Statistical process control of assembly lines in manufacturing

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~~Is it convenient to automate the data collection in process capability assessment? Lessons from four case studies~~

~~S~~tatistical Process Control of Assembly Lines in Manufacturing

ABSTRACT:

Data collection is often a time-consuming activity and sometimes instantaneously required. Moving to automation could bring multiple benefits, but sometimes it may not ~~always~~ be convenient. In this paper four different situations are analyzed, and for each of them a re-engineered solution enabled by information integration for automating the data collection, if applicable, is proposed. More into detail, the data collection is performed so as to apply a Statistical Process Control for quality management purposes on four different operations carried out on a filler machine produced by an Italian company. It consists in determining two process capability indexes whose values, for completeness, are then compared with their relative Six Sigma level. One of the peculiarity of these case studies, is that before collecting the measurements the systems and instruments were validated through the ANOVA Gage Reproducibility & Repeatability method. This is somehow an innovative procedure, since quite often the preliminary validation step is neglected, thus risking an inaccurate and distorted outcome.~~.~~

Keywords: Automated Statistical Process Control; Six Sigma; ANOVA Gage R&R; Automated Data Collection; instrument validation; measurement system.

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 of each business is customer satisfaction: when a consumer receives quality products, in return his/her 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 already essential at the process stage, for ensuring compliances of the final item. A recent study also demonstrates that total quality management (TQM) is an essential driver towards process innovations [3].

Among the main tools adopted in the manufacturing context having this purpose, ~~so in other words~~ namely aiming at verifying an adequate quality level of processes, it is worth mentioning the Statistical Process Control (SPC), which allows to monitor and control quality by tracking production metrics which usually have to observe determined targets, or the famous Six Sigma method, which uses five key steps (Define, Measure, Analyze, Improve and Control – DMAIC or in case of new processes or products Define, Measure, Analyze, Design and Verify – DMADV) to ensure that products meet customers' requirements and have zero defects. Indeed, 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 to be achieved [5]. The reference to these two examples is no coincidence. Indeed, in this paper four different cases ~~studies~~ are presented, carried out in a company based in the north of Italy (anonymous for the sake of privacy) that designs and produces food machinery;~~, and~~ for each ~~case ~~of them, an SPC was implemented for the relating operations performed on a~~the~~ filler machine. Specifically, two capability indexes are determined for all the processes under investigation, and their values are then compared with those obtained through the abovementioned Six Sigma theory, with the aim of reaching different Sigma levels defined *ad hoc* for each process. The operations in question are the following: (1) slewing ring-pinion backlash check; (2) flatness check for the clamp support group; (3) center alignment of the rotating structure on the fixed structure; (4) handling clamps check.

In addition to that, this manuscript addresses two main key questions, which are somehow related each other: the reliability of the measurement system, which is essential for a proper data collection, and the data collection itself. As far as the first issue, in this paper for all the four cases the systems of measurement and instruments were preliminarily evaluated and validated through the Anova Gage R&R method (AGRR in the following, where R&R stands for “repeatability” and “reproducibility”, implied of the measurement) by using Minitab™ software; indeed, quite often this aspect is ignored in studies which deal with SPC, as it will also emerge from the literature analysis section, but at the same time it is essential for the quality of collected data, and consequently for the reliability of the whole analyses and outcomes. ~~Specifically~~Into detail, for repeatability it is meant the variation caused by the instrumentation or the variation which is observed when the same operator measures the same part many times with the same instrument; reproducibility, instead, corresponds to the variation caused by the measurement system or the variation observed when different operators measure the same part with the same instrumentation [6]. Allowing to include both these aspects, according to the opinion of the authors the AGRR is considered one of the best and complete tools having this purpose, and this is the reason why the choice has fallen on this specific method; more details on the procedure are provided in the Material and Methods section.

For the topic of data collection, instead, the discussion is wider: indeed, in step with the latest trends brought from the recent Industry4.0 paradigm and the big data era, there is a shift that leads to an automation of data collection, that allows to pass from an SPC to an Automated Process Control (APC) [7], which falls within the macro topic of Advanced Process Control, namely techniques and technologies implemented to improve production capacity, monitor process parameters and operate with greater flexibility and safety [[8], [9]], enabled in most cases by information integration. Clearly, benefits would arise; indeed, this is a critical point since quite often the data collection is a time-consuming activity, and in addition to that frequently the need is for real-time and above all precise and accurate measurements [10]. In addition, [11] recognized among the main benefits achieved by companies having advanced automated data collection methods, the increased availability of high quality production data and the reduced lead time of input data management; literature also stresses the fact that quality needs to be at the forefront of transformation under digitalization [12], given its importance. In practical terms, in this paper this is translated in providing a practical solution for those operations among the four under investigation in which automating the data collection could be implementable and suitable, and shows how the industrial information integration may be appropriate in these cases, serving as guide for practitioners who have to deal with similar cases. For completeness, an example of a situation in which the automation is not recommended is also included.

It follows that the novelty and the contribution of the present manuscript are~~is~~ twofold: on one side it presents a real and practical case study of implementation of the theoretical process control methodology, which~~ith~~ begins with the essential phase of the measurement system validation (through the abovementioned AGRR), continues with the SPC and finally identifies the Six Sigma level achieved; second, which is the most prominent outcome, it provides for some selected case studies a solution under an Industry 4.0 perspective, which can lead to an APC by means of automated data collection and information integration. Moreover, according to the classification framework proposed in [13] and [14], the paper treats the topic “instrumentation and measurement”, which manifests a growing trend of interest when dealing with industrial information integration; accordingly, it also enriches scientific contributions in this sense by providing practical evidences.

Note that the steps of the analyses were carried out in accordance with the company's requests, and similarly, the metrics or tools involved and the targets set were determined by directly discussing with the company's managers. The solutions for automating the data collection were also discussed with them.

The remainder of the paper is as follows: section 2 presents a brief overview on the literature concerning the main topics of this study, followed by section 3 which illustrates the material and methods involved, including the AGRR and the two process capability indexes; section 4 deals with the presentation of the four case studies including the measuring system validation and the process capability determination, as well as their proposed re-engineering of data collection, if suggested. Section 5, finally, presents conclusions and future research directions on the basis of the obtained results.

2. Literature Overview

Different contributions are required and merged together to pursue the aim of the present work: first of all, the main topic is that of quality management, since all the efforts are made for enhancing the quality level for the ~~four~~ processes in question and, consequently, for the whole assembly line; second, for sure the strategy adopted for monitoring these operations, namely the Statistical Process Control specifically by determining two different metrics, i.e. process capability indexes; before proceeding with measurements for identifying the values of these two indexes, the instruments and in general the whole systems of measurement were validated through the AGRR method; the obtained values of the capability indexes were then compared with their relative Six Sigma level and finally, a new procedure for automating the data collection is proposed for some of the cases.

Literature related to the quality management is clearly very copious, as the topic is extremely debated since the early decades of the 20st century, and certainly varied. In line with the present study, the authors care about mentioning more recent general developments and results, such as [15], who carried out an interesting bibliometric analysis on data mining methods ~~used~~ for quality management in the manufacturing field; [16], who analyzed the main barriers towards the implementation of TQM in the context of supply chains of manufacturing organizations, or [17], who instead identified the most influencing success factors of TQM applications. As far as quality costs are concerned, interesting issues and future research directions are provided by [18]. Two final and very recent relevant studies the authors highlight, carried out by [19] and [20], deal with the indirect relation between internal quality management of firms and social, environmental and economic sustainability performance dimensions (the well-known triple bottom line) and with the cyber-physical attack vulnerabilities in manufacturing quality control tools. Specifically within the food manufacturing field, which is the one where the company subject of the case studies operates, [21] made a comparative study between small, medium and large companies in an Asiatic country ~~in order~~ to assess the most common quality management practices ~~of quality management~~; from the multi-sector analysis carried out by [22] it emerged that for the food and beverage manufacturing sector the adoption of integrated total productive maintenance (TPM) and TQM approaches brings benefit to the business performances. For an exhaustive overview on policies, procedures and practices applied in the food manufacturing sector, see [23].

