VOLUME 35, NUMBER 3

July-September 2019

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ATMAE
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JTMAE
The Journal of
Technology,
Management, and
Applied Engineering

An Investigation on In-Process SPC Sampling Frequency for a Shaft Bearing Turning Process

Keywords:
Statistical process control (SPC), sampling frequency, average production length (APL)

SUBMITTED FOR *PEER – REFEREED*

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An Investigation on In-Process SPC Sampling Frequency for a Shaft Bearing Turning Process

Abstract

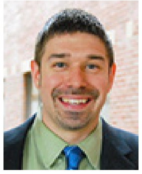
In cellular manufacturing design, the machining processes have the unique ability of allowing for discrete production and flexible scheduling. To ensure the quality of machining products, control charts for Statistical Process Control (SPC) have been implemented in many industries, and in this article we look at the use case for a company to monitor a specific machining process. Sampling is an essential part of data collection for SPC control charts. This study focuses on the investigation of SPC sampling frequencies for a shaft bearing turning process using the technique of Average Production Length (APL). The purpose of the study is to identify the SPC sampling frequency for a turning process. The results show that the 100% inspection has significantly shorter APL than one out of ten (1/10) and one out of twenty (1/20) SPC sampling frequencies, and 1/10 is preferred over 1/20. The results provide insights on the SPC sampling frequencies, which can be a reference for the company to select an economical SPC sampling frequency for a machining manufacturing process.

Introduction

Quality is essential for organizations to succeed in today's competitive globalized market. Manufacturing firms are using different techniques and activities such as sophisticated tools and tooling to assure the quality of the products or services they deliver under the auspices of the Quality Control (QC) and/or Quality Assurance (QA) business functions.. Quality Control is not a new invention or construct, as many sources believed that it started thousands of years ago when manufacturing was instituted by ancient civilizations (Besterfield, 2009; Duncan, 1986; NIST, 2010; Summers, 2010). However, in comparison to QC, Statistical Quality Control (SQC) is a relatively new concept. Statistical Quality Control (SQC), use statistical tools to ensure the quality of product and services, having been first introduced in the 1920s by Walter A. Shewhart in 1931, H.F. Dodge and H.G. Romig published articles about sampling inspection and these three pioneers founded the modern SQC system (Summers, 2010).

Data collection is the essential procedure for gathering information in the SQC activities. In industries, one hundred percent (100%) inspection in SQC is neither practical nor economical (Montgomery, 2005; Sarkadi & Vincze, 1974). A 100% inspection requires more labor and production time during manufacturing process. Especially in products with complex dimensions that require longer inspection time, or products that have to use destructive testing that could be too costly or unrealistic. Statistical Process Control (SPC) is part of SQC, but it focuses on using process control to ensure the quality of products. SPC uses control charts and process performance indexes as tools for quality control. Proper implementation of SPC can dramatically reduce in-process inspection rates by 30% for manufacturers (Guenther, 1977; Litsikas, 1996).

In this study, a Midwestern United States based farming-equipment drivetrain components machining division is experiencing an incorrect SPC sampling frequency issue for a gear and shaft machining process. There are more than one hundred machines in the firm's machining division, including, but not limited to, turning, honing, shaving, shaping and grinding. As per the company's current Quality Assurance manual, the machining division currently applies two types of defined SPC frequencies: (1) 100% inspection, and (2) sampling inspection, in which the inspection is performed on each of three consecutive pieces of products for every four hours. The 100% inspection is initially performed for any new machining project, the second SPC sampling frequency is implemented if Cpk of the process is equal to or greater than 1.33, and 100% inspection is resumed if the process capability index (Cpk) of the process is less than 1.33 (Heizer & Render, 2013). Heizer and Render (2013) discuss this process capability index methodology in more detail. The current SPC sampling plan is inflexible and rigid, and it cannot reflect the complexity and flexibility of the current manufacturing situation that involves different types of machining processes. The current SPC sampling plan was developed when the company started the



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SPC implementation as a daily production quality control tools decade ago. At that time, there was not any statistical literature to support it. Up until now, machine operators still manually perform quality characteristic inspections on manufactured parts among all machining processes instead of automated inspection. Therefore, 100% SPC inspection is uneconomical. However, there is not a clear guideline on a proper SPC sampling method provided by theory or a practical rule of thumb. Therefore, there is a need to evaluate the current SPC sampling plan due to the incapability of the current SPC sampling procedure. A practical and economical SPC inspection frequency needs to be implemented to reduce labor cost while concurrently assuring quality.

As the production departments are only willing to use fixed SPC sampling frequencies, after consulting with the Quality Assurance Group in the company, the researcher selected two other sampling frequency options, One out of ten (1/10) and one out of twenty (1/20). Upon completion and success, the result and findings of this study can be extended to the entire shaft bearing turning process for in entire company.

This study contributes to a gap in the existing literature by determining the sampling frequency for SPC in discrete machining processes. With empirical experimentation, this study provides a SPC sampling plan suggestion for the firm by evaluating the shaft turning process. Our study further provides an SPC sampling plan suggestion for the firm. The knowledge to be established for determining an economic SPC sampling frequency in the shaft turning process can serve as a reference for future related projects.

