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Journals

ISSN

22277390

COVERAGE

2013-2023

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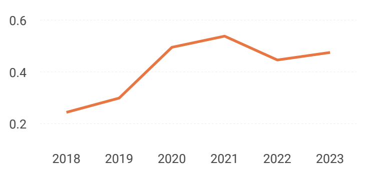

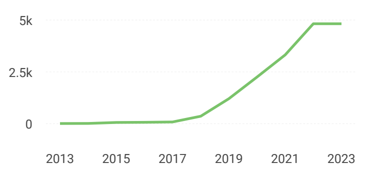

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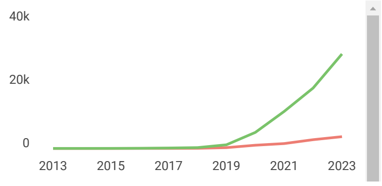

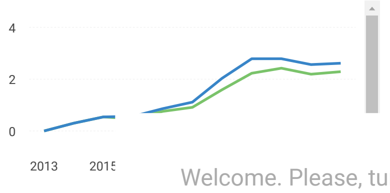

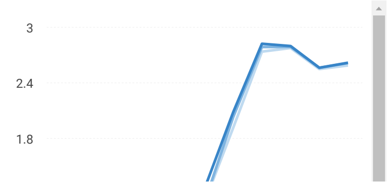

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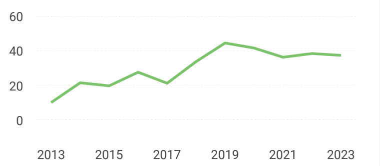

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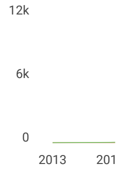

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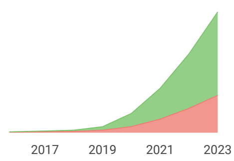

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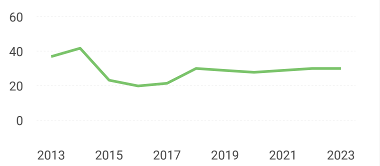

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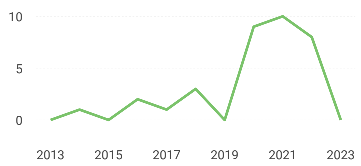

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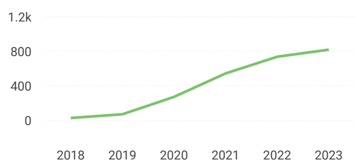

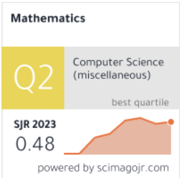

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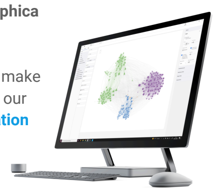

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Article DOIs	Yes

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Volume 12 · Issue 12 June-2 2024

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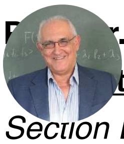

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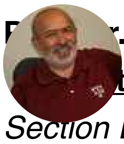
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Bayesian Control Chart for Number of Defects in Production Quality Control (/2227-7390/12/12/1903)

by **Yadpirun Supharakonsakun**

Mathematics **2024**, *12*(12), 1903; **https://doi.org/10.3390/math12121903 (https://doi.org/10.3390/math12121903)** - 19 Jun 2024

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Bayesian Control Chart for Number of Defects in Production Quality Control

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Abstract: This study investigates the extension of the c-chart control chart to Bayesian methodology, utilizing the gamma distribution to establish control limits. By comparing the performance of the Bayesian approach with that of two existing methods (the traditional frequentist method and the Bayesian with Jeffreys method), we assess its effectiveness in terms of the average run lengths (ARLs) and false alarm rates (FARs). Simulation results indicate that the proposed Bayesian method consistently outperforms the existing techniques, offering larger ARLs and smaller FARs that closely approximate the expected nominal values. While the Bayesian approach excels in most scenarios, challenges may arise with large values of the λ parameter, necessitating adjustments to the hyperparameters of the gamma prior. Specifically, smaller values of the rate parameter are recommended for optimal performance. Overall, our findings suggest that the Bayesian extension of the c-chart provides a promising alternative for enhanced process monitoring and control.

Keywords: c-chart; Bayesian approach; Poisson distribution; nonconformity; average run length

MSC: 46N30; 62F15

1. Introduction

The control chart, a fundamental tool in quality control, is utilized in production management to assess the stability of manufacturing or business processes. Often referred to as Shewhart charts, they were pioneered by Walter A. Shewhart in the early 1920s and remain widely employed today. These charts serve as graphical devices for statistical process monitoring, with the aim of enhancing or maintaining process quality by reducing the variability in the product or service characteristics. Traditionally, they are primarily used to monitor process parameters when the underlying process distributions are well understood. The versatility of control charts is evident in their ability to handle various process characteristics, including numeric data, under the assumption of a normal distribution or non-Gaussian distributions such as binomial or Poisson data.

The c-chart is recognized as a foundational tool within the realm of control charts for the tracking of nonconformities. It finds widespread application across various industries, serving to monitor and uphold the process integrity by tallying the occurrence of defects or nonconformities within a sample unit of production. Through the systematic recording and analysis of these data over time, manufacturing operators can effectively identify trends and deviations from the expected performance and take proactive measures to enhance process reliability and product quality.

The primary objective when employing the c-chart is to distinguish between common cause variation arising from inherent fluctuations within the process and special cause variation arising from identifiable factors outside the norm. By establishing control limits on the c-chart, operators and quality control personnel can discriminate between random fluctuations and significant changes in process performance. This differentiation is critical to making informed decisions, implementing corrective actions, and ultimately ensuring that products meet or exceed customer expectations.

