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ROLE OF QUEUING MODELING IN BIOTECHNOLOGY: A CASE STUDY OF BACTERIAL VACCINE QUALITY CONTROL

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ABSTRACT:
The goal of the study is to assess and enhance the efficiency of the vaccination quality assurance queue system to minimize delays and meet the company's long-term target for vaccine manufacturing capacity. The study focuses on the biggest vaccine producers in India and Southeast Asia that use Bacterial Vaccine Quality Control (BVQC). DTP-Hb-Hib, TT, DTP, BCG, BioTT, BioTd, DT, and Td are among the vaccinations used by BVQC. Eight servers, each with a specific purpose, make up the BVQC's queuing system. Between January and June 2024, the current system had delays ranging from 13% to 61%. The existing system's queuing characteristics is identified, and suggestions for improvement will made by changing the servers' assignments. Following the simulation of this concept in November 2024, average amount of time (WS) spent in the system decreased from 0.0098 to 0.0045, the system's queue length (Lq) decreased from 2.85 to 2.55, and performance increased without any delays. According to the research, changing server assignments can be a useful strategy for A system of queuing functionality in the quality control of vaccines. This may improve the company's capacity to provide future vaccination demand by reducing delays, optimizing line lengths, and increasing overall efficiency.

KEYWORDS: Bacterial Vaccine Quality Control, Value Stream Mapping

INTRODUCTION

Queuing analysis is a mathematical technique used to study and optimize waiting lines (queues) in various industries, including both industrial and service sectors. It helps organizations improve efficiency, reduce wait times, and allocate resources effectively. [1,2]. Given the rising the need for vaccinations worldwide and the need of guaranteeing its effectiveness and speed, its use Throughout the medical field, including the creation of vaccines, is very pertinent [3,4]. The quality control of vaccine production procedure is an essential stage in queue analysis since it guarantees the final product's safety and quality prior to distribution. [5,6].

To minimize delays and support the company's long-term objective of expanding vaccine manufacturing capacity, this research evaluates and enhances the efficiency of the queuing system for vaccination quality control. Quality Control for Bacterial Vaccines procedure at the biggest vaccine producer in Southeast Asia and India is the main subject of the study. [7.8]

BVQC oversees vaccines such as DTP-Hb-Hib, DT, TT, DTP, BCG, BioTT, and BioTd, and Td. Its queuing system consists of eight servers, every one allotted specific task. However, the system has experienced delays of 14%, 62%, 23%, 24%, 9%, and 15% in January–June 2024. This study aims to identify bottlenecks and optimize the process to improve efficiency. [9,10]

By issuing Presidential Instruction No. 7 of 2020, the Indian government recognized the significance of increasing Quality Control for Bacterial Vaccines efficiency. In order to guarantee that necessary medications, such as vaccinations, sera as well as bioscience goods, are easily, sustainably, and reasonably available, this directive emphasizes the necessity of quickening the growth of the medical device and pharmaceutical industries. [11,12, 13]

Delays in achieving vaccine manufacturing targets may influence the Long-Term Strategic Plan (RJPP) of the business. To address this, we explored several approaches, including Value Stream Mapping (VSM) to streamline processes by identifying non-value-added activities [14,15], scheduling methods to optimize the prioritization of arrivals [16,17], Using queuing theory to examine and enhance system operation [18,19]. After assessment these approaches and considering the specific challenges encountered, queuing theory is chosen as the preferred analytical method. Based on this framework, strategic enhancements will be implemented. Therefore, the objective of this research is to assess and enhance the effectiveness of the vaccine quality control queueing system in order to minimize delays and help the company achieve its capacity for long-term vaccine production targets [20,21]

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Material and methods

Three steps are used in this study: (a) Evaluation of the existing queuing structures; (b) Improvement through configuration modification and subsequent analysis; and (c) Comparison of the prior and subsequent improvements.

