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(Article begins on next page)

Is it convenient to automate the data collection in process capability assessment? Lessons from four case studies Statistical Process Control of Assembly Lines in Manufacturing

ABSTRACT:

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9 Data collection is often a time-consuming activity and sometimes instantaneously required. Moving to 10 automation could bring multiple benefits, but sometimes it may not always be convenient. In this paper four 11 different situations are analyzed, and for each of them a re-engineered solution enabled by information 12 integration for automating the data collection, if applicable, is proposed. More into detail, the data collection 13 is performed so as to apply a Statistical Process Control for quality management purposes on four different 14 operations carried out on a filler machine produced by an Italian company. It consists in determining two 15 process capability indexes whose values, for completeness, are then compared with their relative Six Sigma 16 level. One of the peculiarity of these case studies, is that before collecting the measurements the systems 17 and instruments were validated through the ANOVA Gage Reproducibility & Repeatability method. This is 18 somehow an innovative procedure, since quite often the preliminary validation step is neglected, thus risking 19 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].

27 The basic definition of quality refers to one or more desirable characteristics that a product, a service or a 28 process should possess [2] in order to satisfy implicit and explicit customer's requirements. Indeed, the 29 fulcrum of each business is customer satisfaction: when a consumer receives quality products, in return 30 his/her loyalty increases, the company's position on the market is maintained or even improved, liability risks 31 are reduced, the brand gets good reputation and, consequently, benefits arise. It follows that, within the 32 industrial context, an appropriate quality control is already essential at the process stage, for ensuring 33 compliances of the final item. A recent study also demonstrates that total quality management (TQM) is an 34 essential driver towards process innovations [3].

35 Among the main tools adopted in the manufacturing context having this purpose, so in other words-namely 36 aiming at verifying an adequate quality level of processes, it is worth mentioning the Statistical Process 37 Control (SPC), which allows to monitor and control quality by tracking production metrics which usually have 38 to observe determined targets, or the famous Six Sigma method, which uses five key steps (Define, Measure, 39 Analyze, Improve and Control - DMAIC or in case of new processes or products Define, Measure, Analyze, 40 Design and Verify – DMADV) to ensure that products meet customers' requirements and have zero defects. 41 Indeed, the term Six Sigma refers to a statistically derived performance target of operating with only 3.4 42 defects per million opportunities (DPMO) [4], which represents a 99.99966% process yield meaning that 43 99.99966% of output products do not have any defects, and consequently requires significant efforts to be 44 achieved [5]. The reference to these two examples is no coincidence. Indeed, in this paper four different cases 45 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 machinery¹₂, and for each <u>case-of them</u>, an SPC was implemented for the relating operations performed on <u>athe</u> 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.

53 In addition to that, this manuscript addresses two main key questions, which are somehow related each 54 other: the reliability of the measurement system, which is essential for a proper data collection, and the data 55 collection itself. As far as the first issue, in this paper for all the four cases the systems of measurement and 56 instruments were preliminarily evaluated and validated through the Anova Gage R&R method (AGRR in the 57 following, where R&R stands for "repeatability" and "reproducibility", implied of the measurement) by using 58 Minitab[™] software; indeed, quite often this aspect is ignored in studies which deal with SPC, as it will also 59 emerge from the literature analysis section, but at the same time it is essential for the quality of collected 60 data, and consequently for the reliability of the whole analyses and outcomes. SpecificallyInto detail, for 61 repeatability it is meant the variation caused by the instrumentation or the variation which is observed when 62 the same operator measures the same part many times with the same instrument; reproducibility, instead, 63 corresponds to the variation caused by the measurement system or the variation observed when different 64 operators measure the same part with the same instrumentation [6]. Allowing to include both these aspects, 65 according to the opinion of the authors the AGRR is considered one of the best and complete tools having 66 this purpose, and this is the reason why the choice has fallen on this specific method; more details on the 67 procedure are provided in the Material and Methods section.