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The establishment of control limits on the c-chart is typically based on the estimation of the average number of nonconformities in an initial sample λ. It is denoted by $\overline{\lambda}$. The control limits can be defined as follows [1]:

$$\begin{aligned} UCL &= \overline{\lambda} + 3\sqrt{\overline{\lambda}}, \\ CL &= \overline{\lambda}, \\ LCL &= \overline{\lambda} - 3\sqrt{\overline{\lambda}}. \end{aligned} \tag{1}$$

The statistical boundaries mentioned above help to determine whether a process is in a state of statistical control, even when the value of λ is unknown, by identifying when the number of defects per unit is significantly lower or higher than expected. Deviations beyond these control limits suggest the presence of special causes of variation, which may require investigation and corrective action. By effectively utilizing the c-chart, organizations can maintain a high level of process control, swiftly detect issues, and make data-driven improvements, ensuring consistent product quality and operational efficiency.

The aforementioned control limits of control charts were proposed based on their performance through the evaluation of the average run length (ARL) values. The ARL is a statistical measurement commonly used in quality control and process monitoring; it considers the number of observations taken before an out-of-control signal is detected. A higher ARL is desired when a process is in control, as it leads to fewer false alarm signals.

However, even when a process operates within the expected parameters, there is an approximately 0.27% probability that a data point will exceed the 3-sigma control limits. The run lengths follow a geometric distribution [2]. Consequently, even a well-monitored process depicted on a well-constructed control chart may trigger a warning regarding the potential existence of an unusual occurrence, even if no event has occurred. For the Shewhart control chart using 3-sigma limits, this false alarm rate occurs, on average, once every 1/0.0027 or 370.4 observations. Therefore, the average run length (ARL) of a Shewhart chart under normal conditions is 370.4.

Many researchers have utilized the average run lengths (ARLs) to compare the performance of control charts, as the average typically follows a geometric distribution for both the classical and Bayesian approaches. Chakraborti and Human [3] proposed the false alarm rate (FAR) and ARL of the c-chart through the classical estimation of the true unknown average number of nonconformities in an inspection unit, denoted by ‘c’. Their results revealed significant differences in the performance of the chart in terms of both the FAR and the in-control ARL. Particularly in cases where ‘c’ is small, the actual FAR and in-control ARL can deviate substantially from the nominal expected values, such as 0.0027 for FAR or 370.4 for ARL. Subsequently, Raubenheimer and Merwe [4] extended the conventional operation of the c-chart by introducing a Bayesian approach. They used a noninformative Jeffreys prior to derive the predictive density in order to obtain the upper and lower control limits of the chart. A simulation study compared the unconditional ARLs and FARs using their proposed Bayesian method with the frequentist approach [3]. The upper and lower control limits were calculated for given values of inspection unit m and parameter λ, consistent with those used by Chakraborti and Human. The results indicated that the Bayesian approach yielded larger values of the unconditional ARL and smaller values of the unconditional FAR than the classical method for most variations in m and λ, with the exception of λ values of 8, 10, and 20.

Bayesian methods have been recommended due to their effectiveness over classical methods in predictive tasks and uncertainty management, their flexibility in accommodating complex models and sequential situations, and the ease of integrating prior information, as described by Bayrri and Garcia-Donato [5]. Several studies by Calabrese [6], Taylor [7], and Taylor [8] also support the superiority of Bayesian methods over classical methods regarding action decisions, the sampling size, and the frequency, based on posterior probability determination during out-of-control states. Additionally, Bayesian approaches have been applied to control charts for the mean of a normal distribution, utilizing predictive distributions to derive rejection regions and construct control charts, as proposed by Menzefricke [9,10].

This approach has been extended to the development of combined exponentially weighted moving average charts for the mean and variance of a normal distribution, using Bayesian methods for chart construction, as proposed by Menzefricke [11]. Saghir [12,13] investigated the X-bar chart for normality and the S2-chart for variance, using a Bayesian framework for the characterization of uncertainty, and compared it with the frequentist design structure. The proposed Bayesian design structure demonstrated superior performance in detecting shifts in the process parameters. Consequently, the Bayesian method was applied to construct control charts using a normal prior [14], exponential prior [15], and uniform prior [16]. An exponentially weighted moving average (EWMA) control chart was utilized for the monitoring of the variance of a distribution-free process [17], as well as to implement a ranked set sampling procedure with measurement errors in industrial engineering [18,19]. Recently, Alshahrani et al. [20] used the Bayesian framework to identify posterior and predictive densities for the construction of control limits for the monitoring of the Maxwell scale parameter. Their proposed method was compared with existing control charts and performed well in monitoring the Maxwell scale parameter.

As demonstrated by the aforementioned studies, there is growing interest in enhancing the efficiency of the c-chart for the monitoring of nonconformities using Bayesian approaches. Of particular interest is the development of Bayesian methods based on informative gamma priors, which are well suited for the modeling of the Poisson distribution [21,22]. These methods leverage predictive distribution techniques to achieve superior performance. This study's findings will be compared with those obtained using frequentist approaches and the methods proposed by Raubenheimer and Merwe. Specifically, variations in the parameters of the gamma prior will be explored in terms of their impact on the average run lengths (ARLs) and false alarm rates (FARs).