Finally, note that most of the studies dealing with quality management both from a theoretical and a practical point of view are within the pharmaceutical field; indeed, together with that of food, this context presents stringent constraints and requirements for guaranteeing the quality of final products, designed for human consumption.

As already said, in this paper the quality is monitored through two process capability indexes, quite common metrics involved in the manufacturing context; examples of their application are by [24], who proposed and applied a procedure for process capability assessment within manufacturing, by [25] who computed these indexes for a 3D printing process, or by [26] who instead carried out a process capability analysis during a wire electrical discharge machining. Interesting applications in the food industry instead were carried out by [27] or [28]. Less common, instead, is the fact that before collecting data for defining the indexes the instruments involved were validated, which is pretty unusual, yet it represents a peculiarity of the procedure followed in the present study. Indeed, exception made for the study by [24] who have clearly stated that they performed an AGRR and stressed the importance of this operation, in none of the other studies relating to SPC this step was included. This further contributes to the value of the case studies under investigation, as well as to emphasize the contribution of these applications. As far as other examples of AGRR implementation within the manufacturing field, however, it is worth mentioning the validation of the measurement system used in a motorcycle company for the measurement of the tappet clearance, i.e. the gap between the rocker arm and the shim tappet of a motorcycle [29], or the assessment of some lathe machines in order to evaluate their reliability performance and state whether the machine affects the diameter of machined pieces or not [30]. However, to be honest, practical applications aimed at carrying out and recording real measurements are quite lacking; indeed, most of the screened papers in which the AGRR is mentioned deals with a theoretical point of view or assessments of its reliability; in support of this, the authors propose interesting works by [31], who defined a systematic procedure to determine the optimal experimental design for applying the AGRR or by [32] who examined problems which may derive from the application of the ANOVA to an R&R study. Two other practical case studies for the AGRR implementation are by [33] or [34]. No references to the context under investigation i.e., food machinery production, were found.

The values obtained for the two process capability indexes are compared with those resulting from the Six Sigma theory. For a complete overview and comprehension of the state-of-art on this theory, [35] and [36] are recalled; specifically, in this last paper, its adoption in European organizations is treated. For further practical applications within the manufacturing field, interesting outcomes are provided by [37] who adopted it for improving the operational efficiency of handicraft manufacturing, by [38] who proposed and successfully implemented a DMAIC approach for reducing soldering defects in an assembly line producing mobile phones, or by [39] within the automotive industry, who used the Six Sigma methodology for decreasing nonconformity. In the food industry field instead, [40] implemented this tool for improving cash flow deficit in a company producing food cans, while [41] in a plain yogurt production; finally, interesting step-by-step guidelines and critical elements of the implementation of a Six Sigma process control technique in a food production line were presented by [42]. However, there is no evidence of the joint use of capability indexes compared with Six Sigma values in the context under investigation.

Concerning the final aspect, i.e., automating the data collection, [43] in their study dealing with possibilities for integrating quality management tools and methods with digital technologies clearly stated that quality management needs to be automated, thus stressing the relevance of the topic. In this perspective [12], by addressing digitalization priorities of quality practices for small and medium enterprises with the support of Industry4.0 technologies, have included the data handling automation among the actions to be implemented for pursuing this digitalization; at the same time they highlighted, however, that this topic still requires significant human intervention, and accordingly it deserves attention and further studies. As far as practical applications of automated data collection for quality management purposes, an first interesting study (both theoretical and applied) has been by [44], who implemented the Radio Frequency Identification (RFID) technology to enhance automated data collection and information management in the construction field. Some years later, [45] as well have proposed RFID as a tool for the automation of data collection, always in the construction industry; same application and same context for [46]. Conversely, in the manufacturing context, applications of automation of data collection for quality management are quite lacking; most of the examples found in literature are not intended for quality management (although have potential to be also involved for these purposes), and for instance it is worth mentioning studies by [47] who designed and implemented an intelligent automated production-line control system, with the possibility to include Internet-of-Things (IoT) sensors for data collection; [48] have contemplated again the use of RFID in the manufacturing context for automating the collection of data; [49] as well implemented sensors for real time collection for creating a digital shadow during the production of thermoplastic composite layers in unbounded flexible pipes. However, most of the contributions which deals with this issue do not evaluate the practical outcomes; rather, they have only presented designs or frameworks. Examples of these studies are [50] who proposed a framework for advanced data collection for manufacturing systems, emphasizing real applications as research topics, or [51] who presented a platform ("Argonne-developed Manufacturing Data and Machine Learning") able to analyze and use IoT devices in manufacturing experiments, including the automation of data collection.

At the end of this brief literature overview, it can be further stated that the contributions of this paper are manifold, as it combines tools and techniques whose joint use can be significantly valuable (i.e. system of measurement validation, SPC and Six Sigma theory), as well as it presents a practical solution for enabling an automated collection of data and consequently to reach a level of APC through an information integration, which is a topic quite spread in literature, but not from a practical side and above all for a quality management purpose. For completeness, moreover, the authors recall the following literature reviews on industrial information integration: [13] and [14].

3. Material and Methods

This section provides the reader with a short description of the tools involved, as well as the methodology followed for the different case studies. First of all, for each case the AS-IS scenario is studied, including the current system of measurement and the procedure for collecting data. This last is then subject to validation through the AGRR method; in case this step returns unsatisfactory results, corrective actions are undertaken for letting the system be reliable. Once the measurement system passes the AGRR assessment, the two SPC indexes can be determined with the collected data (with subsequent comparison with the Six Sigma levels). As for the AGRR stage, in case the process under investigation is not under control, some corrective actions will be undertaken. Finally, as already stressed, for those processes for which it is suitable to develop an automated data collection procedure, a possible solution is briefly detailed.

Before presenting the four case studies, in the two subsections that follow the process capability indexes and the AGRR method are illustrated.

3.1. Process capability indexes

The metrics investigated are the process capability indexes C_p and C_{pk}, which both measure the ability of a process to meet engineering limits [52]. The first index evaluates the performance of the process related to the production specifications and is obtained by applying the following equation:

$$C_p = \frac{USL-LSL}{6\sigma} \tag{1}$$

In eq.1, 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:

$$C_{pk} = \min\left(\frac{USL-\mu}{3\sigma}; \frac{\mu-LSL}{3\sigma}\right) \tag{2}$$

In eq.2, besides the already defined parameters USL and LSL, μ is the mean of the process output. In this case as well, whenever its value is greater than 1.00, then the process is considered as capable.
These indexes are both common when dealing with this kind of measures, as recalled in the literature section. As already stated, the values obtained are then compared with those deriving from the Six Sigma theory; more in detail, Table 1~~Table 1~~ reports the correlations between achieved sigma level, goods conformity percentage, C_{pk} index, PPM (part per million) of defective goods, and time wasted for bad production in one month [53].