The first step involves analysing the current queuing system by looking at its setup and functionality the number of servers (c). λ is the monthly number of test arrivals, while μ is the monthly number of tests served. are the data gathered for queue performance study. The information is gathered directly from firm data and observation. The following performance metrics are measured:

The probability that there is no activity on the system:

$$P0 = \frac{1}{[\sum_{n=0}^{n=c-1} \frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n] + \frac{1}{c!}\left(\frac{\lambda}{\mu}\right)^c \frac{c\mu}{c\mu-\lambda}} \quad (1)$$

The queuing system's average number of test types:

$$L_s = \frac{\lambda\mu(\lambda/\mu)^c}{(c-1)!(M\mu-\lambda)^2} P_0 + \frac{\lambda}{\mu} \quad (2)$$

The mean duration of a single testing type over the whole queuing system:

$$W_s = \frac{L_s}{\lambda} \quad (3)$$

In a queue, the average number of test types waiting:

$$L_q = L_s \frac{\lambda}{\mu} \quad (4)$$

The typical amount of time that one kind of test must wait in line before being served:

$$W_q = \frac{L_q}{\lambda} \quad (5)$$

The second step involves changing the settings while taking the current queueing performance into account and speaking with the BVQC (Bacterial vaccine quality check) manager. Reducing delays is the goal of this improvement. After the improvement has been carried out, it is next put into practice in order to get accurate performance metrics. Following the improvement, additional performance evaluations are conducted using the same computation formulas as in the initial phase.

The third step involves comparing the performance before and after the improvement is implemented. In order to comprehend the performance improvements brought about by the upgrade, this comparison is being made. Using the same performance indicators as the first and second stages, the comparison made. An understanding of the improvement's efficacy can be gained from this comparison.

RESULTS

Current queuing structures and operation

As seen in Figure 1, each server in Currently, the queue service assignment is offered a task in the kind of a certain testing service type. Fig. 2 depicts the current server's flow process. For instance, server 4 is the one that will finish this service if a sample contains a particular kind of pH test. The testing service procedure is then carried out by the server to complete the result documentation. Depending on the sample type, the manager receives the completed result document for review. For instance, due to PFB samples undergo two different types of testing thimerosal and thimerosal managers must wait

for thimerosal testing before delivering results. The manager delivers the test result files to the sender. after reviewing the test results. Table 1 shows the performance of the queueing mechanism.
Improved queuing systems and performance
The suggested service is assigned to a customized server that has been tested by a prepared operator. Fig. 2 depicts the improved server's flow procedure.
As a result of service disparities that cause delays, the primary queuing system has been designated as a supporting server. With scores of 165, 703, 88, 580, 1295, and 783 for servers 1 through 7, respectively, an analysis of the testing volume and difficulty level revealed that Server 3 had the lowest performance score, making it the main contender for change. After Server 3 is moved to concentrate on documentation duties, the queuing system's performance increased on all metrics. In addition to addressing the initial delays, this strategy change creates the opportunity for server 3 to be reassigned to other departments within the organization in the future, possibly freeing up administrative staff to perform documentation duties and further maximizing resource utilization. The flow of the service process explains how multiple samples arrive, each of which needs a particular kind of examination. After assigning the incoming samples to the proper server, after that, the server completes the result documentation and does the testing. Depending on the sample type, the results are forwarded to the management for evaluation after they have been documented. For example, because Both kinds of testing are performed on PFB samples. the results of the thimerosal test must be considered before the results of the pH test. After reviewing the test results, the manager returns the completed documents to the sender. For instance, the manager forwards the results back to the manufacturing department if the PFB sample came from there.Table 2 displays the updated queuing system's performance.[22]

Table 1 Delegated testing types for every server.

Server	Types of testing
1	Protein Lowry, Total PRP & Free PRP Orcinol, Fenol/Kresol, GC 2-PE
2	Reconstituting, CCIT, Extractable volume, O-Acetyl, MC, Thimerosal, Total PRP & Free PRP HPAEC.
3	Conductivities, TOC, Asam Nucleate, Residue ADH, NaCl
4	pH, Color and clarity test, Iron Identification, Cl Identification, Density, A Identification, UV Identification, Na Identification
5	Particle size, Aluminum, Molecular Size & KD, Free sulphate, Phosphate Levels, Anti xa, Anti 2a
6	Osmolarities
7	Protein Nitrogen, Formaldehyde

Types of Testing Server (1)
- **Protein Lowry Assay –** A widely method to use the reaction to calculate the protein concentration between proteins and the Folin-Ciocalteu reagent. It measures the absorbance of the protein-dye complex at around 750 nm.
- **Total PRP (Proline-Rich Proteins) & Free PRP –** PRPs are salivary proteins that play a role in oral health and digestion. Measuring total and free PRPs helps in studying protein interactions, especially with tannins in food.
- **Orcinol Assay –** A method used to detect pentoses (like ribose and deoxyribose) in nucleic acids and carbohydrates. The reaction with orcinol in acidic conditions produces a green-coloured complex.
- **Phenol/Kresol (Phenol-Cresol) –** These are aromatic organic compounds often used in biochemical assays and industrial applications. They may also be used in protein or nucleic acid extractions.
- **GC2-PE(Gas Chromatography of 2-Phenylethanol) –** 2-Phenylethanol is an aromatic alcohol commonly found in fermentation processes, essential oils, and food flavouring. Gas Chromatography (GC) is used to analyse and quantify it in various samples.