2. Predictive Density of C-Chart

If individual inspection units are randomly chosen at evenly spaced intervals of time, the number of nonconformities in the i$^{\text{th}}$ inspection will adhere to a Poisson distribution with parameter and is given by

$$f(x_i|\lambda) = \frac{e^{-\lambda}\lambda^{x_i}}{x_i!},\ x_i = 0, 1, 2, \ldots, i = 1, \ldots, n;\ \lambda > 0. \tag{2}$$

In this study, the utilization of an informative conjugate prior is deemed suitable for the Bayesian approach. Let us assume that a random variable, denoted as X, follows a gamma distribution with parameters a and b, noted as X~$Gamma(a, b)$. Supharakonsakun [23] and Song and Kim [24] propose the following informative prior for the Poisson distribution:

$$g(\lambda|a, b) = \frac{b^a}{\Gamma(a)}\lambda^{a-1}e^{-b\lambda};\ a, b > 0. \tag{3}$$

The posterior distribution can be derived as follows:

$$h(\lambda|\underline{X}) = \frac{L(\lambda)g(\lambda|a, b)}{\int L(\lambda)g(\lambda|a, b)d\lambda}, \tag{4}$$

where $L(\lambda)$ represents the likelihood function of the Poisson mass probability function.

Therefore, the posterior distribution can be presented as follows:

$$h(\lambda|\underline{X}) = \frac{(n+b)^{\sum_{i=1}^{n} x_i + a}}{\Gamma\left(\sum_{i=1}^{n} x_i + a\right)}\lambda^{\sum_{i=1}^{n} x_i + a - 1}e^{-(n+b)\lambda}. \tag{5}$$

The posterior distribution of the parameter λ is a gamma distribution, denoted as $Gamma(\sum_{i=1}^{n} X_i + a, n + b)$. It can be expressed in the following form:

$$\pi_j(\lambda|data) = \frac{(n+b)^{\sum_{i=1}^{n} x_i + a}}{\Gamma\left(\sum_{i=1}^{n} x_i + a\right)} e^{-(n+b)\lambda} \lambda^{\sum_{i=1}^{n} x_i + \alpha - 1}. \tag{6}$$

The unconditional predictive density can be obtained as follows [25]:

$$f\left(x_f \middle| data\right) = \int_0^\infty f\left(x_f \middle| \lambda\right) \pi_j(\lambda|data) d\lambda, \tag{7}$$

where X_f is the number of nonconformities in a future inspection unit.

Here,

$$\begin{aligned} f\left(x_f \middle| data\right) &= \int_0^\infty \frac{e^{-\lambda} \lambda^{X_f}}{X_f!} \frac{(n+\beta)^{\sum_{i=1}^{n} X_i + \alpha}}{\Gamma\left(\sum_{i=1}^{n} X_i + \alpha\right)} e^{-(n+\beta)\lambda} \lambda^{\sum_{i=1}^{n} X_i + \alpha - 1} d\lambda \\ &= \frac{(n+b)^{\sum_{i=1}^{n} X_i + a}}{X_f! \Gamma\left(\sum_{i=1}^{m} X_i + a\right)} \int_0^\infty e^{-(n+b+1)\lambda} \lambda^{\sum_{i=1}^{n} X_i + X_f + a - 1} d\lambda \\ &= \frac{(n+b)^{\sum_{i=1}^{n} X_i + \alpha} \Gamma\left(\sum_{i=1}^{n} X_i + X_f + a\right)}{X_f! \Gamma\left(\sum_{i=1}^{n} X_i + a\right) (n+b+1)^{\sum_{i=1}^{n} X_i + X_f + a}} \int_0^\infty \frac{(n+b+1)^{\sum_{i=1}^{n} X_i + X_f + \alpha} e^{-(n+b+1)\lambda} \cdot \lambda^{\sum_{i=1}^{n} X_i + X_f + a - 1}}{\Gamma\left(\sum_{i=1}^{n} X_i + X_f + a\right)} d\lambda. \end{aligned}$$

Hence,

$$f\left(x_f \middle| data\right) = \frac{(n+b)^{\sum_{i=1}^{n} X_i + \alpha} \Gamma\left(\sum_{i=1}^{n} X_i + X_f + a\right)}{X_f! \Gamma\left(\sum_{i=1}^{n} X_i + a\right) (n+b+1)^{\sum_{i=1}^{n} X_i + X_f + a}}. \tag{8}$$

The aforementioned expression can be reformulated in the form of a predictive density, as shown below:

$$f\left(x_f \middle| data\right) = \frac{\left(\sum_{i=1}^{n} X_i + X_f + a - 1\right)!}{\left(\sum_{i=1}^{n} X_i + a - 1\right)! \left(X_f\right)!} \left(\frac{n+b}{n+b+1}\right)^{\sum_{i=1}^{n} X_i + a} \left(\frac{1}{n+b+1}\right)^{X_f}. \tag{9}$$

Specifically,

$$f\left(x_f \middle| data\right) = \binom{\sum_{i=1}^{n} X_i + X_f + a - 1}{X_f} \left(\frac{n+b}{n+b+1}\right)^{\sum_{i=1}^{n} X_i + a} \left(\frac{1}{n+b+1}\right)^{X_f}. \tag{10}$$

Therefore, the predictive density follows a negative binomial distribution with parameters $\sum_{i=1}^{n} X_i + a$ and $\frac{n+b}{n+b+1}$. It can be denoted as

$$X_f \sim NB\left(\sum_{i=1}^{n} X_i + a, \frac{n+b}{n+b+1}\right) \tag{11}$$

To establish the c-chart, the predictive density is utilized to determine the upper and lower control limits through simulation studies. The parameters of λ and inspection unit n will be varied in this process.