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

σ	Conformity %	C_{pk}	PPM	Time wasted / 720 h
±1	68.26	0.33	317,400	228.5 h
±2	95.46	0.67	45,500	32.8 h
±3	99.73	1.00	2,700	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	2.00	0.002	0.005 s

3.2. ANOVA GAGE R&R

Before collecting data and starting the measurement, a crucial issue is clearly to possess the appropriate instruments, as well as correct methods and properly trained operators. For validating these instruments, several tools can be involved; one of the most widespread, even if as it turned out this aspect is normally neglected in studies of this kind, is the AGRR, 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; (6) evaluate the adequacy precision for the measurement system according to criteria; (7) perform subsequent actions such as improvements of the system according to the results [31]. According to the Automotive Industry Action Group (AIAG) [54], in case Gage R&R < 10% the measurement system is acceptable; if 10% < Gage R&R < 30% the system is conditionally acceptable, while it is not acceptable for remaining values. In this study, Minitab™ software was used for carrying out the ANOVA analysis. Compared to the two other common methods of Gage R&R analysis, namely the A&R (Average and Range method) and the EMP (Evaluating the Measurement Process), the AGRR determines what sources of variation have a significant impact on the results and adds another source of variation to the mix and it is able to identify the operator-part interactions [55].

4. Case Studies

4.1. Case 1: Slewing ring-pinion backlash check

4.1.1. AS-IS scenario analysis

The first case study refers to a quality check which is carried out during the assembly operations of the filler machine in question. More into detail, the check consists in measuring the slewing ring-pinion backlash, and ~~the aim is~~ to verify 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~~Figure 1~~. A certain backlash between the teeth, according to the design specifications, is important to avoid friction and overheating problems or unexpected forces.

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Figure 1 - Geometry and real implementation of the rotating structure.

The correct value of backlash, as well as its the minimum and maximum values, are manually reported by the operators in a control sheet, which also includes 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 one 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 in a manner that one side of the pinion tooth is in contact with the tooth of the slewing ring (second step), as shown in Figure 2~~Figure 2~~.

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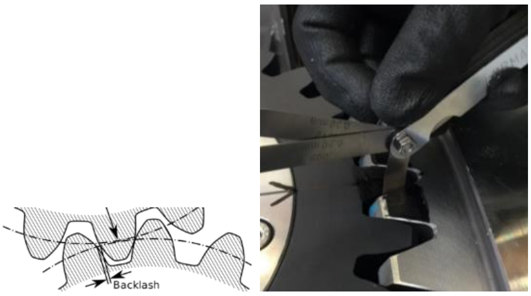

Figure 2 - Contact between the pinion tooth and the tooth of the slewing ring.

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 by 360 degrees so that the backlash between the same tooth of the pinion is checked again and measured with respect to a different tooth of the slewing ring.
For our purposes, the procedure is repeated three times by two operators, with five samples of measures each time, resulting in thirty values overall to be analyzed.

4.1.2. Measuring system validation

Minitab™ software, used to carry out the ANOVA analysis of the measurement values and compute the AGRR, returned the outcomes reported in Table 2~~Table 2~~. Note that, for completeness, in all the tables in which AGRR results are computed, the full outcome returned by Minitab™ is reported, including all the variance component contributions; however, the AGRR total result useful for our purposes is in the first row and last column, in bold (%Study Var).

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Table 2 - Results from the AGRR analysis for case study 1.

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 can be noticed that the Total AGRR value for this first case is 71.77%, so the variance of the results obtained ~~according to the measurement procedure described~~ is mainly caused by the low repeatability and reproducibility of the measurement process, which actually generate high variance; indeed, the process is fully manual. This is a very poor result, as according to the AIAG standard acceptable values of %Study Var must be less than 30% for ensuring reliability of the measuring system. As a consequence, the calculation of the process capability indexes cannot be performed until the measuring system is not improved.
To this end, by observing the two operators ~~while~~ 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 their spontaneity. A Standard Operation Procedure (SOP) consisting of clear and simple images guiding the employees was designed to this end, as reported in Figure 3~~Figure 3~~, and proposed to the workers.

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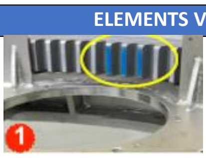
STEP	ELEMENTS VIEW	DESCRIPTION
1		Identification of the teeth aligned with the common diameter of the external and internal gears (slewing ring and pinion)
2		Internal pinion placement and installation

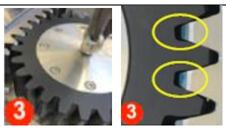
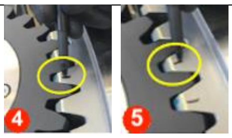
3		Alignment of pinion teeth with the common diameter
4 - 5		Identification and marking of the left (4) and right (5) slewing ring teeth
FINAL		Final gears assembly with marked teeth ready for backlash measurement

Figure 3 - SOP steps.

After the introduction of the SOP and the training of the operators, a second measurement session was carried out; again, thirty values were recorded, according to the same procedure previously described. After a data analysis, the following AGRR results were obtained (Table 3~~Table 3~~):

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Table 3 - Results from the AGRR analysis for case study 1 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

Firstly, it is noticed that, according to the SOP's aim, the operators' variance component is zeroed. The %Study Var is reduced from 71.77% to 46.58%, which however is still too high for considering the measurement system as reliable. Hence, to further lower the value, another action that could somehow bring variability has 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 ~~any support~~ of any tool or equipment~~, relying on his visual skills and experience only. This visual inspection which guides the alignment ~~can lead to a~~may be the responsible of such great variability in the repeatability of the measurement. To overcome this issue, 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 clearly indicate the correct position of the tooth in relation to the slewing ring. Since this specific tool was not available on the market, it was *ad hoc* designed using a 3D modelling software and then 3D printed using additive-manufacturing techniques; its model and usage are shown in Figure 4~~Figure 4~~.

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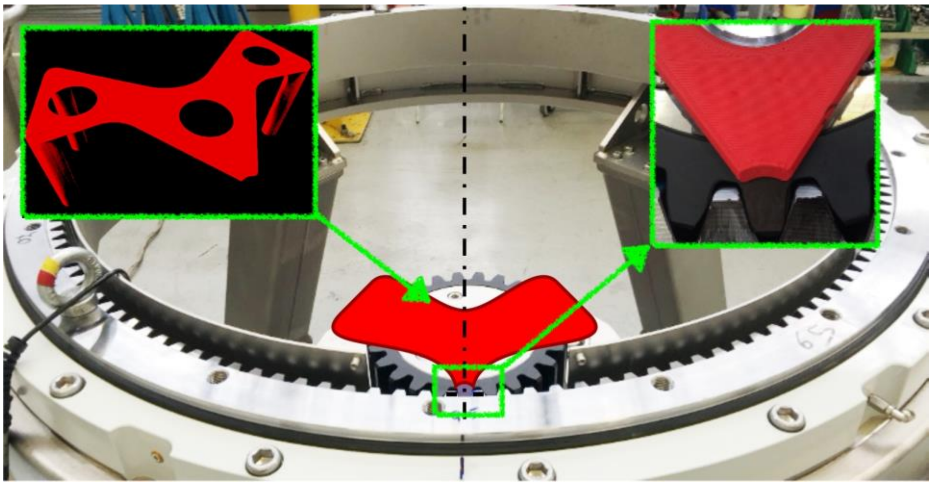

Figure 4 - 3D Model of the alignment tool.

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 provides fixed reference points for tooth alignment. A third final measurement campaign was performed with thirty measures and excellent results were obtained from the data processed by Minitab, as shown in Table 4~~Table 4~~.

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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 jig has significantly reduced the probability of error caused by the operators. The measuring system finally obtained can be considered reliable and therefore repeatable and reproducible, allowing to proceed with the process capability analysis.

4.1.3. Process capability calculation

The last set of data collected during the validation of the measurement system has been plotted in Figure 5~~Figure 5~~ and used to compute the capability indexes of the whole process by means of an Excel spreadsheet.

