

Research Article

Fixed Batch Service Queueing Model Under Deterministic Arrivals with Multiple Vacations and Reset Mechanism

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Abstract

In this present work A single server fixed batch queueing method is considered with fixed arrival and service occurs according to poisson process, under multiple vacation and system reset. Further, It is supposed that the vacation has an exponential distribution and that the system reset happens as a Poisson process. In this model, the system starts with k customers, and the server immediately begins service for a batch of size k . When a service is finished and there are fewer than k customers in line, the server takes a vacation. When the vacation ends, If the count of customers is still insufficient, the server continues taking multiple vacations of average length $1/\alpha$. If there are k or more customers, the server selects the first k customers and starts the next batch service. The system also considers the possibility of a system reset. Whenever a reset occurs, all customers in the system are removed, and the server goes on a vacation. Numerical experiments and graphical representations are used to study the mean and variance change with different Different rates for service rate, batch size, vacation rate, and reset rate have been considered in the present study. It has been observed that the developed model is helpful in the analysis of the performance of automatic service systems facing periodic disruptions.

Keywords

Deterministic Arrival, Fixed Batch Service, System Reset, Vacation, Variance

1. Introduction

Queueing models are used extensively to study and optimize performance in a wide range of real-life systems such as manufacturing plants, computer networks, communication systems, and transportation services [6, 13]. Customers are assumed to arrive and be serviced one at a time in traditional queueing system. but in many practical applications—such as loading and unloading operations, data packet transmissions,

or group scheduling—service is provided to batches of customers rather than to individuals. This has led to the development of bulk or batch service queueing models, first introduced by Bailey [2] and later extended by Jaiswal [7], Miller [14], Powell [16] and Neuts [15]. These studies laid the foundation for analyzing queueing systems with fixed or variable batch sizes.

Later studies made these models more realistic by including

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things like server breaks (vacations) and system interruptions like server failures [19]. Doshi [3] and Takagi [18] reviewed vacation queueing systems in detail, while Fuhrmann and Cooper [5] introduced the important stochastic decomposition property for M/G/1 vacation models. Lee and colleagues [11] looked at queues with batch arrivals under N-policy with single or multiple vacations and Sree Parimala and Palaniammal [17] studied single-server systems incorporating delayed vacations and switch-over states. Dshalalow and Yellen [4] studied batch service systems that don't serve all customers at once, using multiple vacations and the quorum policy. These studies suggest that adding vacations makes system more efficient, reduce idle time, and better reflect how services work in real life.

The study by Ayyappan et al. [1] served as the inspiration for our effort. They investigated a fixed batch service queueing system with catastrophic occurrences and multiple vacation policies. Similar studies Kim and Lee [9] have investigated similar M/G/1 queueing model with disasters and working breakdowns. Recently, Yatim et al. [20] have studied an automatic manufacturing system with disaster, breakdown and vacation policies, whereas Kumar [10] has worked on queueing model with feedback and catastrophes having state dependent arrival rates. On the same line, Karpagam and Lokesh [8] have presented a two stage bulk queueing model with batch arrivals, rework, closedown and multiple vacation policy, whereas Lokesh and Karpagam [12] have further extended the same model to analyze chemical/pharmaceutical batch processing systems with starting failures and vacations using ANFIS approach. The study of Ayyappan et al. [1] assumes a Poisson process for the arrival of customers in their model. our study modifies this assumption by considering deterministic arrivals. This change allows for the analysis of systems where inputs occur at fixed intervals, such as automated production lines or scheduled service systems.

2. Research Gap

As far as we know from our study, there is no existing research which considers the analysis of a batch-service queueing model under the assumption of deterministic arrivals with multiple vacations and system resetting process. The current research fills this research gap by analyzing the distributions of batch size and system size, and deducing the performance measures as well as numerically demonstrating the joint effect of the service rate, batch size, vacation rate, and reset rate. This is indicative of practical situations such as production and service scheduling.

3. The System's Mathematical Model

In our study, We examine a fixed batch service queueing system with single server, several vacations, predictable arrivals, and the potential for system reset.

The system is designed to serve customers in fixed-size batches of size k . Customers arrive at the system at constant, deterministic intervals (i.e., the inter-arrival time is fixed and equal to $1/\lambda$). Service times and vacation durations are assumed to be exponentially distributed with parameters μ and α , respectively. Additionally, system reset occur at random in accordance to Poisson process with rate v .