3. Results

This study aims to compare the unconditional average run lengths (ARLs) and unconditional false alarm rates (FARs) using the classical method, the Bayesian approach with the Jeffreys prior, and the proposed method. The variations in inspection unit n and parameter λ when calculating the lower and upper control limits follow the methodology outlined by Raubenheimer and Merwe (B_J). The control limits are derived from the predictive density provided by the Jeffreys and proposed Bayesian approaches. Meanwhile, the frequentist method, as described by Chakraborti and Human (F), is employed to obtain the control limits.

The numerical simulation study considers parameter values of n = 5, 10, 15, 20, 25, 30, 50, 100, 200 and λ = 1, 2, 3, 4, 5, 8, 10, 15, 20, 50. The hyperparameters of the gamma prior for the proposed Bayesian method are set to (a, b) = (5, 0.25) and (5, 0.5). These parameter values are applied in the proposed Bayesian method to determine the unconditional average run lengths (ARLs) and false alarm rates (FARs). The simulations are repeated 20,000 times for robustness.

The results of all three methods are presented in Tables 1–4. The average run length (ARL) is a well-known measure used to evaluate the performance of control charts. It represents the expected number of inspection units sampled before the initial signal appears on the chart and is preferred to be as large as possible. The hyperparameters of the gamma prior are varied within (a, b) = (5, 0.25) for Tables 1 and 2 and (a, b) = (5, 0.5) for Tables 3 and 4 to assess their impacts on the unconditional ARL and FAR values.

Table 1. Unconditional ARLs given (a, b) = (5, 0.25).

λ	F	B_J	B_G	F	B_J	B_G	F	B_J	B_G
		n = 5			n = 10			n = 15	
1	2.5213	2.4565	**2.6787**	2.5927	2.5489	**2.6723**	2.6169	2.5894	**2.6679**
2	6.6119	6.3843	**7.0773**	6.8370	6.6884	**7.0620**	6.8810	6.7807	**7.0383**
3	16.6544	15.9202	**18.2051**	17.3270	16.8506	**18.1016**	17.4702	17.1052	**18.0182**
4	39.2982	38.0653	**44.8697**	40.8478	39.7670	**44.1196**	41.4880	40.5102	**43.6796**
5	87.7513	86.3532	**105.0799**	87.7049	87.2830	**99.4738**	87.9545	87.6690	**96.5618**
8	454.9500	494.6330	**599.6453**	383.5887	480.5528	**556.3826**	330.5614	415.8965	**475.5315**
10	398.9501	382.9649	**432.2839**	382.6195	409.4388	**448.5112**	354.0101	397.3419	**430.3330**
15	**323.9318**	284.3721	294.5420	**343.5854**	330.6152	339.2149	340.5875	340.7814	**348.3136**
20	**303.0356**	258.3695	258.3695	**330.1730**	305.3085	304.7872	**340.5875**	320.0669	315.7853
50	**257.3339**	209.1611	189.9394	**294.7512**	257.1939	237.9175	**312.0903**	280.9855	264.5450
		n = 20			n = 25			n = 30	
1	2.6267	2.6061	**2.6647**	2.6348	2.6189	**2.6638**	2.6367	2.6240	**2.6617**
2	6.9377	6.8562	**7.0468**	6.9360	6.8745	**7.0312**	6.9612	6.9132	**7.0357**
3	17.6675	17.3812	**18.0483**	17.6565	17.4120	**18.0166**	17.7847	17.5371	**18.0392**
4	41.8971	41.1831	**43.6275**	42.2358	41.4934	**43.4372**	42.1687	41.5009	**43.2472**
5	87.5315	87.4401	**94.6250**	87.5459	87.4412	**92.9462**	88.0608	88.0290	**92.9611**
8	320.0732	391.8287	**436.8171**	302.7570	364.3714	**402.3618**	293.0335	344.1186	**374.0170**
10	353.4235	388.8555	**416.8962**	344.5182	379.2704	**402.8741**	336.8641	367.9865	**386.4273**
15	338.9864	343.0262	**351.6103**	338.5060	344.1869	**350.5746**	334.8327	344.5416	**346.9817**
20	**340.2283**	331.0582	332.7987	**337.3543**	333.3624	331.6497	**335.0866**	334.1162	332.5582
50	**321.2072**	295.6685	280.1818	**326.9583**	304.7529	292.0903	**331.7540**	311.6192	298.6964
		n = 50			n = 100			n = 200	

Table 1. *Cont.*

λ	F	B_J	B_G	F	B_J	B_G	F	B_J	B_G
1	2.6393	2.6329	**2.6572**	2.6398	2.6401	**2.6527**	2.6390	2.6394	**2.6485**
2	6.9886	6.9554	**7.0286**	7.0307	6.9939	**7.0339**	**7.0820**	7.0363	7.0558
3	17.8675	17.7380	**18.0204**	17.9925	17.8715	**18.0304**	**18.1618**	17.9982	18.0830
4	42.4864	42.1223	**43.1579**	42.6179	42.5305	**43.1355**	42.5747	42.5554	**42.9669**
5	88.7302	88.7932	**91.9146**	88.1357	88.1357	**90.4300**	86.1348	88.0959	**89.0128**
8	277.0461	306.9855	**324.1538**	261.3801	277.1624	**284.7046**	252.8359	263.1057	**266.9809**
10	322.4659	344.2188	**356.2091**	307.6547	322.7460	**331.3688**	294.3781	308.2915	**310.5624**
15	332.9095	340.9520	**342.4873**	324.5143	331.8624	**334.5469**	314.0639	314.0639	**325.2001**
20	334.6021	**337.9960**	336.2559	335.1888	335.9407	**336.0102**	**333.4542**	333.2912	332.8310
50	**338.8756**	327.2756	317.3416	**345.4461**	338.7309	334.0351	**348.5869**	344.8088	341.6380

Note: Bold values indicate the maximal ARL for the method.