Literature review and hypothesis development

In SPC, sampling inspection is the method of collecting samples of data from a population, rather than 100 percent of the population. A commonly used SPC sampling inspection method was originally developed by Dodge and Romig (1929) who published a set of inspection tables for the lot-by-lot acceptance of product by sampling for attributes, namely Continuous Sampling Plan (CSP) (Balamurali & Jun, 2006). The purpose of Dodge and Romig's sampling inspection is to decide whether to accept the lot or reject it. Because of sampling, there are always statistical errors (type I and type II) associated with sampling. Furthermore, Dodge and Romig's sampling method has a limitation in that it deals with the batch production whereas machining processes produce individual parts (Summers, 2010). When this method was designed, it had no intention to provide a guideline on sampling frequency during a discrete manufacturing process that consists of individual units (Duncan, 1956).

Dodge (1943) published sampling inspection method for continuous production on a Go-NoGo basis. Continuous production consists of individual units, such as parts in gear manufacturing. Dodge's inspection method also had been known as Continuous Sampling Plan (CSP-1). CSP-1, which is the current sampling plan used by the Midwestern United States manufacturing company for this case, consists of two stages: first, 100% inspection stage, then after i consecutive units are free of nonconforming units, the next stage, inspection will only be performed on a fraction f (such as 1/10) of units, as shown in Figure 1. The parameters, i and f, can be determined according to ASQ's Average Outgoing Quality Level (AOQL).

Cellular manufacturing has been used in manufacturing companies for years, and it involves production of parts families and limited quantity per production run from a single manufacturing cell unit. The limitation of the current sampling method is due to a lack of flexibility, which is a very important criterion for cellular manufacturing of machining processes (Irani, 1999; Singh & Rajamani, 1996).

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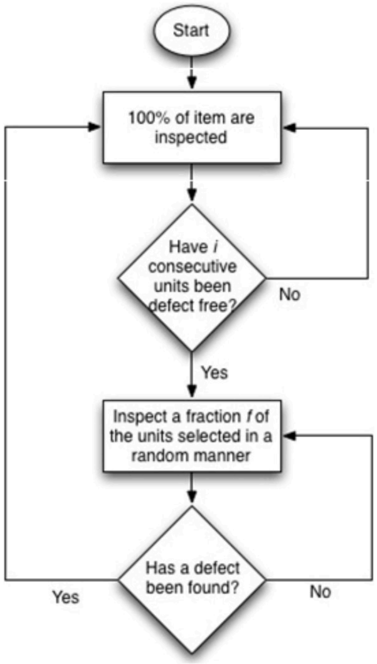
Figure 1. Procedure for CSP-1 Plan



There is a difference in sampling for CSP versus SPC. In CSP, one sample is chosen from a lot of products whereas in SPC a small subgroup of parts are chosen and the same subgroup size of parts will be selected for many subgroups that will be displayed in control charts. The subgroup size is a key element for control chart design. Average Run Length (ARL) provides the average number of points that must be plotted before a point indicates the process is out-of-control (Montgomery, 2005, p. 160), or in other words, the ARL denotes the average number of observations until the SPC alarm signals.

$$\mathrm{ARL} = \frac{1}{p}$$

In the formula of ARL, p is the probability that any point exceeds the control limits.

Keats et al. (1995) suggested three major items researchers should particularly take into consideration when the topic involves control chart design of SPC: (1) SPC sampling frequency, (2) subgroup size of samples and (3) control limits. Different from other researchers focusing on ARL, Keats et al. (1995) promoted the idea of incorporating the three factors above to minimize the amount of production occurring between a shift in the process mean and its detection, which is expressed as the average production length (APL). APL is defined as the average amount of production between the occurrence of a shift and its detection. APL uses sampling frequency as one important variable for evaluating the process performance on targeting, therefore, is a better choice determining the sampling frequency and sample subgroup size in SPC.
Whereas,

1. n = number of units in a sample subgroup.
2. S = the number of subgroups sampled between occurrence of a shift and a signal of the shift.
3. $E(S)$ = the expected number made before a signal occurs. It also equals to Average Run Length (ARL) for a X control scheme.
4. Z = the number of items produced between a shift and the first subgroup sampled after the shift.
5. $E(Z)$ = the expected number of units produced between a process shift and the next sample.
6. L = the production run length or total number of items produced between a shift and a signal.
7. h = the number of items produced between subgroups

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8. r = sample rate, a ratio of sampled units to total units that were produced during that period as shown in Figure 3,

$$r = \frac{n}{n+h}$$

9. p = the probability that a change in the process mean is signaled.
10. Φ = the standard normal cumulative distribution function.
11. k = the control limit width parameter (upper control limit,

$$UCL = \mu_0 + k\frac{\sigma}{\sqrt{n}}$$

and lower control limit,

$$LCL = \mu_0 - k\frac{\sigma}{\sqrt{n}})$$

12. d = the deviation or shift of the process mean from the target value of mean in multiples of the process standard deviation,