The server instantly begins serving a batch of size k if there are at least k customers in line. If the number of waiting customers is fewer than k , the server takes a vacation which is exponentially distributed duration with parameter α . After returning from a vacation, if there are still less than k customers, the server continues taking multiple consecutive vacations until at least k customers accumulate. When a system failure occurs, all customers present in the system (either waiting or in service) are instantaneously removed i.e. system reset occurs, and the server goes on a vacation.

Consider $\langle N(t), S(t) \rangle$ be a stochastic process, where:

- 1) $N(t)$ denotes the number of customers present in the system at time t .
- 2) $S(t)$ denotes the server state at time t , defined as

$$S(t) = \begin{cases} 1, & \text{if the server is busy,} \\ 2, & \text{if the server is on vacation.} \end{cases}$$

We define the state probabilities as:

$P_{n,1}(t)$ = The probability of having n number of customer in the system at time t and server is busy.

$P_{n,2}(t)$ = The probability of having n number of customers in the system at time t and server is on vacation.

In D/M/1: k model arrivals are fixed and departures are exponential, hence the arrival rate λ is constant given by A . Using the results given by Ayyappan et al. [1]. The steady state probabilities and performance measures for D/M/1: k

$$P_{0,1} = \frac{N_r}{D_r} \quad (1)$$

$$N_r = 1 - \sum_{n=0}^{k-1} \left(\frac{A}{A+\mu} \right)^n \frac{v}{A+v} - \frac{v}{\alpha+v} \left(\frac{A}{A+v} \right)^k$$

$$D_r = \frac{1}{(1-s)(1-r)} + \frac{\mu}{A+v} \left[\sum_{n=0}^{k-1} \left[s^n \left(1 + \frac{r}{s} + \dots + \left(\frac{r}{s} \right)^n \right) + \frac{A}{A+v} s^{n-1} \left(1 + \frac{r}{s} + \dots + \left(\frac{r}{s} \right)^{n-1} \right) + \left(\frac{A}{A+v} \right)^n \right] + \frac{\mu}{A+\mu} \left[s^{k-1} \left(1 + \frac{r}{s} + \dots + \left(\frac{r}{s} \right)^{k-1} \right) + \frac{A}{A+v} s^{k-2} \left(1 + \frac{r}{s} + \dots + \left(\frac{r}{s} \right)^{k-2} \right) + \left(\frac{A}{A+v} \right)^{k-1} \right] \frac{A}{\alpha+v} \right]$$

$$P_{n,1} = P_{0,1} s^n \left(1 + \frac{r}{s} + \dots + \left(\frac{r}{s} \right)^n \right) \text{ for } n=0,1,2,\dots \quad (2)$$

$$P_{n,2} = \frac{\mu}{A+v} P_{0,1} \left[s^n \left(1 + \frac{r}{s} + \dots + \left(\frac{r}{s} \right)^n \right) + \frac{A}{A+v} s^{n-1} \left(1 + \frac{r}{s} + \dots + \left(\frac{r}{s} \right)^{n-1} \right) + \left(\frac{A}{A+v} \right)^n \frac{v}{A+v} \right] \text{ for } n=0,1,2,\dots \quad (3)$$

$$P_{n,2} = \left(\frac{A}{A+\alpha+v}\right)^{n-k+1} P_{k-1,2} \text{ for } n \geq k \quad (4)$$

$$L_s = \sum_{n=0}^{\infty} (n+k) P_{n,1} + n P_{n,2} \quad (5)$$

$$L_q = \sum_{n=0}^{\infty} n (P_{n,1} + P_{n,2}) \quad (6)$$

$$V(x) = \left(\sum_{n=0}^{\infty} (n+k)^2 P_{n,1} + \sum_{n=0}^{\infty} n^2 P_{n,2}\right) - (L_s)^2 \quad (7)$$

4. Numerical Study

a) Steady state analysis: In this part, we initially estimated the probabilities of steady states for various service rates, batch sizes, vacation rates, and system reset rates while maintaining a constant arrival rate. As follows:

Table 1. Probabilities of steady states for different service rates when $A=3$, $v=1$, $\alpha=2$, $k=5$.