Table 2. Unconditional FARs given (a, b) = (5, 0.25).

λ	F	B_J	B_G	F	B_J	B_G	F	B_J	B_G
		$n = 5$			$n = 10$			$n = 15$	
1	0.39662270	0.40708550	**0.40708550**	0.38569400	0.39232380	**0.37421000**	0.38212840	0.38618380	**0.37482830**
2	0.15124300	0.15663420	**0.14129660**	0.14626240	0.14951160	**0.14160280**	0.14532670	0.14747760	**0.14208050**
3	0.06004426	0.06281317	**0.05492979**	0.05771337	0.05934518	**0.05524374**	0.05724033	0.05846155	**0.05549938**
4	0.02544645	0.02627064	**0.02228677**	0.02448115	0.02514650	**0.02266568**	0.02410337	0.02468512	**0.02289396**
5	0.01139585	0.01158035	**0.00951657**	0.01140187	0.01145698	**0.01005290**	0.01136951	0.01136951	**0.01035606**
8	0.00219804	0.00202170	**0.00166765**	0.00260696	0.00208094	**0.00179732**	0.00302516	0.00240444	**0.00210291**
10	0.00250658	0.00261121	**0.00231329**	0.00261356	0.00244237	**0.00222960**	0.00282478	0.00251673	**0.00232378**
15	**0.00308707**	0.00351652	0.00339510	**0.00291048**	0.00302467	0.00294798	0.00293610	0.00293443	**0.00287098**
20	**0.00329994**	0.00387043	0.00388933	**0.00302872**	0.00327538	0.00328098	**0.00300033**	0.00312435	0.00316671
50	**0.00388600**	0.00478100	0.00526484	**0.00339269**	0.00388812	0.00420314	**0.00320420**	0.00355890	0.00378008
		$n = 20$			$n = 25$			$n = 30$	
1	0.38070290	0.38371150	**0.37527970**	0.37953070	0.38184120	**0.37540080**	0.37926550	0.38109870	**0.37569620**
2	0.14414100	0.14585320	**0.14190820**	0.14417550	0.14546450	**0.14222320**	0.14365370	0.14464900	**0.14213290**
3	0.05660097	0.05753329	**0.05540701**	0.05663632	0.05743179	**0.05550451**	0.05622827	0.05543484	**0.05543484**
4	0.02386803	0.02428183	**0.02292132**	0.02367660	0.02410020	**0.02302176**	0.02371426	0.02409589	**0.02312288**
5	0.01142446	0.01143640	**0.01056803**	0.01142258	0.01143625	**0.01075891**	0.01135580	0.01135989	**0.01075718**
8	0.00312429	0.00255214	**0.00228929**	0.00330298	0.00274445	**0.00248533**	0.00341258	0.00290598	**0.00267368**
10	0.00282947	0.00257165	**0.00239868**	0.00290260	0.00263664	**0.00248217**	0.00296856	0.00271749	**0.00258781**
15	0.00294997	0.00291523	**0.00284406**	0.00295416	0.00290540	**0.00285246**	0.00298657	0.00290241	**0.00258781**
20	**0.00293920**	0.00302062	0.00300482	**0.00296424**	0.00299974	0.00301523	**0.00298430**	0.00299297	0.00300699
50	**0.00311326**	0.00338217	0.00356911	**0.00305849**	0.00328135	0.00342360	**0.00301428**	0.00320905	0.00334788
		$n = 50$			$n = 100$			$n = 200$	
1	0.37889310	0.37980500	**0.37633970**	0.37882120	0.37877600	**0.37698020**	0.37892750	0.37886810	**0.37757490**
2	0.14309070	0.14377280	**0.14227490**	0.14223350	0.14298200	**0.14216920**	**0.14120300**	0.14212070	0.14172810
3	0.05596745	0.05637619	**0.05549266**	0.05557858	0.05595490	**0.05546201**	**0.05506071**	0.05556127	0.05530066
4	0.02353694	0.02374041	**0.02317074**	0.02346430	0.02351255	**0.02318279**	0.02348811	0.02349877	**0.02327374**
5	0.01127012	0.01126212	**0.01087967**	0.01134614	0.01127120	**0.01105828**	0.01160971	0.01135127	**0.01123434**
8	0.00360951	0.00325748	**0.00308496**	0.00382585	0.00360799	**0.00351241**	0.00395513	0.00380075	**0.00374559**
10	0.00310110	0.00290513	**0.00280734**	0.00325040	0.00309841	**0.00301779**	0.00339699	0.00324368	**0.00321997**
15	0.00300382	0.00293296	**0.00291982**	0.00308153	0.00301330	**0.00298912**	0.00318407	0.00307384	**0.00307503**
20	0.00298863	**0.00295861**	0.00297393	0.00298339	0.00297672	**0.00297610**	**0.00299891**	0.00300038	0.00300453
50	**0.00295094**	0.00305553	0.00315118	**0.00289481**	0.00295220	0.00299370	**0.00286873**	0.00290016	0.00292708

Note: Bold values indicate the minimal ARL for the method.

Table 3. Unconditional ARLs given (a, b) = (5, 0.5).