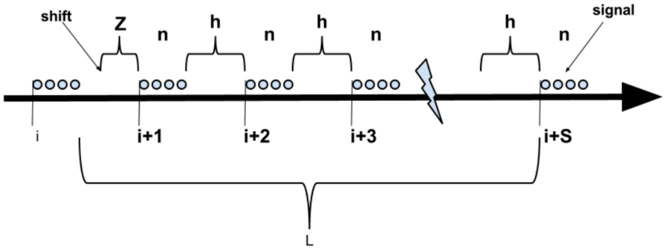
$$d = \frac{|\mu - \mu_0|}{\sigma}$$

From the Figure 2, the relation between L, Z, S, n, h, and i are showed clearly for SPC sampling on a manufacturing process. Then, the equation can be described as:

$$L = Z + hS - h + nS$$

The relation between n and h can be showed as following, n is sample size and h is sampling interval:

Figure 2. Process Shift, Signal, and Sampling over time

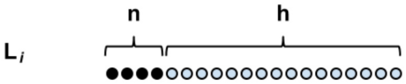


Sampling rate r can be calculated by the following equation:

Hence, APL can be described as:

$$r = \frac{n}{n+h}$$

Figure 3. Sampling Rate with Sample Size



In the equation of APL, $E(Z)$ represents the expected number of units produced between a process shift occurrence and the next sample unit. Reynolds, Amin, Arnold and Nachlas (1988) simulated $E(Z)$ based on a model created by Duncan (1956). Their work showed a very robust way to calculate $E(Z)$ as showed below.

$$E(Z) = \frac{h+n}{2} = \frac{\left[\left(\frac{n}{r}\right) - n + n\right]}{2} = \frac{n}{2r}$$

For an $\bar{X}$ control chart system, $E(S)$ is the same with ARL, and it can be transformed as the standard normal cumulative distribution function below,

$$E(Z) = \frac{h+n}{2} = \frac{\left[\left(\frac{n}{r}\right) - n + n\right]}{2} = \frac{n}{2r}$$

Ultimately, the notation of APL can be substituted by E(Z) and E(S) with d ≥ 0, where APL can also can be introduced as APL_d.

$$E(S) = ARL = \frac{1}{p} = \frac{1}{1 - \Phi\left(k - d\sqrt{n}\right) + \Phi\left(-k - d\sqrt{n}\right)}$$

As APL, the amount of production occurring between a shift in the process mean and its detection, can be considered a production waste, it should be the smaller the better case (Keats et al., 1995). Using APL_d as the measuring metrics, this study will determine the effectiveness of SPC sampling frequencies. Unlike the ARL, which does not address sampling frequency, APL considers sampling frequency as an important characteristic of SPC sampling plan. Therefore, using APL to evaluate the effectiveness of different SPC sampling frequencies would satisfy the need of this study.

It is hypothesized in this study that, for a SPC process, 100% inspection of SPC is unnecessary and other sampling frequencies in SPC study is preferable. The proposed alternate sampling frequency options include sampling frequency (sampling interval) of 1/10 and 1/20 with both SPC sampling scheme at subgroup size of one.

It is also hypothesized there was no significant difference in the shaft bearing turning process in terms of Average Production Level (APL) when 1/10 sampling frequency or 1/20 sampling frequency was implemented.

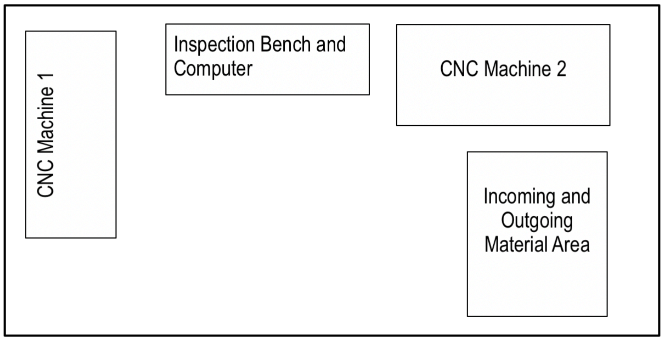
It should be noted that raw forging materials are uniform and meet the material specifications, operators are capable of performing turning operations and corresponding inspections, and all machining equipment and inspection equipment are in workable conditions. It is noteworthy operators are capable of performing the turning operations with repeatability and reproducibility (gauge R&R) (McLain, Bumblauskas, White & Gransburg, 2016).

Method

DEVELOPMENT OF SPC SAMPLING PLAN

This study focuses on only one machining process — the shaft bearing turning process. Figure 4 shows the manufacturing cell setup at the organization's manufacturing plant.

Figure 4. Cellular Manufacturing Setup of the Shaft Bearing Turning Process



Two operators operate the machines. One operator was the 1st shift operator and the other operator was the 3rd shift operator. Table 1 shows the data structure of the shaft bearing turning process.