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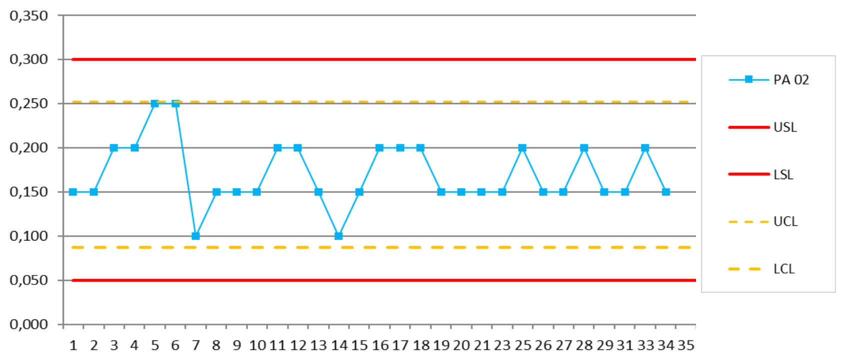

Figure 5 - Process capability calculation (case study 1).

The computation of the indexes returned a result of C_p=1.51 and C_{pk}=1.45. These values fit perfectly the target set by the company, and more precisely they exceed the expectations, ~~giving~~ corresponding to a Sigma level of 4.3, whereas the target level for this first process was set at ~~a Sigma level of~~ 4 by the company's management. This is consistent with the data plotted in Figure 5~~Figure 5~~, which clearly shows that the process is centered with respect to the project specifications (LSL - USL, the red lines of the graph). Thus, the process can be declared under statistical control.

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4.1.4. TO-BE re-engineering

The next step to further improve and optimize the backlash check is to evaluate the possibility of introducing automation for collecting data, since the ultimate purpose of this paper is also to provide a possible solution to this issue. However, in this case, it must be noticed that the usage of the new SOP and jig did not cause any slowdown to the process and thus AGRR requirements were achieved without any negative impact on labor efficiency. Due to the complexity of the process and the needs for operators to manually handle the slewing ring and pinion, this example represents an operation for which it is clearly not convenient to introduce expensive automatic handling systems. The management of the company agreed as well with that~~.~~.

4.2. Case 2: Flatness check for the clamp support group

4.2.1. AS-IS scenario analysis

The second process refers to the check of the correct flatness between the disc of the carousel (depicted in grey in Figure 6~~Figure 6~~) and its hub (brown color of Figure 6~~Figure 6~~), which is specifically performed on the assembly line.

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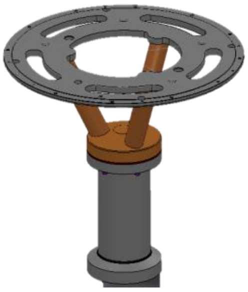

Figure 6 - The disc and its hub whose flatness has to be checked.

Different clamps are mounted on the disc in order to handle the bottles among different sections of the machine; normally, a filler machine is equipped with 5 to 7 discs having different diameters, which rotate and interact while handling the bottles. The rotary handling allows to speed up the machine and to reduce its size. There are five different sizes of the bottle transfer groups: the smallest one has a diameter of 360 mm, while the bigger reaches 1880 mm. The correct flatness of the discs is very important to correctly pick and release the bottles; in case of misalignment of the clamps the bottles' loss may occur during the transfer. The check is manually carried out by positioning a dial caliber underneath the disc and clamping it on a proper fixed reference point as shown in Figure 7~~Figure 7~~; then the hub and disc are rotated and the operator marks the highest and lowest points on the disc by means of an electric pen.

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Figure 7 – Dial caliber used for measurement.

In the control chart the ~~allowable~~ allowed tolerance limits are reported, which vary according to the diameter of the disc; however, they normally settle around a few tenths of millimeter.

If the recorded measurement value fits the tolerance range, the disc continues its assembly process and reaches the subsequent station in which the clamps are mounted and compared (case study 4); otherwise, corrective actions have to be performed (e.g. internal mechanical reworking or return in case they are bought from an external supplier).

4.2.2. Measuring system validation

Two operators and three different discs were involved for the assessment of the measurement system; each worker recorded three measurements so a total of eighteen values were analyzed with Minitab™. The results from the data collected are presented in Table 5~~Table 5~~, while the AGRR outcomes are detailed in Table 6~~Table 6~~.

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Table 5 - Data collected for the AGRR validation for case study 2.

Parts	Operator	Value	Parts	Operator	Value
2	1	+/- 0.09	3	2	+/- 0.09
1	1	+/- 0.16	2	2	+/- 0.09
3	1	+/- 0.09	1	2	+/- 0.16
2	2	+/- 0.09	3	1	+/- 0.09
1	2	+/- 0.16	2	1	+/- 0.09
3	2	+/- 0.09	1	1	+/- 0.16
3	1	+/- 0.08	3	2	+/- 0.09
1	1	+/- 0.16	2	2	+/- 0.09
2	1	+/- 0.09	1	2	+/- 0.16

Table 6 - Results from the AGRR analysis for case study 2.

Source	VarComp	%Contribution (of VarComp)	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.0000056	0.33	0.0023570	0.014142	**5.75**
Repeatability	0.0000056	0.33	0.0023570	0.014142	5.75
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	0.0016722	99.67	0.0408928	0.245357	99.83
Total Variation	0.0016778	100.00	0.0409607	0.245764	100.00

As it can be deduced from the first line of Table 6~~Table 5~~, Minitab™ returned a value of Total Gage R&R equal to 5.75%, meaning that, conversely to the first case study, in this second case the measurement system is completely reliable. According to that, the two capability indexes can be immediately determined.

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4.2.3. Process capability calculation

By elaborating the data collected for the AGRR, performance indexes have been computed, obtaining a C_p=3.39 and C_{pk}=2.29 (**Errore. L'origine riferimento non è stata trovata.**~~Figure 8~~).

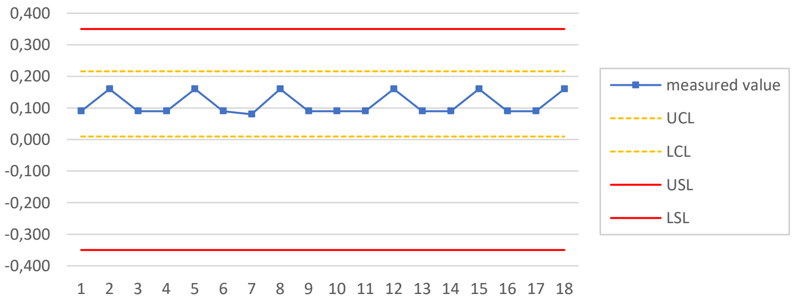

Figure 8 – Process capability calculation (case study 2).

Both values are great enough to support the correct capability index of the process. In fact, both indexes are higher than 1.33 which is the value of the indexes which corresponds to a Six Sigma level of 4, which was the target set for this operation. This means that the process is centered as shown Figure 8~~Figure 8~~, where the measured value perfectly fits the range identified by the USL and LSL.

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4.2.4. TO-BE reengineering

According to the measured capability indexes, at present it can be stated that the process in examination is under statistical control and no interventions are further required. However, in order to maintain this satisfying result, it is necessary to continuously monitor values and, to this extent, the introduction of automation is highly recommended in order to speed up data collection. The dial caliber can be replaced by a confocal displacement sensor connected to a PLC capable of managing the rotation of the carousel and data acquisition. According to a marketing analysis, t~~T~~he cost of this hardware upgrade and software integration is approximately 25,000 euros, while no significant reduction in manpower can be considered.

4.3. Case 3: Center alignment of the rotating structure on the fixed structure

4.3.1. AS-IS scenario analysis

The third operation refers to the check of the alignment between the rotating disc (carousel, shown in Figure 9) and the fixed structures, which ~~takes place~~occurs in the first station of the testing area. The disc is positioned in the appropriate holes by means of an overhead travelling crane. Using a dial caliber attached to the fixed structure, the concentricity between the two parts is measured while rotating the disc; more into detail, the deviation is checked in four different positions (every 90°) and then reported in the proper control chart for further verification.