P_i	$\mu = 10$	$\mu = 15$	$\mu = 20$
$P_{0,1}$	0.006757	0.004887	0.003825
$P_{1,1}$	0.004829	0.003216	0.002391
$P_{2,1}$	0.002726	0.001727	0.001255
$P_{3,1}$	0.001430	0.000884	0.000635
$P_{4,1}$	0.000729	0.000445	0.000318
$P_{5,1}$	0.000368	0.000223	0.000159
$P_{6,1}$	0.000184	0.000112	0.000080
$P_{7,1}$	0.000092	0.000056	0.000040
$P_{8,1}$	0.000046	0.000028	0.000020
$P_{9,1}$	0.000023	0.000014	0.000010
$P_{10,1}$	0.000012	0.000007	0.000005
$P_{11,1}$	0.000006	0.000003	0.000002
$P_{12,1}$	0.000000	0.000002	0.000001
$P_{13,1}$	0.000000	0.000001	0.000000
$P_{0,2}$	0.283785	0.286652	0.288250
$P_{1,2}$	0.258695	0.263700	0.266391
$P_{2,2}$	0.237190	0.242664	0.245515
$P_{3,2}$	0.217844	0.223419	0.226309
$P_{4,2}$	0.201325	0.164371	0.209967
$P_{5,2}$	0.100663	0.103503	0.104983
$P_{6,2}$	0.050331	0.051752	0.052492
$P_{7,2}$	0.025166	0.025876	0.026246
$P_{8,2}$	0.012583	0.012938	0.013123

P_i	$\mu = 10$	$\mu = 15$	$\mu = 20$
$P_{9,2}$	0.006291	0.006469	0.006561
$P_{10,2}$	0.003146	0.003234	0.003281
$P_{11,2}$	0.001573	0.001617	0.001640
$P_{12,2}$	0.000786	0.000809	0.000820
$P_{13,2}$	0.000393	0.000404	0.000410
$P_{14,2}$	0.000197	0.000202	0.000205
$P_{15,2}$	0.000098	0.000101	0.000103
$P_{16,2}$	0.000049	0.000051	0.000051
$P_{17,2}$	0.000025	0.000025	0.000026
$P_{18,2}$	0.000012	0.000013	0.000013
$P_{19,2}$	0.000006	0.000006	0.000006
$P_{20,2}$	0.000000	0.000003	0.000003
$P_{21,2}$	0.000000	0.000000	0.000000

Table 2. Probabilities of steady states for different batch sizes when $A=3$, $\mu=10$, $v=1$, $\alpha=2$.

P_i	$k = 3$	$k = 4$	$k = 5$
$P_{0,1}$	0.013588	0.009357	0.006757
$P_{1,1}$	0.009812	0.006698	0.004829
$P_{2,1}$	0.005576	0.003785	0.002726
$P_{3,1}$	0.002937	0.001987	0.001430
$P_{4,1}$	0.001502	0.001014	0.000729
$P_{5,1}$	0.000758	0.000511	0.000368
$P_{6,1}$	0.000381	0.000257	0.000184
$P_{7,1}$	0.000191	0.000128	0.000092
$P_{8,1}$	0.000095	0.000064	0.000046
$P_{9,1}$	0.000048	0.000032	0.000023
$P_{10,1}$	0.000024	0.000016	0.000012
$P_{11,1}$	0.000012	0.000008	0.000006
$P_{12,1}$	0.000006	0.000004	0.000000
$P_{13,1}$	0.000003	0.000002	0.000000
$P_{14,1}$	0.000001	0.000000	0.000000
$P_{15,1}$	0.000000	0.000000	0.000000
$P_{0,2}$	0.317940	0.296785	0.283785
$P_{1,2}$	0.330925	0.286119	0.258695
$P_{2,2}$	0.335497	0.274423	0.237190

P_i	$k = 3$	$k = 4$	$k = 5$
$P_{3,2}$	0.265184	0.261199	0.217844
$P_{4,2}$	0.132592	0.130600	0.201325
$P_{5,2}$	0.041937	0.065300	0.100663
$P_{6,2}$	0.020969	0.032650	0.050331
$P_{7,2}$	0.010484	0.016325	0.025166
$P_{8,2}$	0.005242	0.008162	0.012583
$P_{9,2}$	0.002621	0.004081	0.006291
$P_{10,2}$	0.001311	0.002041	0.003146
$P_{11,2}$	0.000655	0.001020	0.001573
$P_{12,2}$	0.000328	0.000510	0.000786
$P_{13,2}$	0.000164	0.000255	0.000393
$P_{14,2}$	0.000082	0.000128	0.000197
$P_{15,2}$	0.000041	0.000064	0.000098
$P_{16,2}$	0.000020	0.000032	0.000049
$P_{17,2}$	0.000010	0.000016	0.000025
$P_{18,2}$	0.000005	0.000008	0.000012
$P_{19,2}$	0.000003	0.000004	0.000006
$P_{20,2}$	0.000001	0.000002	0.000003
$P_{21,2}$	0.000000	0.000001	0.000002