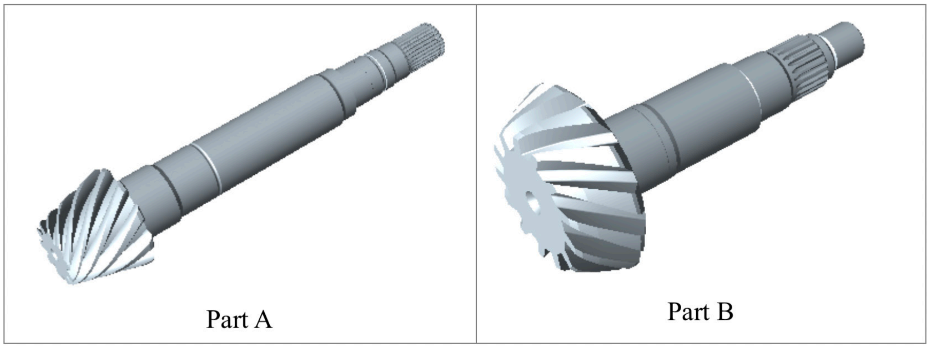
In this study, Part A and Part B have been selected for data collection, and the three-dimensional (3D) draft models are shown in Figure 5.

TABLE 1

Manufacturing Cell Structure of the Shaft Bearing Turning Process Shaft Bearing Turning Process

		Shaft Bearing Turning Process			
		Machine 1		Machine 2	
		Part A	Part B	Part A	Part B
Operator	1st shift	Head Bearing	Head Bearing	Head Bearing	Head Bearing
		Tail Bearing	Tail Bearing	Tail Bearing	Tail Bearing
	3rd shift	Head Bearing	Head Bearing	Head Bearing	Head Bearing
		Tail Bearing	Tail Bearing	Tail Bearing	Tail Bearing

The criterion for parts selection was based on the yearly production of the parts and the critical level. Production quantity for both Part A and Part B are over 1000 units per year per machine per shift. Both parts are differential drive shafts in farming equipment. They both are critical components in the final product to customers. Each part has two similar features that are turned in the same process by the same machine, (1) head bearing and (2) tailing bearing. The diameter of the bearing is the critical feature of this study. Trained operators collected the bearing diameter data using snap gages with wireless transmitters. The transmitters send inspection reading of the outside diameter to a computer with the specialized SPC data collection software from InfinityQS (InfinityQS, n.d.), and the computer receives and stores the information to the company's SPC database.



Part A

Part B

Figure 5. 3D Model of Part A and Part B

The study focused on the comparison between 1/10 sampling frequency and 1/20 sampling frequency for SPC inspection. When sampling was performed, only one subgroup size was used. The reason for choosing the subgroup size as one is that the current process has the process capability index (Cpk) of 1.33 or above.

DATA COLLECTION AND SAMPLE SELECTION

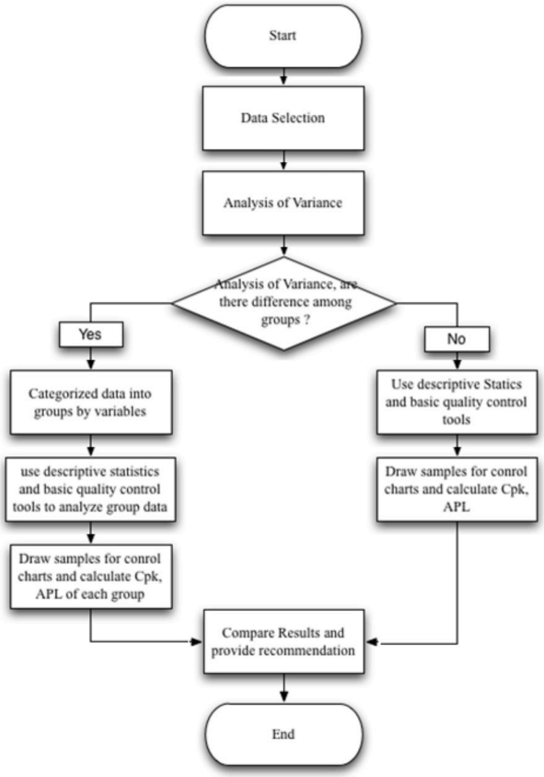
During a two-year period in the study, 100% inspection of head bearing diameter and tail bearing diameter of the shaft bearing turning process was performed. The collected data is based on offsets of target value of the outside diameter specification. Only the actual offset deviated from the target value is recorded. This study considered the data collected during the two-year period as population data. The process of shaft bearing turning involves 27 parts that are from one part family. All 27 parts require similar tooling, machining, operations and fixtures during the manufacturing process. These two parts (A and B) contributed for approximately 35% of entire process production population over the two years period, as part A contributed for 20.70% and part B 13.67% of overall population. Once the parts were selected, the experiment data for the study were extracted from an already-existing population database. To compare 1/10 and 1/20 SPC frequencies with 100% inspection, one every tenth and one every twentieth from the database was drawn to form individual subgroup to be included in the data analysis. Accordingly, APL_d was computed.

DATA ANALYSIS

Population data represented the shaft bearings' outside diameter of two similar parts collected by two operators from two identical Computer Numerical Control (CNC) machines. The collected data of shaft bearing outside diameter was categorized into four independent variables: (1) operator, (2) machine, (3) part and (4) bearing locations.