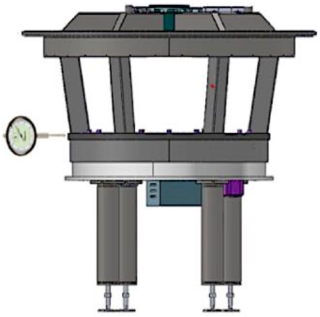

Figure 9 – The rotating disc of the carousel.

4.3.2. Measuring system validation

Two operators and two machines were involved for recording the first dataset of this process; for each position, three different measures were recorded. As said just above, the measurement takes place in four different positions, but the first is used for setting the instrument bias, and thus, accordingly, it will not be considered. It follows that the number of samples analyzed by Minitab™ is eighteen for each machine. Table 7~~Table 7~~ reports the first data collection, followed by Table 8~~Table 8~~ in which the results from the AGRR are presented.

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Table 7 - Data collected for the AGRR validation for case study 3; note that RFH_180 and RFH_182 are the nomenclatures for indicating the two machines.

Parts	Operator	RFH_180	RFH_182	Parts	Operator	RFH_180	RFH_182
1	1	0.09	0.068	2	2	-0-113	0.232
1	1	0.08	0.07	2	2	-0.109	0.229
1	1	0.08	0.07	2	2	-0.11	0.241
1	2	0.077	0.068	3	1	-0.169	0.205
1	2	0.087	0.068	3	1	-0.168	0.204
1	2	0.087	0.071	3	1	-0.17	0.205
2	1	-0.106	0.225	3	2	-0.17	0.195
2	1	-0.107	0.225	3	2	-0.169	0.196
2	1	-0.106	0.226	3	2	-0.169	0.198

Table 8 - Results from the AGRR analysis for case study 3.

Source	VarComp	%Contribution (of VarComp)	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.0000117	0.07	0.003427	0.020563	**2.60**
Repeatability	0.0000117	0.07	0.003427	0.020563	2.60
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	0.0173955	99.93	0.131892	0.791353	99.97
Total Variation	0.0174073	100.00	0.131937	0.791620	100.00

The Total Gage R&R has a value lower than 10% as previously resulted for case study 2, thus the instrument can be defined as reliable and data already collected can be used to compute the capability of this~~e~~ process ~~under investigation~~.

4.3.3. Process capability calculation

Results from case study 3 return a value of C_p= 0.6, while C_{pk} corresponds to 0.4 (~~reference~~ control chart depicted in Figure 10~~Figure 10~~), which in turn refers to a Sigma Level between 1 and 2.

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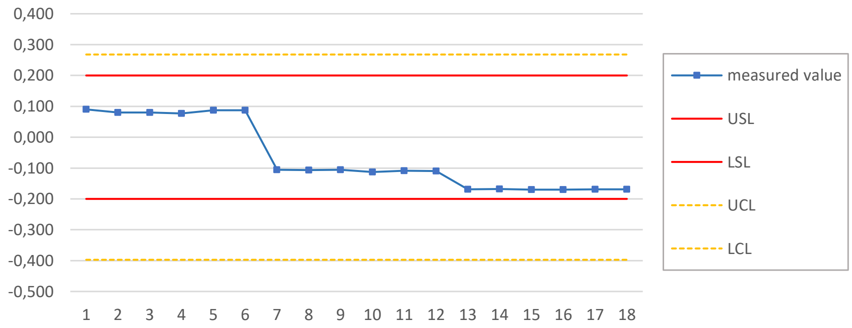

Figure 10 - Capability process calculation (case study 3).

In this case, both values are quite low, and this may lead to state that the process is not under statistical control and not centered. However, according to Figure 10, it can be noticed that all the measures are within the range identified from the two limits (USL and LSL), and thus, ~~the process is centered~~ according to the collected data, the process is centered. Despite that, in the light of such behavior, ~~in order~~ to have a more accurate result and firmly state whether the process is centered or not it is recommended to collect other data to update the spreadsheet developed and reaching the desired Six Sigma level of 4; in this perspective, the redesign of this process described in the following subsection could be helpful.

4.3.4. TO-BE reengineering

According to the previous results, it is paramount important to set up a proper data collection system capable of monitoring the trend of process capability indexes. In fact, due to the specific features of the process, the feasible operations which can positively impact the indexes and lower the variance are very labor-intense; thus, before changing production processes, a detailed monitoring action has to be implemented aimed at assessing the need for changes. More into detail, two possible interventions can be done: (1) reduction of the manufacturing tolerances of the disc and the structure, with particular respect to the drilling phase;~~,~~ (2) rework of the rotating disc of the carousel and the fixed structures, in order to improve their relative alignment. The first solution requires improvements in the manufacturing process, and the specific cost (per part) is ~~not very high~~modest, but it affects all the produced parts; the second option, instead, encompasses a higher specific cost (assembly, check, disassembly, rework, reassembly, recheck) but involves only defective ones. Under~~In~~ a lean perspective of continuous improvement, the first option is the most suitable, although an economic evaluation must be carried out.

According to this statement, a precise and detailed data collection campaign is needed to proceed with the evaluation, and to this extent an automation system is considered. As for the previous use case, the dial caliber can be replaced by a confocal displacement sensor connected to a PLC capable of managing the rotation of the carousel and data acquisition. The cost of this hardware upgrade and software integration, as already said, is about 25,000 euros, while no significant savings in manpower can be considered. Unfortunately, the operations described in the last couple of use cases cannot be jointly executed in the same station as they involve different equipment and different assembly stages, and two different solutions should be purchased.

Since the control check is a required step in the assembly process, eventually the company may decide to firstly implement the automated data collection system, and then to adapt it to work according to the previous case study. For the first piloting campaign, software integration with PLC was reduced to the minimum, since data was exported in Excel and hence analyzed.

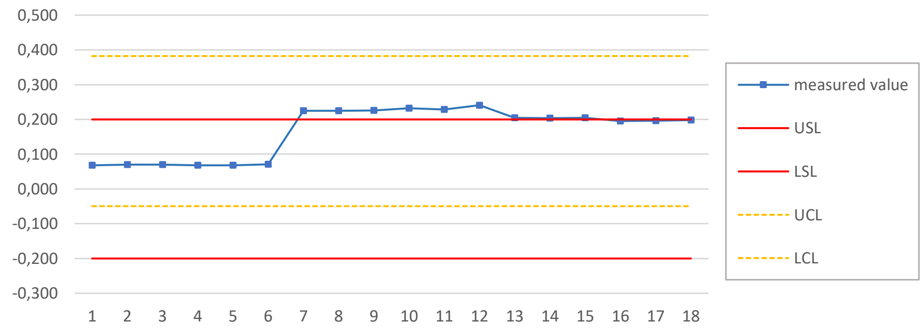

Figure 11 - Capability process calculation after implementation of automation (case study 3).

As it can be noticed in Figure 11~~Figure 11~~, reporting data collected by confocal displacement sensor on two more machines, the process is not fully under statistical control and not centered. Thus, in the light of such behavior, in order to have a more accurate result and firmly state the trend of the process~~,~~ it is recommended to collect other data. Nonetheless, the reduction of the manufacturing tolerances of the disc and the structure, which guarantee higher accuracy in the alignment and Industry 4.0 compliance, seems the next (required) step to be implemented.

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4.4. Case 4: Handling clamps check

4.4.1. AS-IS scenario analysis

The fourth and last analyzed process~~, instead,~~ refers the clamps check, and it is performed on all the handling clamps connected to the rotation support (carousel): for each clamp the precise height "*h*" with respect to a fixed reference point is measured as shown in Figure 12~~Figure 12~~. The carousel consists of several clamps used for sorting bottles and transferring them from one point to another of the machine. In one machine there are several carousels rotating and interacting with each other; given these interactions, it is mandatory that the clamps are positioned correctly so that the bottle transfer can be carried out successfully.