Table 3. Probabilities of steady states at different values of v when $A=3$, $\mu=10$, $\alpha=2$, $k=5$.

P_i	$v = 2$	$v = 3$	$v = 4$
$P_{0,1}$	0.002707	0.001212	0.000597
$P_{1,1}$	0.001702	0.000682	0.000304
$P_{2,1}$	0.000838	0.000298	0.000120
$P_{3,1}$	0.000381	0.000120	0.000043
$P_{4,1}$	0.000168	0.000046	0.000015
$P_{5,1}$	0.000073	0.000018	0.000005
$P_{6,1}$	0.000031	0.000007	0.000002
$P_{7,1}$	0.000013	0.000003	0.000001
$P_{8,1}$	0.000006	0.000001	0.000000
$P_{9,1}$	0.000002	0.000000	0.000000
$P_{10,1}$	0.000001	0.000000	0.000000
$P_{0,2}$	0.410828	0.504040	0.573134
$P_{1,2}$	0.260729	0.257197	0.247769

P_i	$v = 2$	$v = 3$	$v = 4$
$P_{2,2}$	0.135429	0.133767	0.108342
$P_{3,2}$	0.115734	0.071968	0.048569
$P_{4,2}$	0.082668	0.041022	0.022933
$P_{5,2}$	0.035429	0.015383	0.007647
$P_{6,2}$	0.015184	0.005769	0.002549
$P_{7,2}$	0.006507	0.002163	0.000850
$P_{8,2}$	0.002789	0.000811	0.000283
$P_{9,2}$	0.001195	0.000304	0.000094
$P_{10,2}$	0.000512	0.000114	0.000031
$P_{11,2}$	0.000220	0.000043	0.000010
$P_{12,2}$	0.000094	0.000016	0.000003
$P_{13,2}$	0.000040	0.000006	0.000001
$P_{14,2}$	0.000017	0.000002	0.000000
$P_{15,2}$	0.000007	0.000000	0.000000

Table 4. Probabilities of steady states at different values of α , when $A=3$, $\mu=10$, $v=1$, $k=5$.

P_i	$\alpha = 3$	$\alpha = 4$	$\alpha = 5$
$P_{0,1}$	0.008462	0.009666	0.010562
$P_{1,1}$	0.005443	0.005699	0.005784
$P_{2,1}$	0.002722	0.002582	0.002412
$P_{3,1}$	0.001250	0.001064	0.000908
$P_{4,1}$	0.000554	0.000419	0.000325
$P_{5,1}$	0.000241	0.000162	0.000113
$P_{6,1}$	0.000104	0.000062	0.000039
$P_{7,1}$	0.000045	0.000023	0.000013
$P_{8,1}$	0.000019	0.000009	0.000004
$P_{9,1}$	0.000008	0.000003	0.000001
$P_{10,1}$	0.000003	0.000001	0.000000
$P_{11,1}$	0.000002	0.000000	0.000000
$P_{0,2}$	0.292310	0.298330	0.302810
$P_{1,2}$	0.275149	0.286325	0.294377
$P_{2,2}$	0.257184	0.270185	0.279231
$P_{3,2}$	0.239183	0.252725	0.262007
$P_{4,2}$	0.223238	0.237048	0.246508
$P_{5,2}$	0.095674	0.088893	0.082169

P_i	$\alpha = 3$	$\alpha = 4$	$\alpha = 5$
$P_{6,2}$	0.041003	0.033335	0.027390
$P_{7,2}$	0.017573	0.012501	0.009130
$P_{8,2}$	0.007531	0.004688	0.003043
$P_{9,2}$	0.003228	0.001758	0.001014
$P_{10,2}$	0.001383	0.000659	0.000338
$P_{11,2}$	0.000593	0.000630	0.000113
$P_{12,2}$	0.000254	0.000093	0.000038
$P_{13,2}$	0.000109	0.000035	0.000013
$P_{14,2}$	0.000047	0.000013	0.000004
$P_{15,2}$	0.00002	0.000005	0.000000

b) System performance measures: In this part, we computed number of customers in the system queue and the variance as follows:

Table 5. System measures for different service rates when $A=3$, $v=1$, $\alpha=2$, $k=5$.