Types of Testing Server (2)
- **Reconstituting –** The process of dissolving a lyophilized (freeze-dried) substance, typically a drug or vaccine, in a diluent before administration.
- **CCIT (Container Closure Integrity Testing) –** A crucial test in pharmaceuticals to ensure that a container (vial, syringe, ampoule) maintains its sterility and prevents microbial contamination. Methods include dye ingress, vacuum decay, and high-voltage leak detection.
- **Extractable Volume –** The volume of liquid that can be withdrawn from a vial or ampoule, ensuring the correct dose is available for administration. This is tested to confirm compliance with pharmacopeial standards (e.g., USP, EP).
- **O-Acetyl (O-Acetylation Measurement) –** O-Acetyl groups are chemical modifications often found in polysaccharides, including bacterial capsular polysaccharides used in vaccines. Measuring O-Acetylation helps determine the structural integrity and efficacy of polysaccharide-based vaccines.
- **MC (Moisture Content) –** The amount of water present in a substance, usually measured by techniques like Karl Fischer titration or thermogravimetric analysis (TGA). It's crucial for the stability of lyophilized pharmaceuticals.
- **Thimerosal –** An organomercury compound used as a preservative in some vaccines to prevent microbial contamination. Its concentration is monitored for safety and regulatory compliance.
- **Total PRP & Free PRP HPAEC (High-Performance Anion Exchange Chromatography) –**
- **Total PRP (Proline-Rich Proteins) & Free PRP**: Important in studying protein composition, especially in pharmaceutical formulations.

- **HPAEC:** A high-resolution chromatography technique used for analyzing carbohydrates, polysaccharides, and PRPs. It helps in determining purity, composition, and degradation products.

Types of Testing Server (3)

- Conductivities Measurement of a solution's ability to conduct electricity, often used in water quality testing (e.g., Purified Water, WFI – Water for Injection). Conductivity helps ensure compliance with pharmacopeial standards (USP, EP).
- **TOC (Total Organic Carbon) –** A critical test for measuring organic contaminants in water, pharmaceutical products, and cleaning validation. High TOC levels indicate the presence of impurities or residues.
- **Asam Nucleate (Likely "Asam Nukleat" – Nucleic Acid) –** Refers to DNA or RNA content in a sample. Testing nucleic acids is essential in biopharmaceuticals, vaccines, genetic research, and contamination control.
- **Residue ADH (Alcohol Dehydrogenase Residue?) –** If referring to residual enzyme activity, this could be related to enzyme purification, bioprocess monitoring, or cleaning validation in pharmaceutical manufacturing.
- **NaCl (Sodium Chloride) –** A commonly used salt in buffer solutions, IV fluids, and pharmaceutical formulations. NaCl concentration is analyzed to ensure proper osmolarity and stability of formulations.

Types of Testing Server (4)

pH Measurement

- Determines the acidity or alkalinity of a solution.
- Essential for drug formulations, injections, and buffer solutions to ensure stability and compatibility.
- Measured using pH meters following pharmacopeial guidelines (USP, EP).

Colour and Clarity Test

- Used for visual inspection of liquids, solutions, and injections to check for colour deviations and particulate matter.
- Ensuresproduct consistency and safety in pharmaceuticals and chemicals.
- Measured against reference standards (USP, EP, JP).

Iron Identification Test

- Detects the presence of iron ions (Fe^{2+} or Fe^{3+}) in a sample.
- Commonly performed using colorimetric methods (e.g., reaction with thioglycolic acid or phenanthroline).
- Ensures compliance with impurity limits in pharmaceutical formulations.

Chloride (Cl^-) Identification Test

- Confirms the presence of chloride ions in a sample.
- Common method: Silver nitrate ($AgNO_3$) test, which forms a white precipitate of silver chloride (AgCl).
- Used in water testing, pharmaceuticals, and raw material analysis.

Density Measurement

- Determines mass per unit volume (g/mL or kg/m^3) of a liquid or solid.
- Critical for quality control in pharmaceuticals, food, and chemicals.
- Measured using densitometers, pycnometers, or hydrometers.