68 For the topic of data collection, instead, the discussion is wider: indeed, in step with the latest trends brought 69 from the recent Industry4.0 paradigm and the big data era, there is a shift that leads to an automation of 70 data collection, that allows to pass from an SPC to an Automated Process Control (APC) [7], which falls within 71 the macro topic of Advanced Process Control, namely techniques and technologies implemented to improve 72 production capacity, monitor process parameters and operate with greater flexibility and safety [[8], [9]], 73 enabled in most cases by information integration. Clearly, benefits would arise; indeed, this is a critical point 74 since quite often the data collection is a time-consuming activity, and in addition to that frequently the need 75 is for real-time and above all precise and accurate measurements [10]. In addition, [11] recognized among 76 the main benefits achieved by companies having advanced automated data collection methods, the 77 increased availability of high quality production data and the reduced lead time of input data management; 78 literature also stresses the fact that quality needs to be at the forefront of transformation under digitalization 79 [12], given its importance. In practical terms, in this paper this is translated in providing a practical solution 80 for those operations among the four under investigation in which automating the data collection could be 81 implementable and suitable, and shows how the industrial information integration may be appropriate in 82 these cases, serving as guide for practitioners who have to deal with similar cases. For completeness, an 83 example of a situation in which the automation is not recommended is also included. 84

It follows that the novelty <u>and the contribution</u> of the present manuscript <u>areis</u> twofold: on one side it presents a real and practical case study of implementation of the theoretical process control methodology, w<u>hichith</u> 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 92 industrial information integration; accordingly, it also enriches scientific contributions in this sense by 93 providing practical evidences.

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

97 The remainder of the paper is as follows: section 2 presents a brief overview on the literature concerning the 98 main topics of this study, followed by section 3 which illustrates the material and methods involved, including 99 the AGRR and the two process capability indexes; section 4 deals with the presentation of the four case 100 studies including the measuring system validation and the process capability determination, as well as their 101 proposed re-engineering of data collection, if suggested. Section 5, finally, presents conclusions and future 102 research directions on the basis of the obtained results.

104 2. Literature Overview

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106 Different contributions are required and merged together to pursue the aim of the present work: first of all, 107 the main topic is that of quality management, since all the efforts are made for enhancing the quality level 108 for the_-four-processes in question and, consequently, for the whole assembly line; second, for sure the 109 strategy adopted for monitoring these operations, namely the Statistical Process Control specifically by 110 determining two different metrics, i.e. process capability indexes; before proceeding with measurements for 111 identifying the values of these two indexes, the instruments and in general the whole systems of 112 measurement were validated through the AGRR method; the obtained values of the capability indexes were 113 then compared with their relative Six Sigma level and finally, a new procedure for automating the data 114 collection is proposed for some of the cases.

115 Literature related to the quality management is clearly very copious, as the topic is extremely debated since 116 the early decades of the 20st century, and certainly varied. In line with the present study, the authors care 117 about mentioning more recent general developments and results, such as [15], who carried out an interesting 118 bibliometric analysis on data mining methods used for quality management in the manufacturing field: [16]. 119 who analyzed the main barriers towards the implementation of TQM in the context of supply chains of 120 manufacturing organizations, or [17], who instead identified the most influencing success factors of TQM 121 applications. As far as quality costs are concerned, interesting issues and future research directions are 122 provided by [18]. Two final and very recent relevant studies the authors highlight, carried out by [19] and 123 [20], deal with the indirect relation between internal quality management of firms and social, environmental 124 and economic sustainability performance dimensions (the well-known triple bottom line) and with the cyber-125 physical attack vulnerabilities in manufacturing quality control tools. Specifically within the food 126 manufacturing field, which is the one where the company subject of the case studies operates, [21] made a 127 comparative study between small, medium and large companies in an Asiatic country in order to assess the 128 most common guality management practices of quality management; from the multi-sector analysis carried 129 out by [22] it emerged that for the food and beverage manufacturing sector the adoption of integrated total 130 productive maintenance (TPM) and TQM approaches brings benefit to the business performances. For an 131 exhaustive overview on policies, procedures and practices applied in the food manufacturing sector, see [23]. 132 Finally, note that most of the studies dealing with quality management both from a theoretical and a practical 133 point of view are within the pharmaceutical field; indeed, together with that of food, this context presents 134 stringent constraints and requirements for guaranteeing the quality of final products, designed for human 135 consumption.