The independent variables have been used as factors for Analysis of Variance (ANOVA) to study the homogeneity of data. To answer the research question, a comparison of APL_d has been performed to discover which sampling frequency is better for the shaft bearing turning process. Figure 6 shows the procedures of data analysis in a flow chart.

Figure 6. Flow Chart of Procedures for Analysis of Data



Statistical software package STATISTICA 10 and IBM SPSS Statistics 20 have been used for statistical analysis, and also Microsoft Excel has been utilized for raw data filtering and formatting.

Results

ANALYSIS OF VARIANCE (ANOVA)

A four-way ANOVA design was conducted to evaluate the interactions of four independent variables on the dependent variable. Before the ANOVA test, a normal probability plot was performed to examine the normality of collected data. Figure 6 shows the data is normally distributed. Table 2 shows the result of the four-way ANOVA with alpha level $a = 0.05$. The p-value for effect of Operator*Machine*Part*Location is equal to 0.00, which is less than 0.05, showing the significant difference of variance with effect of all variables.

Figure 7. Normal Probability Plot of All Data

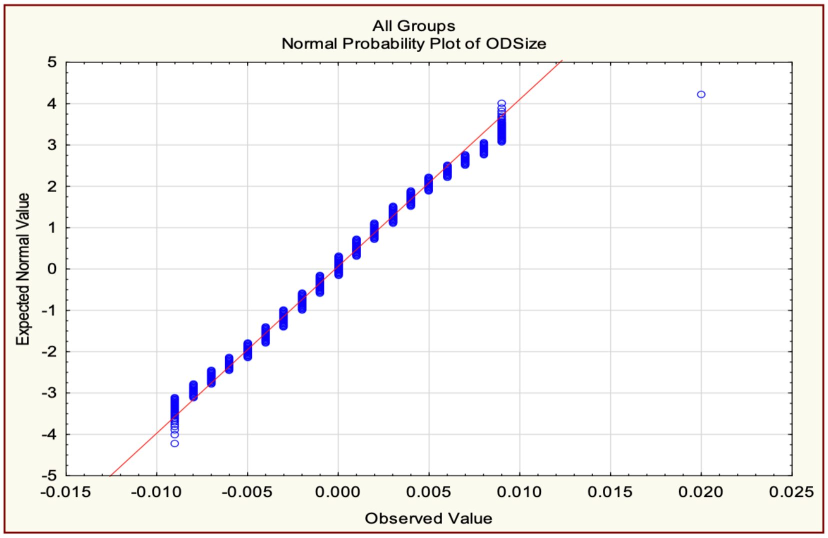


TABLE 2

4-Way ANOVA of Factorial design of Variables: Operator, Machine, Parts and Bearing Location

	SS	Degr. of	MS	F	p
Intercept	0.000146	1	0.000146	25.300	0.000000
(1)Operator	0.000232	1	0.000232	40.185	0.000000
(2)Machine	0.000213	1	0.000213	36.832	0.000000
(3)Part	0.001171	1	0.001171	202.937	0.000000
(4)Location	0.006772	1	0.006772	1173.491	0.000000
Operator*Machine	0.000082	1	0.000082	14.269	0.000159
Operator*Part	0.000012	1	0.000012	2.091	0.148146
Machine*Part	0.000574	1	0.000574	99.408	0.000000
Operator*Location	0.000730	1	0.000730	126.438	0.000000
Machine*Location	0.001388	1	0.001388	240.549	0.000000
Part*Location	0.000063	1	0.000063	10.839	0.000994
Operator*Machine*Part	0.000289	1	0.000289	50.113	0.000000
Operator*Machine*Location	0.000122	1	0.000122	21.124	0.000004
Operator*Part*Location	0.000076	1	0.000076	13.127	0.000291
Machine*Part*Location	0.000025	1	0.000025	4.289	0.038365
1*2*3*4	0.000389	1	0.000389	67.324	0.000000
Error	0.308632	53478	0.000006		

The four-way ANOVA in Table 2 indicated there were differences among each variable and there was a need to study each variable individually. It also indicated the data cannot be treated as one group. Therefore, the data was categorized into 16 groups and another one-way ANOVA was performed to test the variance among all groups. The categorization of these 16 groups is showed in Table 3.

TABLE 3

Data Groups by Combination of Variables: Operator, Machine, parts and Bearing Location Group

Group	Operator	Machine	Part	Bearing Location
1	1st shift	Machine 1	A	Head Bearing
2	1st shift	Machine 1	A	Tail Bearing
3	1st shift	Machine 1	B	Head Bearing
4	1st shift	Machine 1	B	Tail Bearing
5	1st shift	Machine 2	A	Head Bearing
6	1st shift	Machine 2	A	Tail Bearing
7	1st shift	Machine 2	B	Head Bearing
8	1st shift	Machine 2	B	Tail Bearing
9	3rd shift	Machine 1	A	Head Bearing
10	3rd shift	Machine 1	A	Tail Bearing
11	3rd shift	Machine 1	B	Head Bearing
12	3rd shift	Machine 1	B	Tail Bearing
13	3rd shift	Machine 2	A	Head Bearing
14	3rd shift	Machine 2	A	Tail Bearing
15	3rd shift	Machine 2	B	Head Bearing
16	3rd shift	Machine 2	B	Tail Bearing

One-Way ANOVA was performed on all groups first and also on each part groups separately. One-way ANOVA result in Tables 4 clearly indicated that there was evidence of significant difference among the means of all 16 groups. In other words, these 16 groups needed to be studied individually.