	$\mu=10$	$\mu=15$	$\mu=20$
L_s	3.589551	3.491997	3.390468
L_q	3.545906	3.421560	3.332503
V_x	2.085065	2.558477	2.713219

Table 6. System measures for different batch sizes when $A=3$, $\mu=10$, $v=1$, $\alpha=2$.

	$K=3$	$K=4$	$K=5$
L_s	2.980721	3.050335	3.507639
L_q	2.866939	2.955214	3.421711
V_x	1.171046	2.201029	2.450792

Table 7. System measures for different values of v when $A=3$, $\mu=10$, $\alpha=2$, $k=5$.

	$v=2$	$v=3$	$v=4$
L_s	1.401273	1.056446	0.771162
L_q	1.371768	1.044478	0.765727
V_x	3.155450	1.859419	1.282323

Table 8. System measures for different values of α when $A=3$, $\mu=10$, $v=1$, $k=5$.

	$\alpha=3$	$\alpha=4$	$\alpha=5$
L_s	3.475731	3.449276	3.419129
L_q	3.381694	3.350901	3.318324
V_x	1.393493	0.889793	0.537158

5. Graphs

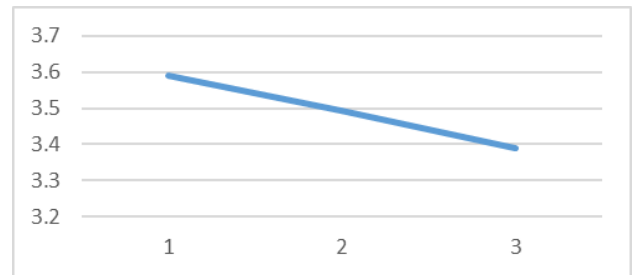


Figure 1. Mean number of customers in the system for different values of service rates.

In Figure 1 shows a declining trend of L_s , as the service rate rises Faster customer clearing is made possible by higher service capacity, which lessens system congestion overall.

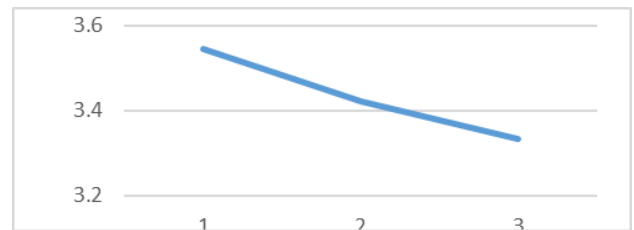


Figure 2. Mean number of customers in queue for different values of service rates.

In Figure 2 shows, When the service rate rises the mean queue length falls, suggesting more effective queue management. Quicker service keeps lines from growing and cuts down on client wait times.

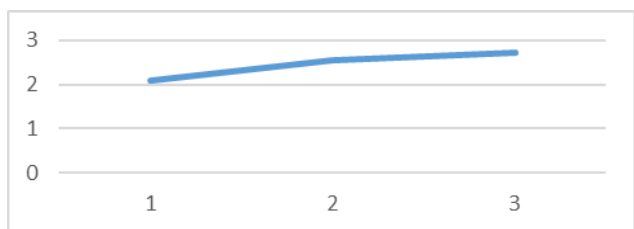


Figure 3. Variance for different values of service rates.

In Figure 3, Shows With increasing service rates, the variance rises despite a decrease in congestion, indicating more system swings. This implies that even if average queue lengths are smaller, faster service creates variability.

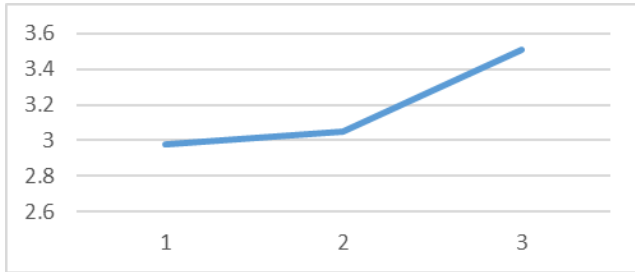


Figure 4. Mean number of customers in the system for different batch sizes.