136 As already said, in this paper the quality is monitored through two process capability indexes, quite common 137 metrics involved in the manufacturing context; examples of their application are by [24], who proposed and 138 applied a procedure for process capability assessment within manufacturing, by [25] who computed these 139 indexes for a 3D printing process, or by [26] who instead carried out a process capability analysis during a 140 wire electrical discharge machining. Interesting applications in the food industry instead were carried out by 141 [27] or [28]. Less common, instead, is the fact that before collecting data for defining the indexes the 142 instruments involved were validated, which is pretty unusual, yet it represents a peculiarity of the procedure 143 followed in the present study. Indeed, exception made for the study by [24] who have clearly stated that 144 they performed an AGRR and stressed the importance of this operation, in none of the other studies relating 145 to SPC this step was included. This further contributes to the value of the case studies under investigation, 146 as well as to emphasize the contribution of these applications. As far as other examples of AGRR 147 implementation within the manufacturing field, however, it is worth mentioning the validation of the 148 measurement system used in a motorcycle company for the measurement of the tappet clearance, i.e. the 149 gap between the rocker arm and the shim tappet of a motorcycle [29], or the assessment of some lathe 150 machines in order to evaluate their reliability performance and state whether the machine affects the 151 diameter of machined pieces or not [30]. However, to be honest, practical applications aimed at carrying out 152 and recording real measurements are quite lacking; indeed, most of the screened papers in which the AGRR 153 is mentioned deals with a theoretical point of view or assessments of its reliability; in support of this, the 154 authors propose interesting works by [31], who defined a systematic procedure to determine the optimal 155 experimental design for applying the AGRR or by [32] who examined problems which may derive from the 156 application of the ANOVA to an R&R study. Two other practical case studies for the AGRR implementation 157 are by [33] or [34]. No references to the context under investigation i.e., food machinery production, were 158 found.

159 The values obtained for the two process capability indexes are compared with those resulting from the Six 160 Sigma theory. For a complete overview and comprehension of the state-of-art on this theory. [35] and [36] 161 are recalled; specifically, in this last paper, its adoption in European organizations is treated. For further 162 practical applications within the manufacturing field, interesting outcomes are provided by [37] who adopted 163 it for improving the operational efficiency of handicraft manufacturing, by [38] who proposed and 164 successfully implemented a DMAIC approach for reducing soldering defects in an assembly line producing 165 mobile phones, or by [39] within the automotive industry, who used the Six Sigma methodology for 166 decreasing nonconformity. In the food industry field instead, [40] implemented this tool for improving cash 167 flow deficit in a company producing food cans, while [41] in a plain yogurt production; finally, interesting 168 step-by-step guidelines and critical elements of the implementation of a Six Sigma process control technique 169 in a food production line were presented by [42]. However, there is no evidence of the joint use of capability 170 indexes compared with Six Sigma values in the context under investigation.

171 Concerning the final aspect, i.e., automating the data collection, [43] in their study dealing with possibilities 172 for integrating quality management tools and methods with digital technologies clearly stated that quality 173 management needs to be automated, thus stressing the relevance of the topic. In this perspective [12], by 174 addressing digitalization priorities of quality practices for small and medium enterprises with the support of 175 Industry4.0 technologies, have included the data handling automation among the actions to be implemented 176 for pursuing this digitalization; at the same time they highlighted, however, that this topic still requires 177 significant human intervention, and accordingly it deserves attention and further studies. As far as practical 178 applications of automated data collection for quality management purposes, an first interesting study (both 179 theoretical and applied) has been by [44], who implemented the Radio Frequency Identification (RFID) 180 technology to enhance automated data collection and information management in the construction field. 181 Some years later, [45] as well have proposed RFID as a tool for the automation of data collection, always in

182 the construction industry; same application and same context for [46]. Conversely, in the manufacturing 183 context, applications of automation of data collection for quality management are quite lacking; most of the 184 examples found in literature are not intended for quality management (although have potential to be also 185 involved for these purposes), and for instance it is worth mentioning studies by [47] who designed and 186 implemented an intelligent automated production-line control system, with the possibility to include 187 Internet-of-Things (IoT) sensors for data collection; [48] have contemplated again the use of RFID in the 188 manufacturing context for automating the collection of data; [49] as well implemented sensors for real time 189 collection for creating a digital shadow during the production of thermoplastic composite layers in 190 unbounded flexible pipes. However, most of the contributions which deals with this issue do not evaluate 191 the practical outcomes; rather, they have only presented designs or frameworks. Examples of these studies 192 are [50] who proposed a framework for advanced data collection for manufacturing systems, emphasizing 193 real applications as research topics, or [51] who presented a platform ("Argonne-developed Manufacturing 194 Data and Machine Learning") able to analyze and use IoT devices in manufacturing experiments, including 195 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].

