.

3.2. Capability Process Calculation

Data collected during the validation process of the measurement system has been plotted in figure 6 and used to compute the capacity indexes of the whole process by means of an Excel spreadsheet.

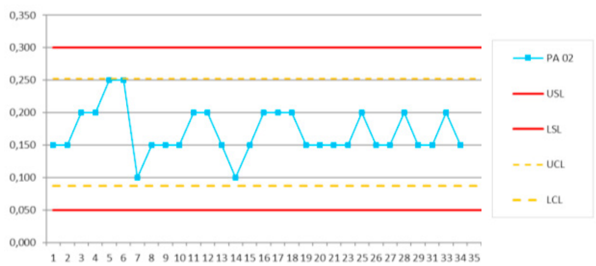

Figure 6. Capability process calculation (case study 1).

The computation of the indexes gives a result of C_p=1.51 and C_{pk}=1.45. These values fit perfectly the target imposed by the company, more precisely they exceed the expectations giving a Sigma level of 4.3. This is consistent with plotted data of figure 6, which clearly shows that the process is centered with respect to the project specifications (LSL - USL, the red lines of the graph). Thus, the control process can be declared under statistical control and no further improvements nor optimizations have been identified since the new SOP has not caused any slowdown in the process of assembly check (backlash measurement).

4. Case Study 2: handling clamps check

As already stated in section 2, as far as case study 2 it is firstly necessary to determinate the different heights. All the measures are then grouped together, the difference between the highest and lowest clamp is computed and checked against the limit value of 0.2 mm defined in the control sheet. This value allows to have a precise and reliable interaction between the clamp that yields and the one that receives during the bottle transfer.

4.1. Data collection

In order to calculate the difference between the highest and lowest clamp, the height of each individual clamp is measured with respect to a reference point, this operation is performed by means of a laser scanner interfaced with a computer using laser triangulation on the clamp surface. Since the reference point is fixed, the values found can be compared and thus the difference easily computed between the clamps.

During measurement with the laser, the star is rotated 360 degrees for three times, so that the measurement of each clamp is averaged over three different values, the standard deviation for each clamp is calculated and the highest and lowest clamp with the respective value is displayed. Figure 7 shows the measurements on a graph.

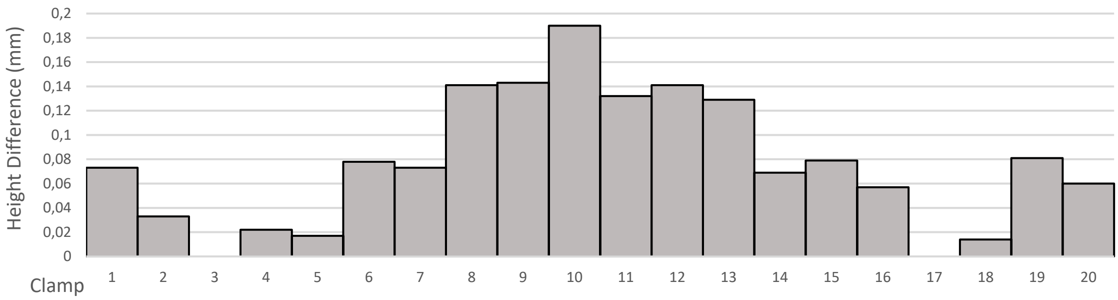

Fig. 7. Clamp heights.

In case the difference between the highest and lowest clamps is more than 0.2 mm, the clamps must be manually adjusted by means of the report composed of diagram and raw data. The operator identifies, completely relying on his own experience and skills, the clamps needing intervention for height adjustment. After the clamps have been modified, the previous step of measure and height calculation shall be repeated in order to check whether the values after the intervention are within the project specifications reported in the control sheet.

4.2. Measuring system validation

Following the same procedure as the previous check, the height difference between clamps of five different rotating stars was measured by repeating the measurements three times with two different operators. The analysis, always performed with Minitab software, shows a %StudyVar of 27%, which is not very far from the upper limit of 30% that allows a positive evaluation of the measurement process. Since the value of the %StudyVar is lower than 30%, the measurement system has been considered as reliable and repeatable at the first stage. After the validation of the measuring system, the next step is the calculation of the capacity indexes in order to evaluate assembly process performance.

4.3. Capability Process calculation

After gathering all required data, performance indexes have been computed, finding a C_p=1.45 and C_{pk}=0.30 (figure 8).