In Figure 4, As the batch size increases, the mean system size rises gradually. Larger batch requirements cause service initiation to be delayed, which results in an accumulation of customers.

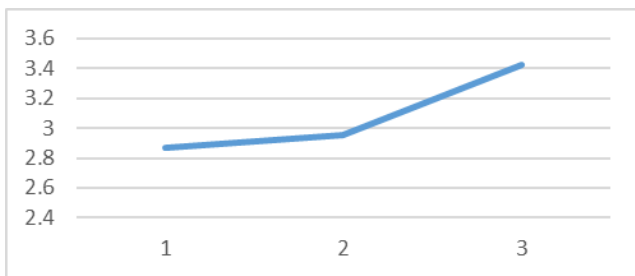


Figure 5. Mean number of customers in queue for different batch sizes.

In Figure 5, As the batch size increases, The queue length increases. This demonstrates that when service starts only when larger batches are generated, users have to wait longer.

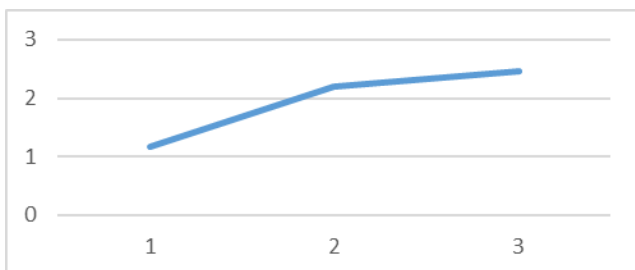


Figure 6. Variance for different batch sizes.

In Figure 6, As the batch size increases, the variance increases significantly, suggesting greater instability and variations in congestion. The uncertainty of system behavior is

greatly increased by larger batches.

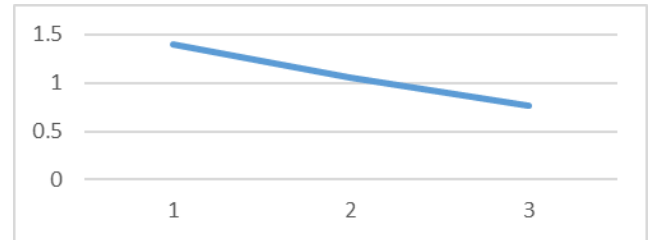


Figure 7. Mean number of customers in the system for different values of v .

In Figure 7, As the vacation rate rises, this graph shows a significant decline in L_s . The server can return to service more frequently, increasing throughput, when vacation completion rates are higher.

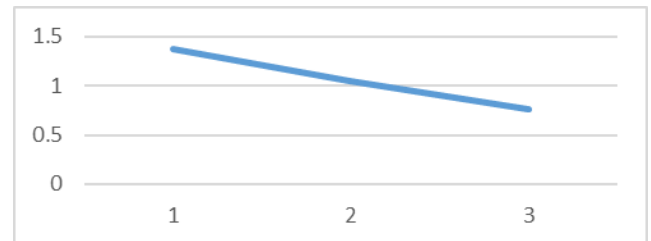


Figure 8. Mean number of customers in queue for different values of v .

In Figure 8, When vacation rates rise, the queue length significantly decreases, suggesting effective queue clearance. This demonstrates how controlled vacations can help reduce traffic.

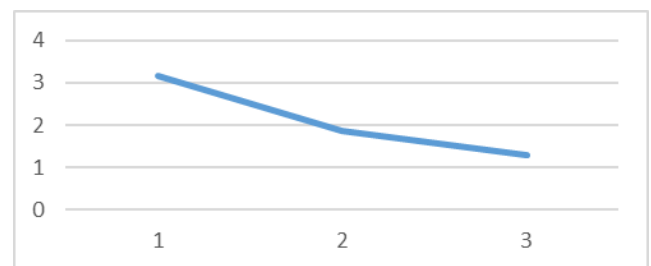


Figure 9. Variance for different values of v .

In Figure 9, As v increases, a significant decrease in variance is seen, suggesting improved system stability. Increased vacation rates aid in mitigating variations in customer service and arrivals.