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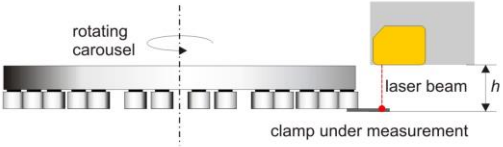

Figure 12 - Clamp height measurement.

All the measures are grouped together; the difference between the highest and lowest clamp is then computed and checked against the limit value of 0.2 mm defined in the control sheet. This value allows for precise and reliable interaction between the clamp that yields and the one that receives the bottle during the transfer. In order to ~~calculate~~ determine 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 using triangulation on the clamp's surface interfaced with a computer through a PLC. Since the reference point is fixed, the values found can be compared and thus the difference between the clamps can be easily computed.

During the 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 then calculated, and the highest and lowest clamp with the respective value is displayed. Figure 13~~Figure 13~~ shows the collected measurements on a graph.

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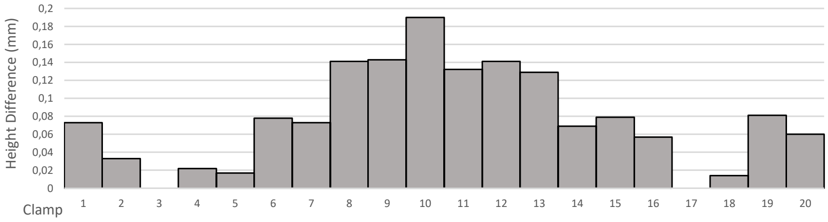

Figure 13 - Clamp heights.

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

4.4.2. Measuring system validation

Following the same procedure of the previous cases, the height difference between clamps of five different rotating stars was measured by repeating the measurements three times with two different operators (five measures recorded each time). The analysis, shown in Table 9~~Table 9~~, reports a %StudyVar of 25% and thus allows a positive evaluation of the measurement process.

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Table 9 - Results from the AGRR analysis for case study 4.

Source	VarComp	%Contribution (of VarComp)	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.0000526	6.27	0.0072521	0.043512	**25.03**
Repeatability	0.0000333	3.97	0.0057735	0.034641	19.93
Reproducibility	0.0000193	2.29	0.0043885	0.026331	15.15
Operators	0.0000000	0.00	0.0000000	0.000000	0.00
Part-To-Part	0.0007867	93.73	0.0280476	0.168285	96.82
Total Variation	0.0008393	100.00	0.0289700	0.173820	100.00

4.4.3. Process capability calculation

After having gathered~~ing~~ all the required data, performance indexes have been computed, finding C_p=1.45 and C_{pk}=0.30 (Figure 14~~Figure 14~~).

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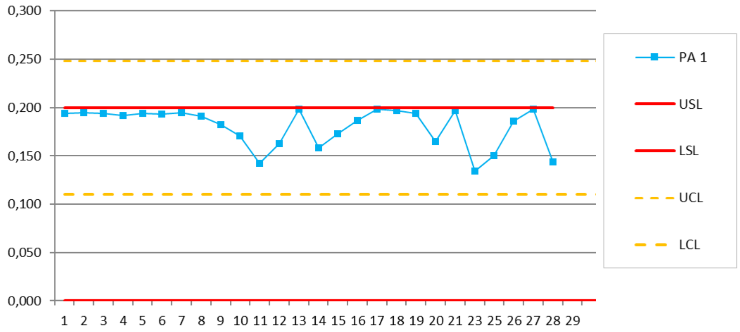

Figure 14 - Capability process calculation (case study 4).

The analysis of the indexes shows that the process is definitely not centered; indeed, although the value of the C_p is satisfying and higher than the target of 1.33 (Sigma Level of 4), the value of the C_{pk} is instead very low, leading the system to a Six Sigma level of 0.9, very far from the target value set by the management for this process. In order to improve C_{pk}, several simulations have been carried out using an Excel spreadsheet; results show that having a maximum difference in clamps height in a range between 0.09 mm and 0.11 mm would bring to a very high C_{pk} centering the process and achieving a Sigma Level of 6 (C_p=4.23 and C_{pk}=4), as reported in Figure 15~~Figure 15~~.

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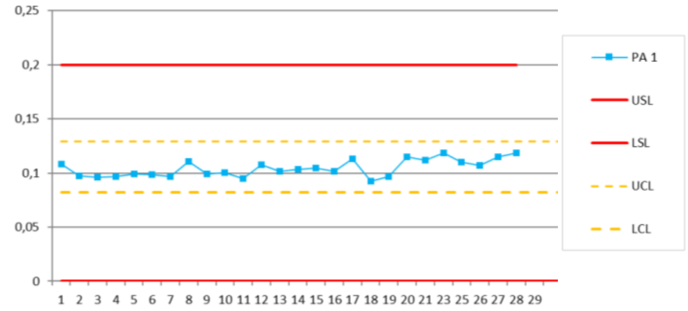

Figure 15 - Capability process calculation after many simulations in order to center the process (case study 4).

In practice, 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 this end, a deeper study of the clamp's adjustment process was carried out to re-engineer it. It was then decided to use washers with a thickness of 0.1 mm (Figure 16~~Figure 16~~), instead of 0.2 mm as previously involved, to get a finer height adjustment of the clamp. This improvement brought very ~~good~~ satisfactory 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 17~~Figure 17~~.

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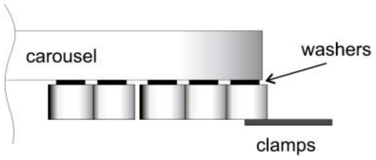

Figure 16 - Detail of the washers.

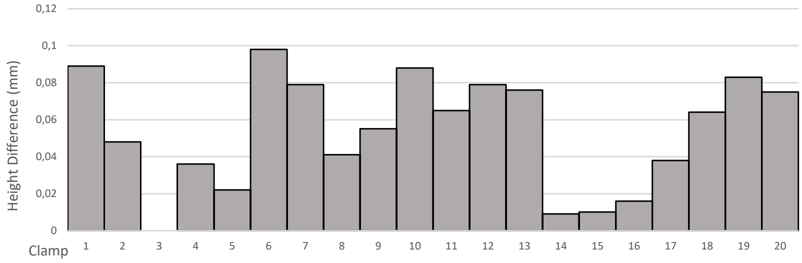

Figure 17 - Clamp heights (with reduced difference).

However, unfortunately, the time needed to perform the height adjustment raised from 45 minutes (AS-IS scenario) to 1 hour and 15 minutes for each carousel (re-engineered process). Thus, although the capability indexes have increased, the machine cycle time has increased too, and further optimization of the process is clearly ~~needed~~recommended; these motivations form the basis for the development of~~ing~~ an improvement software, described in the section below.

4.4.4. TO-BE re-engineering

The process optimization was carried out to find a quicker solution for~~to~~ speeding up the clamp control involving, as far as possible, industrial automation. The increased time to adjust clamps' height ~~gives~~ returns excellent capability index values but is not acceptable. Since the height adjustment is a completely manual operation, a first automation step to improve the efficiency of the whole process involves the development and adoption of a tool able to identify and select only the clamps needing intervention and indicating the exact number of washers to be added.

A visual software was developed and then implemented on Excel™ using Visual Basic for Application (VBA) language (whose interface is shown in Figure 18~~Figure 18~~). A specific and tailored user interface was ~~used~~ designed to make the program more intuitive and user-friendly, to guide the operator in entering data and to facilitate the interpretation of results.