λ	F	B_J	B_G	F	B_J	B_G	F	B_J	B_G
		$n = 5$			$n = 10$			$n = 15$	
1	2.5233	2.4572	**2.6748**	2.5902	2.5443	**2.6675**	2.6174	2.5896	**2.6643**
2	6.6229	6.4023	**7.0214**	6.8260	6.6835	**7.0203**	6.8738	6.7870	**7.0060**
3	16.6449	16.6449	**17.8280**	17.3424	16.8308	**17.9019**	17.4687	17.1058	**17.8753**
4	39.3661	37.8868	**43.1480**	40.7582	39.8308	**42.8859**	41.6155	40.8729	**43.0164**
5	87.5318	86.5160	**98.0466**	87.5600	87.0566	**94.7797**	87.6750	87.7005	**93.0653**
8	456.9219	493.1376	**518.5925**	375.8899	468.6201	**480.5386**	332.8215	419.2790	**426.7985**
10	**402.4407**	387.8796	381.4358	378.7237	**409.0835**	396.0685	358.4815	**398.2550**	388.9642

Table 3. *Cont.*

λ	F	B_J	B_G	F	B_J	B_G	F	B_J	B_G
15	**326.0085**	284.4770	258.4064	**340.9400**	329.3362	298.6948	**338.5840**	338.4772	315.4739
20	**303.9213**	259.1802	221.6345	**329.7544**	303.4682	269.3523	**332.0111**	318.7007	282.2210
50	**256.3661**	210.5426	140.2344	**296.0692**	258.2642	200.4727	**313.9835**	283.3336	233.0509
		$n = 20$			$n = 25$			$n = 30$	
1	2.6288	2.6068	**2.6631**	2.6336	2.6167	**2.6599**	2.6366	2.6248	**2.6601**
2	6.9355	6.8503	**7.0232**	6.9377	6.8787	**7.0113**	6.9631	6.9119	**7.0211**
3	17.6310	17.3377	**17.9002**	17.6617	17.3994	**17.8630**	17.7455	17.5314	**17.9095**
4	41.8540	41.0597	**42.8223**	42.1195	41.4906	**42.8501**	42.1345	41.5007	**42.7617**
5	87.8871	87.7707	**92.3624**	87.7346	87.7406	**91.1625**	87.6568	88.0440	**90.7840**
8	393.3209	393.3209	**397.9287**	302.4668	361.1734	**367.9019**	290.8101	342.4454	**344.9910**
10	356.7776	**394.4178**	384.6940	344.6354	**380.6124**	373.1827	332.6781	**360.8223**	359.1106
15	338.4139	**343.7880**	320.2326	339.4823	**345.9631**	327.5580	333.3335	**340.9038**	324.1026
20	**337.3600**	331.5635	301.3750	**336.1248**	332.8756	305.8301	**334.6695**	333.6483	310.6800
50	**320.6388**	294.8311	252.0554	**326.8175**	305.9600	267.2054	**331.6683**	312.3347	278.4506
		$n = 50$			$n = 100$			$n = 200$	
1	2.6381	2.6318	**2.6549**	2.6398	2.6397	**2.6512**	2.6390	2.6393	**2.6482**
2	6.9853	6.9522	**7.0217**	7.0317	6.9953	**7.0317**	**7.0826**	7.0395	7.0572
3	17.8699	17.7442	**17.9680**	17.9892	17.8775	**17.9930**	**18.1734**	18.0104	18.0739
4	42.5169	42.1612	**42.8746**	42.6079	42.4718	**42.8995**	42.6216	42.6172	**42.8391**
5	88.8421	88.5996	**90.6512**	88.1742	88.8398	**89.8989**	86.1159	87.9510	**88.4350**
8	276.7123	307.2505	**311.8946**	262.5758	278.5654	**279.9313**	251.6594	262.0512	**263.2078**
10	323.3059	**345.7096**	342.3620	309.8530	**325.9426**	323.4057	294.9882	**308.7353**	307.5628
15	333.8996	**340.5693**	329.5273	324.8547	**332.6512**	325.3336	314.2074	**324.1764**	321.4006
20	336.0491	**337.7370**	321.4377	**334.4073**	333.7946	326.4139	333.9665	**334.1646**	328.1677
50	**338.8835**	326.4732	302.0031	**345.7355**	339.9024	323.9124	**349.7454**	346.0734	337.4349

Note: Bold values indicate the maximal ARL for the method.

Table 4. Unconditional FARs given $(a, b) = (5, 0.5)$.