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3. Material and Methods

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206 This section provides the reader with a short description of the tools involved, as well as the methodology 207 followed for the different case studies. First of all, for each case the AS-IS scenario is studied, including the 208 current system of measurement and the procedure for collecting data. This last is then subject to validation 209 through the AGRR method; in case this step returns unsatisfactory results, corrective actions are undertaken 210 for letting the system be reliable. Once the measurement system passes the AGRR assessment, the two SPC 211 indexes can be determined with the collected data (with subsequent comparison with the Six Sigma levels). 212 As for the AGRR stage, in case the process under investigation is not under control, some corrective actions 213 will be undertaken. Finally, as already stressed, for those processes for which it is suitable to develop an 214 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:

 $224 \qquad C_p = \frac{USL - LSL}{6\sigma}$

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(1)

226 In eq.1, USL is the Upper Specification Limit of the quality characteristic, LSL the Lower, and σ is the process 227 standard deviation. In case its value is greater than 1.00, the process is capable. Conversely, C_{pk} takes into 228 account the process location, namely whether a process deviates from half of its range of specifications. It is 229 computed as follows:

231
$$C_{pk} = \min\left(\frac{USL-\mu}{3\sigma}; \frac{\mu-LSL}{3\sigma}\right)$$

233 In eq.2, besides the already defined parameters USL and LSL, μ is the mean of the process output. In this case 234 as well, whenever its value is greater than 1.00, then the process is considered as capable.

235 These indexes are both common when dealing with this kind of measures, as recalled in the literature section.

236 As already stated, the values obtained are then compared with those deriving from the Six Sigma theory; 237 more in detail, Table 1 reports the correlations between achieved sigma level, goods conformity 238

percentage, Cpk index, PPM (part per million) of defective goods, and time wasted for bad production in one

239 month [53].

240 Table 1 - Correlations between sigma level, Cpk 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

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ANOVA GAGE R&R 242 3.2.

244 Before collecting data and starting the measurement, a crucial issue is clearly to possess the appropriate 245 instruments, as well as correct methods and properly trained operators. For validating these instruments, 246 several tools can be involved; one of the most widespread, even if as it turned out this aspect is normally 247 neglected in studies of this kind, is the AGRR, which allows to assess the precision of a measurement system. 248 The peculiarity of this method is that of considering the variation due to the instrument as composed by two 249 different variances, respectively inherent to the repeatability and the reproducibility. The step for applying 250 the AGRR are the following: (1) determine an experimental design (e.g. the number of operators, number of 251 parts, number of replicates) according to rule of thumb, budget and availability; (2) measure the parts for 252 each treatment; (3) conduct the ANOVA using the observations; (4) estimate the variance components for 253 each factor and interaction; (5) calculate various performance metrics using the estimates; (6) evaluate the 254 adequacy precision for the measurement system according to criteria; (7) perform subsequent actions such 255 as improvements of the system according to the results [31]. According to the Automotive Industry Action 256 Group (AIAG) [54], in case Gage R&R < 10% the measurement system is acceptable; if 10% < Gage R&R < 30% 257 the system is conditionally acceptable, while it is not acceptable for remaining values. In this study, Minitab™ 258 software was used for carrying out the ANOVA analysis. Compared to the two other common methods of 259 Gage R&R analysis, namely the A&R (Average and Range method) and the EMP (Evaluating the Measurement 260 Process), the AGRR determines what sources of variation have a significant impact on the results and adds 261 another source of variation to the mix and it is able to identify the operator-part interactions [55].

(2)

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262 4. Case Studies

264 4.1. Case 1: Slewing ring-pinion backlash check

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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 <u>Figure 1</u>. 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 2Figure 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

290 must be rotated by 360 degrees so that the backlash between the same tooth of the pinion is checked again 291 and measured with respect to a different tooth of the slewing ring.