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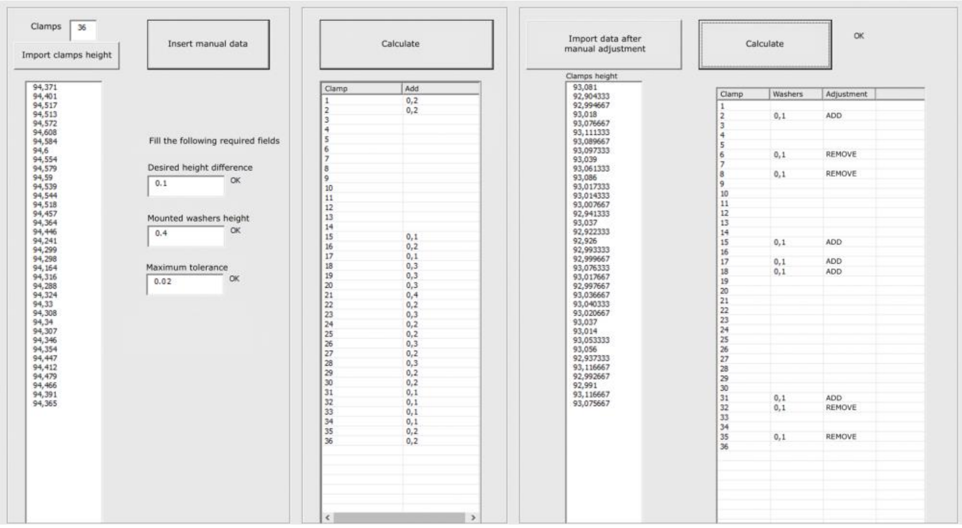


Clamps: 36

94,371
94,401
94,517
94,513
94,572
94,608
94,584
94,6
94,554
94,579
94,59
94,539
94,544
94,518
94,457
94,364
94,446
94,241
94,299
94,298
94,164
94,316
94,288
94,324
94,33
94,308
94,34
94,307
94,346
94,354
94,447
94,412
94,479
94,466
94,391
94,365

Fill the following required fields

Desired height difference: 0.1 OK

Mounted washers height: 0.4 OK

Maximum tolerance: 0.02 OK

Clamp	Add
1	0,2
2	0,2
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	0,1
16	0,2
17	0,1
18	0,3
19	0,3
20	0,3
21	0,4
22	0,2
23	0,3
24	0,2
25	0,2
26	0,3
27	0,2
28	0,3
29	0,2
30	0,2
31	0,1
32	0,1
33	0,1
34	0,1
35	0,2
36	0,2

Clamps height

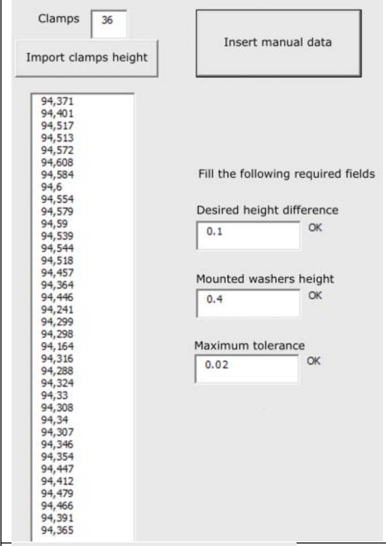
93,081
92,904333
92,994667
93,018
93,076667
93,111333
93,089667
93,097333
93,039
93,061333
93,086
93,017333
93,014333
93,007667
92,941333
93,037
92,922333
92,926
92,993333
92,999667
93,076333
93,017667
92,997667
93,036667
93,040333
93,020667
93,037
93,014
93,053333
93,056
92,937333
93,116667
92,992667
92,991
93,116667
93,075667

OK

Clamp	Washers	Adjustment
1		
2	0,1	ADD
3		
4		
5		
6	0,1	REMOVE
7		
8	0,1	REMOVE
9		
10		
11		
12		
13		
14		
15	0,1	ADD
16		
17	0,1	ADD
18	0,1	ADD
19		
20		
21		
22		
23		
24		
25		
26		
27		
28		
29		
30		
31	0,1	ADD
32	0,1	REMOVE
33		
34		
35	0,1	REMOVE
36		

Figure 18 - Developed software interface.

The software~~It~~ works according to the following steps:



Clamps 36

```
94,371
94,401
94,517
94,513
94,572
94,608
94,584
94,6
94,554
94,579
94,59
94,539
94,544
94,518
94,457
94,364
94,446
94,241
94,299
94,298
94,164
94,316
94,288
94,324
94,33
94,308
94,34
94,307
94,346
94,354
94,447
94,412
94,479
94,466
94,391
94,365
```

Fill the following required fields

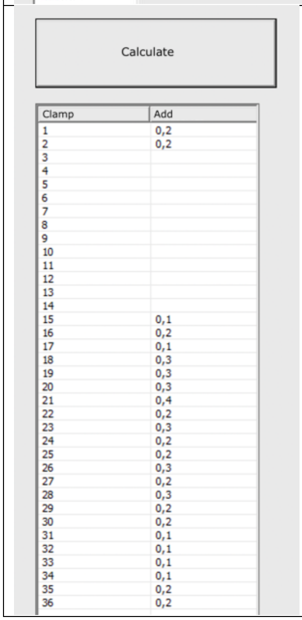
Desired height difference: 0.1

Mounted washers height: 0.4

Maximum tolerance: 0.02

At first, the height measurement of each clamp is imported directly from the laser scanner interfaced with and managed by a PLC. Moreover, the user must input some other parameters needed by the software, in particular:

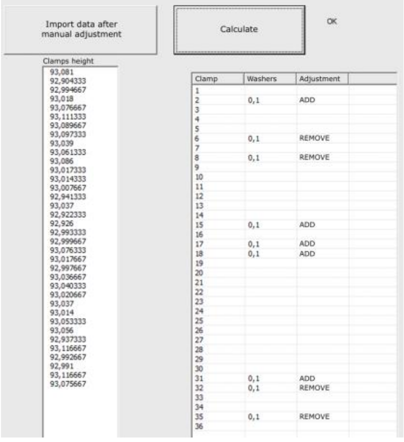
- Desired (average) height difference, set to 0.1 mm according to previous statements. In fact, having a maximum difference in clamps height in a range between 0.09 mm and 0.11 mm (0.10 is the average value) brings to a very high C_{pk}, centers the process and achieves a Sigma Level of 6 as shown in the previous Figure 13;
- Mounted washers height, set to 0.4 as every washer is 0.1 mm thick and 4 washers are installed by default on each clamp;
- Maximum tolerance, whose value is 0.02, which defines the maximum difference allowed in clamps height (between 0.09 mm and 0.11 mm).



Clamp	Add
1	0,2
2	0,2
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	0,1
16	0,2
17	0,1
18	0,3
19	0,3
20	0,3
21	0,4
22	0,2
23	0,3
24	0,2
25	0,2
26	0,3
27	0,2
28	0,3
29	0,2
30	0,2
31	0,1
32	0,1
33	0,1
34	0,1
35	0,2
36	0,2

Secondly, a preliminary optimization round is run in order to adjust the maximum height difference within the desired range. The software calculates the difference between the highest and the lowest clamps; then, for each clamp, shows the number of washers to add in case the difference is not within the specified range.

At this stage, the algorithm takes into account only washers' addition, thus the clamps whose height is not within the range are lowered by adding more washers. Each added washer lowers the clamp of 0.1 mm, increasing its height of the same quantity in the laser scanner reference system.