λ	F	B_J	B_G	F	B_J	B_G	F	B_J	B_G
		$n = 5$			$n = 10$			$n = 15$	
1	0.39630460	0.40697220	**0.37386390**	0.38606500	0.39303320	**0.37487780**	0.38205250	0.38615420	**0.37532930**
2	0.15099010	0.15619350	**0.14242240**	0.14649910	0.14962180	**0.14244380**	0.14547910	0.14734040	**0.14273460**
3	0.06007845	0.06274271	**0.05609142**	0.05766229	0.05941489	**0.05586000**	0.05724533	0.05724533	**0.05594302**
4	0.02540255	0.02639445	**0.02317604**	0.02453494	0.02510619	**0.02331767**	0.02402952	0.02446612	**0.02324695**
5	0.01142442	0.01155856	**0.01019923**	0.01142074	0.01148678	**0.01055079**	0.01140576	0.01140244	**0.01074515**
8	0.00218856	0.00202783	**0.00192830**	0.00266035	0.00213393	**0.00208100**	0.00300461	0.00238505	**0.00234303**
10	**0.00248484**	0.00257812	0.00262167	0.00264045	**0.00244449**	0.00252482	0.00278955	**0.00251095**	0.00257093
15	**0.00306741**	0.00351522	0.00386987	**0.00293307**	0.00303641	0.00334790	**0.00295348**	0.00295441	0.00316983
20	**0.00329033**	0.00385832	0.00451193	**0.00303256**	0.00329524	0.00371261	**0.00301195**	0.00313774	0.00354332
50	**0.00390067**	0.00474963	0.00713092	**0.00337759**	0.00387201	0.00498821	**0.00318488**	0.00352941	0.00429091
		$n = 20$			$n = 25$			$n = 30$	
1	0.38039740	0.38361130	**0.37550780**	0.37970210	0.38215570	**0.37596040**	0.37928360	0.38097830	**0.37592760**
2	0.14418640	0.14597810	**0.14238510**	0.14413970	0.14537660	**0.14262610**	0.14361330	0.14467830	**0.14242800**
3	0.05671837	0.05767788	**0.05586524**	0.05661960	0.05747328	**0.05598164**	0.05635218	0.05704039	**0.05583628**
4	0.02389257	0.02435477	**0.02335234**	0.02374195	0.02410183	**0.02333716**	0.02373350	0.02409597	**0.02409597**
5	0.01137823	0.01139332	**0.01082692**	0.01139802	0.01139723	**0.01096943**	0.01140813	0.01135796	**0.01101516**
8	0.00313724	0.00254245	**0.00251301**	0.00330615	0.00276875	**0.00271812**	0.00343867	0.00292017	**0.00289863**
10	0.00280287	**0.00253538**	0.00259947	0.00290162	**0.00262735**	0.00267965	0.00300591	**0.00277145**	0.00278466
15	0.00295496	**0.00290877**	0.00312273	0.00294566	**0.00289048**	0.00305289	0.00300000	**0.00293338**	0.00308544
20	**0.00296419**	0.00301601	0.00331813	**0.00297509**	0.00300413	0.00326979	**0.00298802**	0.00299717	0.00321869
50	**0.00311877**	0.00339177	0.00396738	**0.00305981**	0.00326840	0.00374244	**0.00301506**	0.00320169	0.00359130
		$n = 50$			$n = 100$			$n = 200$	
1	0.37906670	0.37996640	**0.37666900**	0.37881600	0.37883430	**0.37718550**	0.37893600	0.37889080	**0.37760990**
2	0.14315800	0.14384040	**0.14241610**	0.14221330	0.14295410	**0.14221220**	0.14119100	0.14205480	**0.14170010**
3	0.05595995	0.05635656	**0.05565437**	0.05558894	0.05593614	**0.05557725**	0.05502545	0.05552335	**0.05552335**
4	0.02352006	0.02352006	**0.02332383**	0.02346981	0.02354502	**0.02331030**	0.02346227	0.02346469	**0.02334315**
5	0.01125592	0.01128673	**0.01103129**	0.01134119	0.01125622	**0.01112361**	0.01161226	0.01136997	**0.01130774**
8	0.00361386	0.00325467	**0.00320621**	0.00380842	0.00358982	**0.00357231**	0.00397363	0.00381605	**0.00379928**
10	0.00309305	**0.00289260**	0.00292089	0.00322734	**0.00306803**	0.00309209	0.00338997	**0.00323902**	0.00325137
15	0.00299491	**0.00293626**	0.00303465	0.00307830	**0.00300615**	0.00307377	0.00318261	**0.00308474**	0.00311138
20	0.00297576	**0.00296088**	0.00311102	**0.00299037**	0.00299585	0.00306360	0.00299431	**0.00299254**	0.00304722
50	**0.00295087**	0.00306304	0.00331122	**0.00289239**	0.00294202	0.00308726	**0.00285922**	0.00288956	0.00296354

Note: Bold values indicate the minimal ARL for the method.

Table 1 displays the unconditional average run lengths (ARLs) for various sample sizes (n = 5, 10, 15, 20, 25, 30, 50, 100 and 200). For n = 5 and 10, the Bayesian method with the gamma prior achieves larger ARLs compared to other methods across parameter values λ = 1 to 10. In contrast, the frequentist method exhibits the maximum ARLs when parameter λ ranges from 15 to 50. For n = 15, the Bayesian method with the gamma prior outperforms the others for λ = 1 to 15, while the classical approach excels for λ = 20 to 50. For n = 20, 25, and 30, the results indicate the excellent performance of the Bayesian method with the gamma prior for λ = 1 to 15, while the frequentist method demonstrates efficiency for λ = 20 to 50 across all sample sizes.

As the sample sizes increase to n = 50, 100, and 200, the Bayesian method with the gamma prior maintains strong performance for λ = 1 to 15 at n = 50, with the Bayesian method using Jeffrey's prior providing the largest ARLs for λ = 20. Conversely, the frequentist method performs well for λ = 50. For n = 100, the proposed method yields the largest ARLs for λ = 1 to 20, while the frequentist method shows effectiveness for λ = 50. Finally, at n = 200, the proposed Bayesian method achieves the maximum ARLs for λ = 1, 4, 5, 8, 10, and 15, while the frequentist method yields the largest ARLs for λ = 2, 3, 20, and 50.

Table 2 presents the unconditional false alarm rates (FARs) for the proposed method with hyperparameters (a, b) = (5, 0.25). The simulation results demonstrate that the proposed method offers smaller FARs compared to the existing methods for various combinations of inspection unit (n) and parameter λ. Specifically, for λ = 8, 10, the proposed Bayesian method exhibits significantly smaller FARs, approaching the nominal value of FAR = 0.0027. However, for λ = 1 to 5, the three methods yield slightly different FAR values.