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For our purposes, the procedure is repeated three times by two operators, with five samples of measures 293 each time, resulting in thirty values overall to be analyzed.

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295 4.1.2. Measuring system validation

297 Minitab[™] software, used to carry out the ANOVA analysis of the measurement values and compute the AGRR, 298 returned the outcomes reported in Table 2Table 2. Note that, for completeness, in all the tables in which 299 AGRR results are computed, the full outcome returned by Minitab™ is reported, including all the variance

300 component contributions; however, the AGRR total result useful for our purposes is in the first row and last 301 column, in bold (%Study Var).

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

	%Contribution			Study Var	%Study Var
Source	VarComp	(of VarComp)	StdDev (SD)	(6 × SD)	(%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

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304 It can be noticed that the Total AGRR value for this first case is 71.77%, so the variance of the results obtained 805 according to the measurement procedure described is mainly caused by the low repeatability and 306 reproducibility of the measurement process, which actually generate high variance; indeed, the process is 307 fully manual. This is a very poor result, as according to the AIAG standard acceptable values of %Study Var 308 must be less than 30% for ensuring reliability of the measuring system. As a consequence, the calculation of 309 the process capability indexes cannot be performed until the measuring system is not improved.

810 To this end, by observing the two operators while performing the measurement, some differences in actions' 311 execution were noticed; thus, as a first step, the measuring method has been standardized as much as 312 possible, performing more training on the operators, explaining them how the measurement should be 313 performed without relying on their spontaneity. A Standard Operation Procedure (SOP) consisting of clear 814 and simple images guiding the employees was designed to this end, as reported in Figure 3-Figure 3, and 815 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	2	Internal pinion placement and installation

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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

320 a data analysis, the following AGRR results were obtained (<u>Table 3</u><u>Table 3</u>):

321 Table 3 - Results from the AGRR analysis for case study 1 after the SOP and training of operators.

		%Contribution			%Study Var
Source	VarComp	(of VarComp)	StdDev (SD)	(6 × SD)	(%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

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323 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 amay 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
- \$35 using additive-manufacturing techniques; its model and usage are shown in 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

340 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 <u>Table 4Table 4</u>.

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

	%Contribution			Study Var	%Study Var
Source	VarComp	(of VarComp)	StdDev (SD)	(6 × SD)	(%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

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345 The %Study Var has dropped to 15.56%, significantly below the threshold of 30% typical of a reliable 346 measuring process. The introduction of the jig has significantly reduced the probability of error caused by the 347 operators. The measuring system finally obtained can be considered reliable and therefore repeatable and 348 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 <u>Figure</u> 53 <u>5Figure 5</u> and used to compute the capability indexes of the whole process by means of an Excel spreadsheet. 354 ha formattato: Tipo di carattere: (Predefinito) Calibri, 11 pt



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 5Figure 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.

4.1.4. TO-BE re-engineering

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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.

374 4.2. Case 2: Flatness check for the clamp support group

376 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 <u>Figure 6Figure 6</u>) and its hub (brown color of <u>Figure 6Figure 6</u>), 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.

383 Different clamps are mounted on the disc in order to handle the bottles among different sections of the 384 machine; normally, a filler machine is equipped with 5 to 7 discs having different diameters, which rotate 385 and interact while handling the bottles. The rotary handling allows to speed up the machine and to reduce 386 its size. There are five different sizes of the bottle transfer groups: the smallest one has a diameter of 360 387 mm, while the bigger reaches 1880 mm. The correct flatness of the discs is very important to correctly pick 388 and release the bottles; in case of misalignment of the clamps the bottles' loss may occur during the transfer. 389 The check is manually carried out by positioning a dial caliber underneath the disc and clamping it on a proper 890 fixed reference point as shown in Figure 7, Figure 7; then the hub and disc are rotated and the operator marks 391 the highest and lowest points on the disc by means of an electric pen.

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393 394

Figure 7 - Dial caliber used for measurement

In the control chart the allowable allowed tolerance limits are reported, which vary according to the diameter

396 of the disc; however, they normally settle around a few tenths of millimeter.

397 If the recorded measurement value fits the tolerance range, the disc continues its assembly process and 398 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 boughtfrom an external supplier).