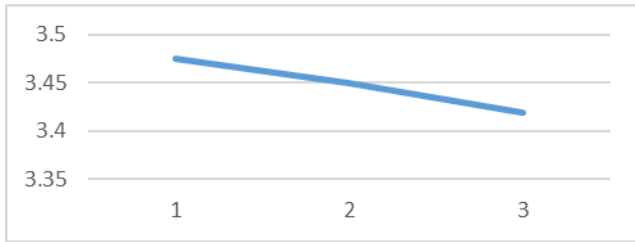


Figure 10. Mean number of customers in the system for different values of α .

In Figure 10, As the rate of catastrophes increases, the mean system size exhibits a minor declining tendency. By resetting the system, frequent catastrophic occurrences stop an excessive buildup of customers.

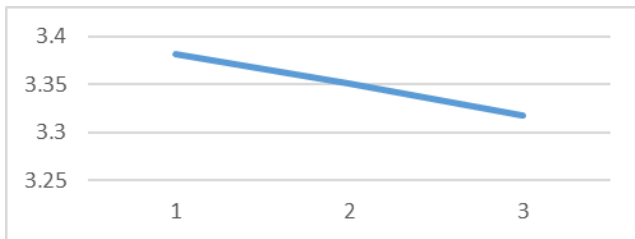


Figure 11. Mean number of customers in the queue for different values of α .

In Figure 11, The queue length is slightly shortened when the catastrophe rate rises, indicating that congestion is managed through regular system clearance.

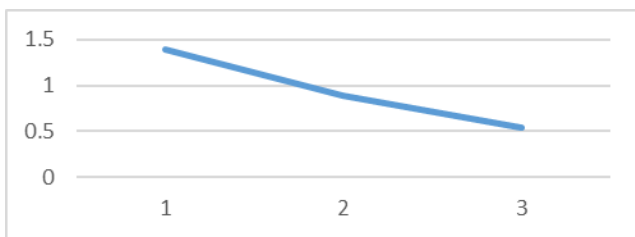


Figure 12. Variance for different values of α .

In Figure 12, Higher catastrophe rates result in a large drop in variance, which suggests decreased instability and better system stability. This demonstrates how catastrophes have a powerful stabilizing influence on system functioning.

6. Result & Discussion

The analysis of steady state and various system performance measures for D/M/1: k where k is the batch size, and the system undergoes multiple vacations and system reset.

Here, The results show that there is an apparent spike in congestion when the batch size is increased from $k=3$ to $k=5$. The variance increases from $V_x=1.17$ to $V_x=2.45$ and the mean system size increases from $L_s=2.98$ to $L_s=3.51$. System performance is greatly enhanced by larger service rates; for example, raising the service rate from $\mu=10$ to $\mu=20$ decreases the mean queue length from $L_q=3.55$ to $L_q=3.33$ and the mean system size from $L_s=3.59$ to $L_s=3.39$. Higher vacation rates show a more noticeable improvement: raising v from 2 to 4 lowers L_s from 1.40 to 0.77 and the variance from 3.16 to 1.28. The variance decreases from 1.39 to 0.54 when the catastrophe rate is increased from $\alpha=3$ to $\alpha=5$, suggesting improved system stability.

7. Conclusion

The study reveals that an increase in the service rate or vacation rate enhances system efficiency by reducing both the average number of customers and the queue length. Conversely, increasing the batch size leads to higher congestion, as more customers must accumulate before service begins. A higher catastrophe rate significantly decreases system congestion by frequently resetting the system to an empty state. Overall, the deterministic arrival pattern produces smoother and more stable system behavior compared to the conventional Poisson-arrival model. This model is highly applicable to automated production or service environments where inputs occur at regular intervals, and service operations are subject to random breakdowns and recovery periods. The results of this study provide the basis that can be used for further result and analysis of such systems; batch sizes need to be decided carefully based on the trade-off between efficiency and congestion, the service rate and the vacation rate can be optimized to increase efficiency, and the rate of resetting can be decided based on the cost of congestion vs. cost of disruption.

Abbreviations

L_s	Mean Number of the Customers in the System
L_q	Mean Number of the Customers in the Queue
V_x	Variance

Author Contributions

Priyanka Sisodiya: Conceptualization, Writing – original draft, Writing – review & editing

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Conflicts of Interest

The Authors declares no Conflicts of Interest.

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