TABLE 4

One-Way ANOVA for OD Size Data in Groups

	SS	Degree of	MS	F	p
Intercept	0.000146	1	0.000146	25.3002	0.000000
Group	0.013922	15	0.000928	160.8218	0.000000
Error	0.308632	53478	0.000006		

MULTIPLE COMPARISONS

One-way ANOVA only showed means are different between groups, but it did not show the exact comparison results between each pair of group means. Therefore, multiple comparison tests were used to identify the group mean differences in detail. Table 5 shows the Bonferroni test results from original data values of OD sizes data.

TABLE 5

Bonferroni Test Results for Original OD Sizes Group

Group	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1																
2	X															
3	X	X														
4																
5																
6				X												
7																
8																
9	X	X	X				X									
10				X		X		X								
11	X	X	X				X		X							
12				X		X				X						
13																
14				X		X		X		X		X				
15	X	X	X		X				X		X					
16	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	

Note: X represents the value that is less than 0.05

TABLE 6

Group Means Table

Group	Mean	Group	Mean
1	-0.000375	9	-0.000371
2	-0.000507	10	0.000455
3	-0.000489	11	-0.000313
4	0.000271	12	0.000178
5	-0.000744	13	-0.001116
6	0.000223	14	0.000435
7	-0.000175	15	-0.000492
8	0.000617	16	0.001359

APL (AVERAGE PRODUCTION LENGTH) CALCULATIONS

The next step of data analysis was to calculate Average Production Length (APL_d) for each sampling frequency: 1/10, 1/20 and 100% inspection. As mentioned before, 1/10 and 1/20 are two sampling frequencies that engineers used in the project to test if the frequencies can replace the 100% inspection in SPC activities. APL_d was calculated for all 16 groups. The APL_d results were split into two parts: Part A and Part B. All 16 groups were separated into two sets of eight groups. Part A contains Group 1, 2, 5, 6, 9, 10, 13 and 14; Part B contains Group 3, 4, 7, 8, 11, 12, 15 and 16.

The sample mean (μ0) of each group has been calculated from collected data, and the population mean (μ) is calculated from 100% inspection data of each group in a two-year period. From Table 7 (for part A) and Table 8 (for Part B), APL_d results for SPC sampling frequency of 1/10 and 1/20 are all bigger than APL_d result for 100% inspection. It's clearly identified that 100% inspection for SPC activities could identify mean shift with a few parts production. However, the practical design of SPC sampling is aiming to eliminate 100% inspection for daily production (Litsikas, 1996). And also, the APL_d is designed for mean shift, not for out of statistical control detection, therefore it is better to be used as a reference to select SPC sampling frequencies to meet the production need (Keats et al., 1995). If one only looks at SPC sampling frequencies of 1/10 and 1/20, 1/10 can identify mean shift in a shorter production length than 1/20. From Table 7 and Table 8, a 1/10 SPC frequency turned out to have a production run of about 30 units; a 1/20 SPC frequency turned out to have a production run of about 60 units. Despite the accuracy of 100% inspection, the SPC sampling frequency of 1/10 is the better one to choose for the shaft bearing turning process, since it reduced 90% of the inspection time. However, Table 9 shows when quality is not in good condition, using 100% inspection, 1/10 and 1/20 sampling frequency have generated discrete results, which means frequency sampling may not catch all the nonconforming parts. For example, 10% sampling only caught five nonconforming parts, in reality 47 nonconforming were found if 100% was used. When quality is in good condition, using 100% inspection and frequency sampling would lead to little difference with respect to the proportion of conforming units.

TABLE 7

APL_d values of 100% inspection and sampling frequency 1/10 and 1/20 for part a groups