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402 4.2.2. Measuring system validation

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

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403

409 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

410

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

		%Contribution			%Study Var
Source	VarComp	(of VarComp)	StdDev (SD)	(6 × SD)	(%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

⁴¹²

As it can be deduced from the first line of <u>Table 6Table 5</u>, Minitab[™] returned a value of Total Gage R&R equal

414 to 5.75%, meaning that, conversely to the first case study, in this second case the measurement system is

415 completely reliable. According to that, the two capability indexes can be immediately determined.

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4.2.3. Process capability calculation

419 By elaborating the data collected for the AGRR, performance indexes have been computed, obtaining a

420 $C_p=3.39$ and $C_{pk}=2.29$ (Errore. L'origine riferimento non è stata trovata. Figure 8).

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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 <u>Figure 8Figure 8</u>, where the
measured value perfectly fits the range identified by the USL and LSL.

4.2.4. TO-BE reengineering

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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, tThe 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

441 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 placeoccurs 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. ha formattato: Tipo di carattere: 11 pt



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461 462 Figure 9 - The rotating disc of the carousel.

4.3.2. Measuring system validation

455 Two operators and two machines were involved for recording the first dataset of this process; for each 456 position, three different measures were recorded. As said just above, the measurement takes place in four 457 different positions, but the first is used for setting the instrument bias, and thus, accordingly, it will not be 458 considered. It follows that the number of samples analyzed by Minitab[™] is eighteen for each machine. <u>Table</u> 459 <u>7Table 7</u> reports the first data collection, followed by <u>Table 8</u> in which the results from the AGRR are 460 presented.

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

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

		%Contribution			%Study Var
Source	VarComp	(of VarComp)	StdDev (SD)	(6 × SD)	(%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

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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 thise process
under investigation.

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470 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

473 depicted in <u>Figure 10Figure 10</u>), 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

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According to the previous results, it is paramount important to set up a proper data collection system capable 488 of monitoring the trend of process capability indexes. In fact, due to the specific features of the process, the 489 feasible operations which can positively impact the indexes and lower the variance are very labor-intense; 490 thus, before changing production processes, a detailed monitoring action has to be implemented aimed at 491 assessing the need for changes. More into detail, two possible interventions can be done: (1) reduction of 492 the manufacturing tolerances of the disc and the structure, with particular respect to the drilling phase_i (2)</sub> 493 rework of the rotating disc of the carousel and the fixed structures, in order to improve their relative 494 alignment. The first solution requires improvements in the manufacturing process, and the specific cost (per 495 part) is not very highmodest, but it affects all the produced parts; the second option, instead, encompasses 496 a higher specific cost (assembly, check, disassembly, rework, reassembly, recheck) but involves only defective

497 ones. <u>Underl+</u> a lean perspective of continuous improvement, the first option is the most suitable, although
 498 an economic evaluation must be carried out.

499 According to this statement, a precise and detailed data collection campaign is needed to proceed with the 500 evaluation, and to this extent an automation system is considered. As for the previous use case, the dial 501 caliber can be replaced by a confocal displacement sensor connected to a PLC capable of managing the 502 rotation of the carousel and data acquisition. The cost of this hardware upgrade and software integration, as 503 already said, is about 25,000 euros, while no significant savings in manpower can be considered. 504 Unfortunately, the operations described in the last couple of use cases cannot be jointly executed in the 505 same station as they involve different equipment and different assembly stages, and two different solutions 506 should be purchased.

507 Since the control check is a required step in the assembly process, eventually the company may decide to 508 firstly implement the automated data collection system, and then to adapt it to work according to the 509 previous case study. For the first piloting campaign, software integration with PLC was reduced to the

510 minimum, since data was exported in Excel and hence analyzed.

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

As it can be noticed in <u>Figure 11Figure 11</u>, 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.

521 4.4. Case 4: Handling clamps check

4.4.1. AS-IS scenario analysis

525 The fourth and last analyzed process <u>, instead</u>, refers the clamps check, and it is performed on all the handling 526 clamps connected to the rotation support (carousel): for each clamp the precise height "h" with respect to a 527 fixed reference point is measured as shown in <u>Figure 12Figure 12</u>. The carousel consists of several clamps 528 used for sorting bottles and transferring them from one point to another of the machine. In one machine 529 there are several carousels rotating and interacting with each other; given these interactions, it is mandatory 530 that the clamps are positioned correctly so that the bottle transfer can be carried out successfully. ha formattato: Tipo di carattere: 11 pt



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Figure 12 - Clamp height measurement.