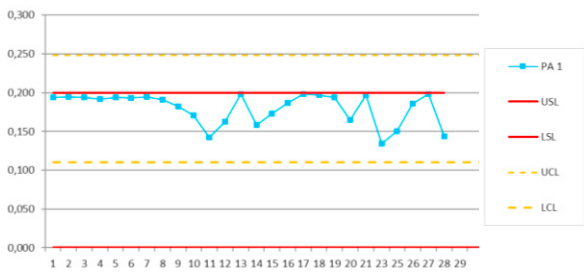

Fig. 8. Capability process calculation (case study 2).

The observation of the indexes shows that the process is not centered; indeed, although the value of the C_p is satisfying and higher than the target of 1.33, the value of the C_{pk} is very low, leading the system to a sigma level of 0.9, very far from the target Sigma Level of 4. In order to improve the C_{pk} several simulations have been carried out using an Excel spreadsheet; the results show that having a maximum difference in clamps height in a range between 0.09 mm and 0.11 mm brings to a very high C_{pk}, centers the process and achieves a Sigma Level of 6 with C_p=4.23 and C_{pk}=4, as reported in figure 9.

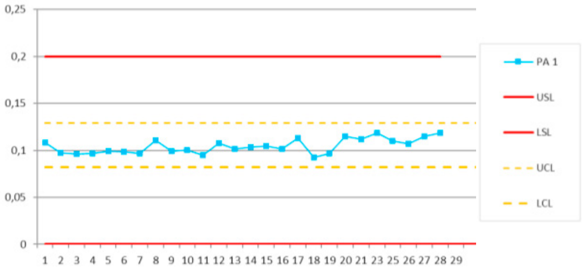

Fig. 9. Capability process calculation after many simulations in order to centre the process (case study 2).

In order to achieve this result, the difference in height between the highest and lowest clamps is reduced to 0.10 mm with a tolerance of ± 0.01 mm. To do this, a deeper study of the clamp's adjustment process was required in order to reengineer it. It was then decided to use washers with a thickness of 0.1 mm, instead of 0.2 mm as previously used, to get a finer height adjustment of the clamp. This improvement brought very good results; in fact, the difference between highest and lowest clamp was reduced in a range from 0.09 mm to 0.12 mm as shown in figure 10.

Conversely, the time needed to perform the height adjustment raised from 45 minutes (current scenario) to 1 hour and 15 minutes for each star (reengineered process). Thus, although the capability indexes have increased, also machine cycle time has increased, and optimization of the process is clearly needed.

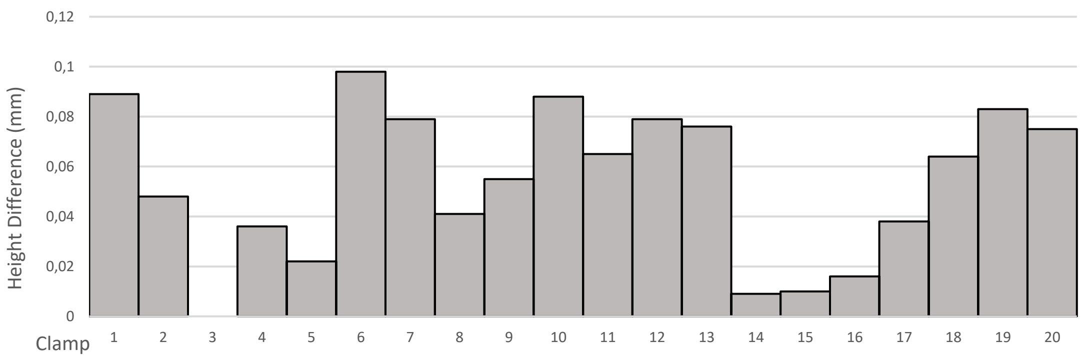

Fig. 10. Clamp heights (with reduced difference).

4.4. Process Optimization

The process optimization was carried out in order to find a quicker solution to speed up the clamp control. The time increase gives excellent capability index values but is not acceptable.

Since the height adjustment is a completely manual operation, a tool capable of identifying the clamps needing intervention and indicating the number of washers to add could improve the efficiency of the whole process.

A visual software was implemented on Excel using Visual Basic for Application language (whose interface is shown in figure 11). A specific and tailored user interface was used to make the program more intuitive, to guide the operator in entering data and to facilitate the interpretation of the results.