Sampling Freq	Group	N	μ_0	σ	n	r	k	d	APL_d
100%	1	6739	-0.000375	0.002521	1	1.0	1	0	3.65
100%	2	6739	-0.000507	0.002512	1	1.0	1	0	3.65
100%	5	5998	-0.000744	0.002003	1	1.0	1	0	3.65
100%	6	5998	0.000223	0.002279	1	1.0	1	0	3.65
100%	9	1133	-0.000371	0.002396	1	1.0	1	0	3.65
100%	10	1133	0.000455	0.002682	1	1.0	1	0	3.65
100%	13	2032	-0.001116	0.002011	1	1.0	1	0	3.65
100%	14	2032	0.000435	0.002302	1	1.0	1	0	3.65
1/10	1	674	-0.000312	0.002579	1	0.1	1	0.024585784	27.50
1/10	2	674	-0.000545	0.002366	1	0.1	1	0.015833962	27.51
1/10	5	600	-0.000730	0.002060	1	0.1	1	0.00683515	27.51
1/10	6	600	0.000207	0.002317	1	0.1	1	0.006938984	27.51
1/10	9	114	-0.000640	0.002410	1	0.1	1	0.111894659	27.22
1/10	10	114	0.000421	0.002899	1	0.1	1	0.011856971	27.51
1/10	13	204	-0.001132	0.002091	1	0.1	1	0.007988864	27.51
1/10	14	204	0.000515	0.002346	1	0.1	1	0.033962982	27.49
1/20	1	337	-0.000365	0.002483	1	0.05	1	0.004025338	54.03
1/20	2	337	-0.000469	0.002459	1	0.05	1	0.015536216	54.02
1/20	5	300	-0.000623	0.002109	1	0.05	1	0.057242492	53.87
1/20	6	300	0.000173	0.002210	1	0.05	1	0.022351468	54.01
1/20	9	57	-0.000930	0.002103	1	0.05	1	0.26584273	50.84
1/20	10	57	0.001158	0.002651	1	0.05	1	0.264974332	50.86
1/20	13	102	-0.001098	0.002160	1	0.05	1	0.008154741	54.03
1/20	14	102	0.000559	0.002464	1	0.05	1	0.050239283	53.91

TABLE 8

APL_d of 100% inspection and sampling frequency 1/10 and 1.20 for part b groups

Sampling Freq	Group	N	μ_0	σ	n	r	k	d	APL_d
100%	3	4615	-0.000489	0.002727	1	1.0	1	0	3.65
100%	4	4615	0.000271	0.002597	1	1.0	1	0	3.65
100%	7	3644	-0.000175	0.002094	1	1.0	1	0	3.65
100%	8	3644	0.000617	0.002525	1	1.0	1	0	3.65
100%	11	1312	-0.000313	0.002498	1	1.0	1	0	3.65
100%	12	1312	0.000178	0.002619	1	1.0	1	0	3.65
100%	15	1274	-0.000492	0.002270	1	1.0	1	0	3.65
100%	16	1274	0.001359	0.002200	1	1.0	1	0	3.65
1/10	3	462	-0.000578	0.002674	1	0.1	1	0.03331178	27.49
1/10	4	462	0.000297	0.002579	1	0.1	1	0.010041463	27.51
1/10	7	365	-0.000145	0.002097	1	0.1	1	0.014244544	27.51
1/10	8	365	0.000600	0.002877	1	0.1	1	0.00606578	27.51
1/10	11	132	-0.000045	0.002710	1	0.1	1	0.098839983	27.28
1/10	12	132	0.000280	0.002645	1	0.1	1	0.038829183	27.48
1/10	15	128	-0.000484	0.002368	1	0.1	1	0.003284061	27.51
1/10	16	128	0.001328	0.002314	1	0.1	1	0.013555911	27.51
1/20	3	231	-0.000502	0.002747	1	0.05	1	0.004850064	54.03
1/20	4	231	0.000238	0.002579	1	0.05	1	0.012618345	54.02
1/20	7	183	-0.000180	0.002200	1	0.05	1	0.002384108	54.03
1/20	8	183	0.000459	0.002649	1	0.05	1	0.059802795	53.86
1/20	11	66	-0.000152	0.002702	1	0.05	1	0.059866222	53.86
1/20	12	66	0.000470	0.002413	1	0.05	1	0.121059326	53.33
1/20	15	64	-0.000375	0.002360	1	0.05	1	0.049631983	53.91
1/20	16	64	0.000969	0.002377	1	0.05	1	0.164391656	52.76

TABLE 9

Number of non-conforming parts list for 100% inspection and sampling frequency 1/10 and 1/20

Group	Population	100%		1/10		1/20	
		NC	% of Population	NC	% of Population	NC	% of Population
1	6739	47	0.70%	5	0.07%	2	0.03%
2	6739	58	0.86%	3	0.04%	1	0.01%
3	4615	60	1.30%	6	0.13%	3	0.07%
4	4615	39	0.85%	2	0.04%	1	0.02%
5	5998	9	0.15%	2	0.03%	2	0.03%
6	5998	19	0.32%	1	0.02%	0	0.00%
7	3644	2	0.05%	0	0.00%	0	0.00%
8	3644	33	0.91%	6	0.16%	2	0.05%
9	1133	6	0.53%	1	0.09%	0	0.00%
10	1133	9	0.79%	0	0.00%	0	0.00%
11	1312	3	0.23%	0	0.00%	0	0.00%
12	1312	7	0.53%	0	0.00%	0	0.00%
13	2032	2	0.10%	1	0.05%	1	0.05%
14	2032	1	0.05%	0	0.00%	0	0.00%
15	1274	1	0.08%	0	0.00%	0	0.00%
16	1274	1	0.08%	0	0.00%	0	0.00%

Conclusions

In this paper, we investigate Statistical Process Control (SPC) sampling frequency for the selected shaft bearing turning process. 100% inspection has the smallest Average Production Length (APL_d), however 100% inspection has high labor costs than SPC sampling. Sampling frequency 1/10 can reduce 90% of the inspection time from 100% inspection, but it can only detect 10% of the non-conforming parts. A machining process is a discrete manufacturing process. With SPC sampling frequency inspections, operators could miss non-conforming parts which were produced within sampling intervals compared with 100% inspection, but SPC was designed to catch the process mean shift and also to identify special cause variations during production process, if they exist. The analysis result of APL_d for each sampling frequency evidently showed 1/10 is a better choice than 1/20 because the APL_d of 1/10 is smaller than APL_d of 1/20.