534 All the measures are grouped together; the difference between the highest and lowest clamp is then 535 computed and checked against the limit value of 0.2 mm defined in the control sheet. This value allows for 536 precise and reliable interaction between the clamp that yields and the one that receives the bottle during the 537 transfer. In order to calculate determine the difference between the highest and lowest clamp, the height of 538 each individual clamp is measured with respect to a reference point; this operation is performed by means 539 of a laser scanner using triangulation on the clamp's surface interfaced with a computer through a PLC. Since 540 the reference point is fixed, the values found can be compared and thus the difference between the clamps 541 can be easily computed.

542 During the measurement with the laser, the star is rotated 360 degrees for three times, so that the 543 measurement of each clamp is averaged over three different values; the standard deviation for each clamp 544 is then_calculated, and the highest and lowest clamp with the respective value is displayed. Figure 13Figure 545 13 shows the collected measurements on a graph.



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549 In case the difference between the highest and lowest clamps is more greater than 0.2 mm, the clamps must 550 be manually adjusted by checking the report composed of diagrams and raw data. The operator, relying on 551 his own experience and skills, identifies the clamps needing intervention for height adjustment. After the 552 clamps have been are modified, the previous step of measure and height calculation shall beis repeated in 553 order to check whether the values after the intervention are within the project specifications reported in the 554 control sheet.

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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 <u>Table 9Table 9</u>, reports a %StudyVar of 25% and thus
allows a positive evaluation of the measurement process.

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

		Study Var	%Study Var		
Source	VarComp	(of VarComp)	StdDev (SD)	(6 × SD)	(%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

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564 4.4.3. Process capability calculation

After <u>having</u> gather<u>eding</u> all <u>the</u> required data, performance indexes have been computed, finding C_p =1.45 and C_{pk} =0.30 (Figure 14Figure 14).

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571 The analysis of the indexes shows that the process is <u>definitely</u> 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

574 this process. In order to improve C_{pk} , several simulations have been carried out using an Excel spreadsheet;

575 results show that having a maximum difference in clamps height in a range between 0.09 mm and 0.11 mm

576 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

577 reported in Figure 15Figure 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 16Figure 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

586 in a range from 0.09 mm to 0.12 mm as shown in Figure 17Figure 17.



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591 However, unfortunately, the time needed to perform the height adjustment raised from 45 minutes (AS-IS 592 scenario) to 1 hour and 15 minutes for each carousel (re-engineered process). Thus, although the capability 593 indexes have increased, the machine cycle time has increased too, and further optimization of the process is 594 clearly <u>needed_recommended</u>; these motivations form the basis for <u>the</u>develop<u>ment ofing</u> an improvement 595 software, described in the section below.

597 4.4.4. TO-BE re-engineering

The process optimization was carried out to find a quicker solution <u>forter</u> speeding up the clamp control involving, as far as possible, industrial automation. The increased time to adjust clamps' height <u>gives-returns</u> 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 <u>exact</u> 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 <u>Figure 18Figure 18</u>). 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 the fully the view of the terms of the second se

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608 to facilitate the interpretation of results.



611 <u>The software</u>^{I‡} works according to the following steps:





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

- enter the required specifications;
- identify only the clamps to be modified;
- adjust these clamps accordingly.

619 The first release of the software, aimed at validating the algorithm and its functionalities, has been 620 implemented in an Excel worksheet; the final version, instead, will be implemented in the same PLC 621 interfaced with the laser scanner in order to build a solid automation system with a common human-machine 622 interface (HMI) for the whole process, including data acquisition and wizard for height adjustments. This 623 represents the second and final step bringing the process to the best achievable automation degree. Due to 624 the process specific activities (manual adjustment of the clamps' height by insertion/removal of the washers), 625 it cannot be fully automated. More into detail, the PLC only manages data acquisition process (rotation of 626 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 627 628 that it was brilliantly achieved.