Additionally, as the inspection unit decreases, the proposed method demonstrates resilience to increasing λ values.

Table 3 presents the unconditional average run lengths (ARLs) for varying sample sizes (n = 5, 10, 15, 20, 25, 30, 50, 100, and 200) and parameter values λ. For n = 5 and 10, the proposed Bayesian method achieves larger ARLs across parameter values λ = 1 to 8, while the frequentist method performs best for λ ranging from 10 to 50. Similarly, for n = 15, the proposed method excels for λ between 1 and 8, with the Raubenheimer and Der Merwe method outperforming the others for λ = 10, and the classical approach is superior for λ = 15 to 50.

For sample sizes n = 20, 25, and 30, the proposed Bayesian method performs consistently well for λ = 1 to 8, with the Bayesian method using the Jeffreys prior showing superior ARLs for λ = 10 and 15 and the frequentist method for λ = 20 to 50.

As the sample sizes increase to n = 50, 100, and 200, the proposed Bayesian method maintains strong performance for λ = 1 to 8. For higher λ values (10 to 20 and λ = 50), the Bayesian method with the Jeffreys prior and the classical method achieve the largest ARLs, respectively. At n = 100, the proposed method dominates for λ = 1 to 8, while the frequentist method and the Bayesian method with the Jeffreys prior perform best for λ = 10 to 15 and λ = 20 to 50, respectively. Finally, at n = 200, the proposed Bayesian method demonstrates the maximum ARLs for λ = 1, 4, 5, and 8, while the Bayesian method with the Jeffreys prior and the classical method excel for λ = 10 to 20 and λ = 2, 3, 50.

Table 4 reports the unconditional FARs for the proposed method with hyperparameters (a, b) = (5, 0.5). The simulation results show that the proposed method consistently provides smaller FARs compared to the existing methods for various combinations of n and λ values. Specifically, for λ = 8 or 10 with n = 25 and 30, the proposed Bayesian method demonstrates significantly smaller FARs, nearing the nominal value of FAR = 0.0027. However, as the sample size increases, the three methods yield slightly different FAR values.

4. Discussion

The extension of the c-chart to the Bayesian methodology, as demonstrated by Raubenheimer and Merwe, offers a novel approach to control limit establishment. By employing the Jeffreys prior, this method presents an alternative to the original frequentist technique introduced by Chakraborti and Human. In this study, we explore the efficacy of an informative prior for the Bayesian method, particularly utilizing the gamma distribution to derive the predictive density for the calculation of control limits.

Our simulation study evaluates the effectiveness of this proposed Bayesian approach alongside two existing methods, with variations in the parameter λ and inspection unit (n). The results consistently demonstrate the superiority of the Bayesian method, providing larger average run lengths (ARLs) and smaller false alarm rates (FARs) that closely approximate the expected nominal value of 0.0027. This superiority can be attributed to the narrower control limits employed by the Bayesian approach, enhancing its ability to detect shifts in the process.

However, it is important to address the computational aspects of Bayesian methods. Bayesian techniques are known for being computationally intensive, and our approach is no exception. In our study, we observed that the time required for the Bayesian computation increases with larger parameter values of λ (20 and 50), where the method may also not perform optimally. Specifically, the computational time for each iteration of the Bayesian control chart was recorded and compared with that of the frequentist method. The results indicated that while the Bayesian approach provided superior statistical performance, it required significantly more computational resources and time, particularly for large datasets.

In our investigation, we employed hyperparameters for the gamma prior with large shape and rate parameters $(a, b) = (5, 0.25), (5, 0.5)$. The variation in the rate parameter b was explored to assess the impact on the performance of the Bayesian method, revealing that smaller values of b are preferable for optimal implementation. Additionally, we found that optimizing these hyperparameters helped to reduce the computational burden, although it was not completely eliminated.

To summarize, while the Bayesian method offers improved detection capabilities and more accurate control limits, it is more time-consuming compared to traditional frequentist methods. Future research could focus on optimizing the computational efficiency of Bayesian algorithms or exploring approximations that maintain the method's advantages without the extensive computational overhead. Additionally, conducting a sensitivity analysis, if feasible, could provide valuable insights into the robustness of our findings under varying conditions, thus further enhancing the applicability and reliability of Bayesian control charts in practice.

5. Conclusions

Our study investigates the extension of the c-chart control chart to Bayesian methodology, leveraging the gamma distribution to establish control limits. We compare the performance of the Bayesian approach with that of two existing methods: the traditional frequentist approach and the Bayesian method using the Jeffreys prior. Our evaluation, based on metrics such as the average run lengths (ARLs) and false alarm rates (FARs), reveals compelling insights into the efficacy of the Bayesian extension.

Simulation results consistently demonstrate the superiority of the proposed Bayesian method over the existing techniques. We observe that the Bayesian approach achieves larger ARLs and smaller FARs, closely aligning with the expected nominal values. This superiority underscores the effectiveness of Bayesian methodology in enhancing process monitoring and control.

A key aspect of our analysis is the investigation of the impact of parameter values, particularly that of parameter λ values, on the performance of each method. While the Bayesian approach excels in most scenarios, challenges may arise with large values of λ. Through meticulous parameter tuning, we identify strategies to optimize the Bayesian method's performance, such as recommending smaller values of the rate parameter for improved results.

Overall, our findings underscore the promise of the Bayesian extension of the c-chart as a robust and effective tool for process monitoring and control. By elucidating the nuances of parameter selection and computational considerations, our study provides actionable insights for practitioners seeking to leverage Bayesian methodology in industrial engineering applications.

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