Clamps height

93,081
92,904333
92,994667
93,018
93,076667
93,111333
93,089667
93,097333
93,039
93,061333
93,086
93,017333
93,014333
93,007667
92,941333
93,037
92,922333
92,926
92,993333
92,999667
93,076333
93,017667
92,997667
93,036667
93,040333
93,020667
93,037
93,014
93,053333
93,056
92,937333
93,116667
92,992667
92,991
93,116667
93,075667

Clamp	Washers	Adjustment
1		
2	0,1	ADD
3		
4		
5		
6	0,1	REMOVE
7		
8	0,1	REMOVE
9		
10		
11		
12		
13		
14		
15	0,1	ADD
16		
17	0,1	ADD
18	0,1	ADD
19		
20		
21		
22		
23		
24		
25		
26		
27		
28		
29		
30		
31	0,1	ADD
32	0,1	REMOVE
33		
34		
35	0,1	REMOVE
36		

After the manual adjustment of the clamps according to the suggestion of the software discussed in the previous step, the height of each clamp is acquired again by the laser scanner in order to check and validate the results of the manual calibration. The final optimization round is run in order to eventually adjust the maximum height difference within the desired range. The software again calculates the difference between the highest and the lowest clamps; then, as done in the previous step, for each clamp it shows the number of washers to add or remove in case the difference is not within the specified range. At this stage, the algorithm takes into account both washers' addition and removal; every added washer lowers the clamp of 0.1 mm, whilst every removed washer lifts the clamp of the same quantity. The algorithm is optimized in order to find the solution involving the minimum number of manual intervention (number of adjusted clamps), finding the best scenario among all the scenarios observing the maximum height tolerance.

In case the obtained result is not acceptable, the process is repeated from the first step.

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

1. enter the required specifications;
2. identify only the clamps to be modified;
3. adjust these clamps accordingly.

The first release of the software, aimed at validating the algorithm and its functionalities, has been implemented in an Excel worksheet; the final version, instead, will be implemented in the same PLC interfaced with the laser scanner in order to build a solid automation system with a common human-machine interface (HMI) for the whole process, including data acquisition and wizard for height adjustments. This represents the second and final step bringing the process to the best achievable automation degree. Due to the process specific activities (manual adjustment of the clamps' height by insertion/removal of the washers), it cannot be fully automated. More into detail, the PLC only manages data acquisition process (rotation of the carousel and the laser measurements) and gives detailed instructions to operators (clamp's adjustment), who is actively involved. However, since the goal was that of automating the data collection, it can be stated that it was brilliantly achieved.

This allows a great saving of time in the execution of the control, with respect to the Sigma Level of 6 imposed by reduced tolerances. The clamps' adjustment is now performed in approximately 20 minutes in the TO-BE scenario, compared to the AS-IS one, both before and after the difference reduction; indeed, the AS-IS procedure counted about 45 minutes, while the time required after the reduction of maximum allowable difference in clamps' height, counted about 75 minutes. The software has been tested on various carousels of different machines, achieving excellent results in every scenario. ~~Thanks to~~With the implementation of the software, it ~~has been~~was possible to save a significant time both for the capability project and for the optimization of the machine cycle; in fact, the process has been speeded up and the human factor has been ~~eliminated~~removed. The implementation cost of the software in the PLC is estimated in 5,000 euros.

5. Conclusions and Future Developments

The study presented in this manuscript deals with an SPC assessed through two process capability indexes which are determined for four operations routinely performed on a filler machine produced by an Italian company. In all the four cases, before proceeding with measures and data collection~~ for computing the indexes~~, the measurement systems were validated by means of a tool which assesses whether the system is reliable or not, namely the AGRR. The particular choice is a peculiarity of the procedure followed in this manuscript, since quite often the validation step is not considered in works dealing with SPCs, thus compromising the full reliability of the analyses. The values of the two indexes for each operation were then compared with the corresponding values returned from the Six Sigma theory, according to the targeted levels set by the management of the company involved in the study. In addition, given the relevance of the topic of automating the data collection, which in turn derives from the pressure towards the digitalization of quality management and an information integration, a solution was suggested *ad hoc* for three of the four operations for which it turned out to be relevant.

Table 10~~Table 10~~ below summarizes the obtained results.

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Table 10 - Results summary.

Case study	Targeted Sigma Level	AS-IS Sigma Level	TO-BE Sigma Level	TO-BE Cost	TO-BE Labor Saving
1	4	4 – 5	-	-	-
2	4	6	-	25,000 €	-
3	4	1 – 2	< 1	25,000 €	-
4	4	0.9	6	5,000 €	-55.5%

As far as the measurement systems validation, exception made for the first case in which the AGRR results were not satisfying at all at the first round, the remaining three ~~brilliantly ~~passed this phase at the first measurements. For case study 1, instead, a SOP for workers and secondly a jig for facilitating the operation were required before the system could be defined as reliable.

Looking at the process capability assessment, instead, in the first case the process was centered since the beginning, and thus no further corrections were required. Same reasoning for the second case, which presented values of indexes which correspond to a Six Sigma level of 6, even higher than the target set for this operation. The third and fourth cases, instead, were the only cases deserving more attention as measured C_{pk} presented a very low value, which results in a process not under statistical control.

In case study 3, the values of process capability indexes referred to a Sigma Level between 1 and 2, forcing the company to invest in an automated data collection system to widen dataset of measures and improve their accuracy. As a result, the update of the indexes brought to a worsening in their values as shown in Table 10~~Table 10~~; thus, further analyses are required to determine their trend.

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Lastly, the most relevant case study is number 4, as it allows to improve the capability indexes overtaking the desired target value of 4. More in detail, with a reasonable investment and a change in the process, it is possible to both enhance the process control and achieve important savings in terms of labor as summarized in Table 11~~Table 11~~.

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Table 11 - Benefits resulting from the implementation of the software (case study 4)

Process	Check time [min]	Time difference [%]
Current (AS-IS)	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)

The most interesting part, ~~instead~~however, is the potential automation of the data collection. The first and second case study involves a manual activity, which is almost impossible to convert into automation, and according to that no solutions were developed for it, agreed with the management. However, a potential solution is proposed for case study 2, as a guideline for practitioners who may deal with this issue and desire to automating the process of data acquisition. For the third and the last cases as well, an alternative and innovative method is proposed, which is implementable through an information integration between the PLC and the Manufacturing Execution System (MES).

Overall, the case studies allowed to see different situations, and they are somehow complementary: indeed, in the first case, the AGRR value was not satisfying at first and correct actions were undertaken in order to let the measurement system be reliable and acceptable, while the capability indexes instead were perfectly in line with the target set; in the third and fourth cases, on the contrary, the AGRR was at first acceptable (and this is actually due to the fact that the measurements were performed by means of digital instrumentation and not manually carried out), but the values of the capability indexes were not aligned with the targets, and accordingly corrective actions were successfully performed to improve them. In the third case the indexes worsened while in the fourth they improved. It follows the perfect completeness of the various scenarios presented. Moreover, with respect to the data collection automation and the information integration issues, in order to respond to the research question posed in the title, the lesson learned from the case studies remarks that one-fits-all approach is not feasible. Indeed, case study 1 demonstrates that, given the complexity of the process under investigation, the introduction of an automation system would not be convenient due to huge investment costs, and poor labor savings. Same considerations are applicable to case study 2 as well, even if the automation solution is more economically feasible as already discussed and could be useful for allowing a continuous and real-time data acquisition. Conversely, for the last two case studies, the introduction of automation is highly recommended, in order to improve the processes. Specifically, for case study 3, this represents the first step of an *in fieri* improvement, while for case study 4 it enables the real and full process information integration. These different practical implications are praiseworthy, being the result of a tangible in field experience.

Future developments will encompass different Critical to Quality (CTQ) 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 further automation of data acquisition and strategic evaluation of investments are future steps; this will lead to an automatic population of Excel spreadsheets and HMI panels for real-time monitoring of process capability indexes and their trend.

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