629 This allows a great saving of time in the execution of the control, with respect to the Sigma Level of 6 imposed 630 by reduced tolerances. The clamps' adjustment is now performed in approximately 20 minutes in the TO-BE 631 scenario, compared to the AS-IS one, both before and after the difference reduction; indeed, the AS-IS 632 procedure counted about 45 minutes, while the time required after the reduction of maximum allowable 633 difference in clamps' height, counted about 75 minutes. The software has been tested on various carousels 634 of different machines, achieving excellent results in every scenario. Thanks to With the implementation of the 635 software, it has beenwas possible to save a significant time both for the capability project and for the 636 optimization of the machine cycle; in fact, the process has been speeded up and the human factor has been 637 eliminatedremoved. The implementation cost of the software in the PLC is estimated in 5,000 euros.

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5. Conclusions and Future Developments

641 The study presented in this manuscript deals with an SPC assessed through two process capability indexes 642 which are determined for four operations routinely performed on a filler machine produced by an Italian 643 company. In all the four cases, before proceeding with measures and data collection for computing the 644 indexes, the measurement systems were validated by means of a tool which assesses whether the system is 645 reliable or not, namely the AGRR. The particular choice is a peculiarity of the procedure followed in this 646 manuscript, since quite often the validation step is not considered in works dealing with SPCs, thus 647 compromising the full reliability of the analyses. The values of the two indexes for each operation were then 648 compared with the corresponding values returned from the Six Sigma theory, according to the targeted levels 649 set by the management of the company involved in the study. In addition, given the relevance of the topic of 650 automating the data collection, which in turn derives from the pressure towards the digitalization of quality 651 management and an information integration, a solution was suggested ad hoc for three of the four operations

652 for which it turned out to be relevant.

53 <u>Table 10 Table 10</u> below summarizes the obtained results.

654 Table 10 - Results summary.

Case study	Target <u>ed</u>	AS-IS Sigma	TO-BE	TO-BE Cost	TO-BE
	Sigma Level	Level	Sigma		Labor
			Level		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%

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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.

660 Looking at the process capability assessment, instead, in the first case the process was centered since the 661 beginning, and thus no further corrections were required. Same reasoning for the second case, which 662 presented values of indexes which correspond to a Six Sigma level of 6, even higher than the target set for 663 this operation. The third and fourth cases, instead, were the only cases deserving more attention as measured

664 *C_{pk}* presented a very low value, which results in a process not under statistical control.
 665 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

668 <u>10</u>Table 10; thus, further analyses are required to determine their trend.

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

671 possible to both enhance the process control and achieve important savings in terms of labor as summarized

672 in <u>Table 11</u>Table 11.

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

Process	Check time [min]	Time difference [%]
Current (AS-IS)	45	-

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Enhanced (manually managed)	75	+66.7 (than the original state)
Enhanced (software driven)	20	-55.5 (than the original state)
Enhanced (software driven)	20	-73.3 (then the previous state)

The most interesting part, insteadhowever, 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).

682 Overall, the case studies allowed to see different situations, and they are somehow complementary: indeed, 683 in the first case, the AGRR value was not satisfying at first and correct actions were undertaken in order to 684 let the measurement system be reliable and acceptable, while the capability indexes instead were perfectly 685 in line with the target set; in the third and fourth cases, on the contrary, the AGRR was at first acceptable 686 (and this is actually due to the fact that the measurements were performed by means of digital 687 instrumentation and not manually carried out), but the values of the capability indexes were not aligned with 688 the targets, and accordingly corrective actions were successfully performed to improve them. In the third 689 case the indexes worsened while in the fourth they improved. It follows the perfect completeness of the 690 various scenarios presented. Moreover, with respect to the data collection automation and the information 691 integration issues, in order to respond to the research question posed in the title, the lesson learned from 692 the case studies remarks that one-fits-all approach is not feasible. Indeed, case study 1 demonstrates that, 693 given the complexity of the process under investigation, the introduction of an automation system would not 694 be convenient due to huge investment costs, and poor labor savings. Same considerations are applicable to 695 case study 2 as well, even if the automation solution is more economically feasible as already discussed and 696 could be useful for allowing a continuous and real-time data acquisition. Conversely, for the last two case 697 studies, the introduction of automation is highly recommended, in order to improve the processes. 698 Specifically, for case study 3, this represents the first step of an in fieri improvement, while for case study 4 699 it enables the real and full process information integration. These different practical implications are 700 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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