Recommendations for further research

There are a couple of limitations to our analysis. First, one machining cell in an off-road equipment manufacturing company in the Midwestern United States was the specific case investigated, and our study focused on the manufacturing cell that performed a shaft bearing turning process. The current study only used subgroup size of one for data analysis. Further studies need to consider different sampling frequencies and different subgroup size options such as $n = 3$ and 5 with different k value to calculate APL_d value for sampling frequency. Moreover, researchers can employ the sampling frequency and collect SPC data of the process to test the APL_d performance of varied sampling frequency. A more flexible design of study can help evaluate the impact brought by multiple criterions, such as sample size (n), control limits width parameter (k), and sampling rate (r) in APL_d equation.

In addition, rectification or removal of nonconforming parts in manufacturing processes can be taken into consideration, in gear machining production, based on SPC inspection results. In sampling stage of CSP-1 plan, Dodge recommended to use rectification and removal to ensure the quality of the product (Dodge, 1943). Vaughan (2001) proposed a more detailed SPC-quarantined design. Both of researchers share the idea of rectification, which is doing rework on out of control parts for inspection, but Vaughan pushed it to the next level. Rectification can prevent Type II errors, which is to release nonconforming products to customers from a manufacturing point of view (Vaughan, 2001). Therefore, researchers may consider including rectification or removal of nonconforming parts with sampling frequency to examine the process quality performance. In addition, future verification could include expanding this methodology to other industries on a larger or aggregate scale.

References

Balamurali, S., & Jun, C.-H. (2006). Average Outgoing Quality of CSP-C Continuous Sampling Plan under Short Run Production Processes. *Journal of Applied Statistics, 33*(2), 139-154.

Besterfield, D. H. (2009). *Quality control* (8th ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Dodge, H. F. (1943). A Sampling Inspection Plan for Continuous Production. *The Annals of Mathematcal Statistics, 14*(3), 264-279.

Dodge, H. F., & Romig, H. G. (1929). A Method of Sampling Inspection. *The Bell System Technical Journal,* 8(4), 613-631.

Duncan, A. J. (1956). The Economic Design of |barX Charts used to Maintain Current Control of a Process. *Journal of the American Statistical Association, 51*(274), 228-242.

Duncan, A. J. (1986). *Quality control and industrial statistics* (5th ed.). Homewood, IL: Irwin.

Guenther, W. C. (1977). *Sampling inspection in statistical quality control* New York, NY: Macmillan.

Heizer, J., & Render, B. (2013). *Operations Management* (11th ed.). Upper Saddle River, NJ: Pearson Prentice-Hall.

InfinityQS. (InfinityQS, n.d.). *InfinityQS.* Retrieved March 19, 2019, from https://www.infinityqs.com/

Irani, S. (1999). *Handbook of Cellular Manufacturing Systems.* New York, NY: John Wiley & Sons, Inc.

Keats, J. B., Miskulin, J. D., & Runger, G. C. (1995). Statistical process control scheme design. *Journal of Quality Technology, 27*(3), 214-225.

Litsikas, M. (1996). SPC cuts inspection time by 95%. *Quality*, 35(12), 58-60.

McLain, K., Bumblauskas, D., White, D., & Gransburg, D., (2018). Comparative Analysis of Repeatability and Reproducibility of Soil Compaction Testing. *Journal of Structural Integrity and Maintenance, 3*(2), pp. 106-1131.

Montgomery, D. C. (2005). *Introduction to statistical quality control* (5th ed.). Hoboken, NJ: John Wiley.

NIST. (2010). NIST/SEMATECH e-Handbook of Statistical Methods. Retrieved from http://www.itl.nist.gov/div898/handbook/

Reynolds, M. R., Amin, R. W., Arnold, J. C., & Nachlas, J. A. (1988). $\bar{X}$ Chart with Variable Sampling Intervals. *Technometrics*, 30(2), 181-192

Sarkadi, K., & Vincze, I. (1974). *Mathematical methods of statistical quality control.* Budapest, Hungary: Academic Press, Inc

Shewhart, W. A. (1931). *Economic control of quality of manufactured product.* Milwaukee, WI: ASQ Quality Press.

Singh, N., & Rajamani, D. (1996). *Cellular Manufacturing Systems Design, Planning and Control.* London, UK: Chapman & Hall.

Summers, D. C. S. (2010). *Quality* (5th ed.). Boston, MA: Prentice Hall.

Vaughan, T. S. (2001). Variables inspection for SPC-quarantined production. *Naval Research Logistics (NRL), 48*(2), 159-171.