The software created has the following specifications:

1. Acquisition of the height of each clamp from the laser scanner;
2. Calculation of the difference between highest and lowest clamp;
3. In case the difference is not within the specified range, it identifies the best solution (in terms of fewer clamps to be modified) in order to get the desired difference between the clamps' height;
4. Show the number of washers to add in each clamp;
5. Acquisition of the height of each clamp from the laser scanner after adjustment and final check;
6. In case the obtained result is not acceptable, the process is repeated from step 2.

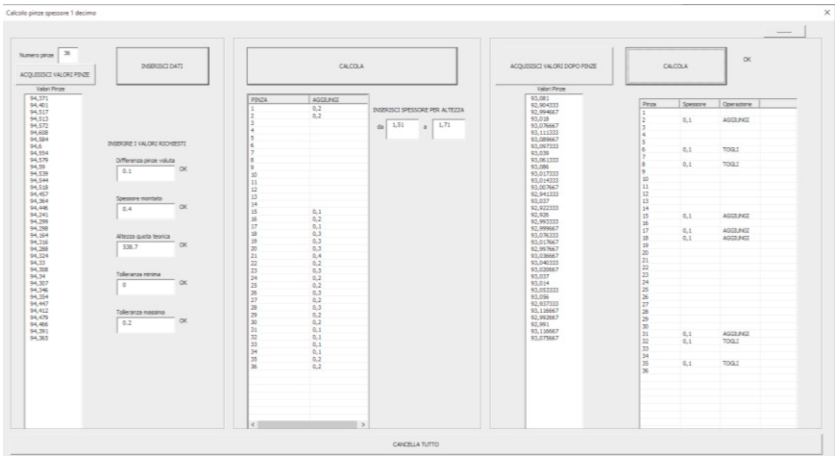

Fig. 11. Developed software interface.

The use of the software helps the operator's activity, as he only has to follow the procedure:

1. enter the required specifications;
2. look for the clamps to be modified;
3. adjust them accordingly.

This allows a great saving of time in the execution of the control; in fact, the whole procedure in performed in about 20 minutes, leading to a time saving of 73%. The software has been tested on various stars of different machines achieving excellent results in every scenario. Thanks to the implementation of the software, it has been possible to save a significant time both for the capability project and for the optimization of the machine cycle, because the process has been speeded up and the human factor has been eliminated.

5. Conclusions and Future Developments

The process capability project introduced in the two case studies reported excellent results.

As far as it concerns the backlash control, after the first measurement according to the current procedure, the process showed a very high value of Gage R&R of 71.77%, significantly above the threshold of 30% typical of a reliable measuring process. Thus, several corrective actions have been made in order to improve it, such as the standardization of the measurement process and the introduction of an operating instruction (SOP). Such interventions didn't improve enough the value of the Gage R&R and consequently a tool for pinion tooth centering was created and introduced in the SOP. Eventually, the Gage R&R value has been reduced to 15.56%, which means that the measuring system is reproducible and repeatable. Subsequently, the process capability indexes were calculated and the process was centered with a sigma level of 4.3. This is a very good result, satisfying the current target set by the company, although the final goal will be to try to improve the process to reach a sigma level equal to 6.

For the star clamp comparison check, on the other hand, the current procedure has been promptly validated as the Gage R&R value was acceptable (27%). Thus, C_p and C_{pk} indexes were calculated and evaluated as not acceptable to achieve a target sigma level of 4. After various simulations and tests, the feasible solution was to adjust the clamps' height using washers with a thickness of 0.10 mm, keeping the maximum difference between them within 0.12 mm. In this case, a sigma level equal to 6 has been achieved, although the reengineered process brought to a substantial increase in time in the execution of the checks. In order to speed up this phase, a dedicated software tool has been implemented to reduce wasted time according to Lean methodology.

Below, table 5 summarizes the benefits in terms of time:

Table 5. Benefits resulting from the implementation of the software.

Process	Check time [min]	Time difference [%]
Current	45	-
Enhanced (manually managed)	75	+66.7 (than the original state)
Enhanced (software driven)	20	-55.5 (than the original state) -73.3 (then the previous state)

Future developments will encompass different CTQ (Critical to Quality) parameters impacting the overall quality; such parameters will be selected not only in pre-assembly department controls but also in other departments of the company. The automation of data acquisition is another future step; this will lead to automatic population of Excel spreadsheet for real-time computation of process capability indexes.

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