An Identification

- This is unclear—could you clarify if "A" refers to a specific element, compound, or assay?

UV Identification (Ultraviolet Spectroscopy)

- Uses UV-V is spectroscopy to analyse the presence and concentration of compounds.
- Identifies active pharmaceutical ingredients (APIs), purity, and impurities.
- Measured at specific wavelengths (λmax) using UV spectrophotometers.

Sodium (Na) Identification Test

- Confirms the presence of sodium ions (Na^+) in a sample.
- Common methods:
- Flame Test: Produces a yellow flame.
- Atomic Absorption Spectroscopy (AAS) or ICP-MS for precise quantification.

Types of Testing Server (5)

I Particle Size Analysis

- Determines the size distribution of particles in a formulation (e.g., suspensions, emulsions, powders).
- Techniques used:
- Laser Diffraction (Malvern Mastersizer, Sympatec, etc.)
- Dynamic Light Scattering (DLS) for nanoparticles

- Microscopy & Image Analysis
- Important for drug formulation, bioavailability, and stability studies.

II. Aluminium (Al) Testing
- Measures the Aluminium content in vaccines, pharmaceuticals, and raw materials.
- Common methods:
- Inductively Coupled Plasma Mass Spectrometry (ICP-MS)
- Atomic Absorption Spectroscopy (AAS)
- Ensures compliance with pharmacopeial limits (USP, EP).

III. Molecular Size & KD (Dissociation Constant)
- Molecular Size:
- Determined using Size Exclusion Chromatography (SEC) or Dynamic Light Scattering (DLS).
- Important for biologics, proteins, and monoclonal antibodies (mAbs).
- KD (Dissociation Constant):
- Measures binding affinity of a ligand to a target (e.g., enzyme-substrate, drug-receptor).
- Analysed using Surface Plasmon Resonance (SPR), Isothermal Titration Calorimetry (ITC), or ELISA.

IV.Free Sulphate
- Measures unbound sulfate ions (SO_4^{2-}) in a sample.
- Common methods:

V. Phosphate Levels
- Determines phosphate concentration in solutions, often in buffer systems.
- Measured using:
- Molybdenum Blue Colorimetric Assay
- Ion Chromatography (IC)
- Spectrophotometry (UV-Vis at 820 nm)
- Critical for vaccine formulations, buffer preparations, and biological studies.

VI Anti-Xa (Anti-Factor Xa Assay)
A coagulation test used to monitor low-molecular-weight heparin (LMWH) and direct Factor Xa inhibitors (e.g., Apixaban, Rivaroxaban).
Measures the ability of heparin or inhibitors to block Factor Xa, preventing clot formation.
Performed using chromogenic substrate assays or calibrated clot-based methods.

VII. Anti-IIa (Anti-Thrombin Assay)
Measures the activity of thrombin inhibitors (e.g., Dabigatran) or unfractionated heparin (UFH).
Used to assess anticoagulant therapy effectiveness.
Common method: Chromogenic Anti-IIa Assay (detects thrombin inhibition by heparin/antithrombin complex).

Types of Testing Server (6)
Osmolarity (Osmotic Concentration) Analysis
Osmolarity measures the total concentration of dissolved solutes (ions, molecules) in a solution and is expressed in Osmoles per litre (Osm/L) or milliosmoles per litre (mOsm/L).
Importance in Pharmaceuticals & Biologics
- **Parenteral (IV) Solutions –** Ensures solutions are isotonic to prevent cell damage.
- **Injectables & Biologics –** Critical for stability and patient safety.
- **Ophthalmic Solutions –** Prevents eye irritation.
- **Dialysis & Nutritional Formulas –** Helps maintain fluid balance in medical therapies.

How is Osmolarity Measured?
- Freezing Point Depression (Most Common – Osmometer)
- Vapor Pressure Osmometry
- Mathematical Calculation

$\text{Osmolarity} = \sum c_i \times n_i$
where c = concentration (mol/L), n = number of particles per molecule (dissociation factor). i=solute
Example Osmolarities:
- Blood Plasma ≈ 275–295 mOsm/L (milliosmoles/liter)
- 0.9% NaCl (Normal Saline) ≈ 308 mOsm/L
- 5% Dextrose (D5W) ≈ 252 mOsm/L

Types of Testing Server (7)
It looks like you're dealing with biochemical or pharmaceutical quality control. Here's a breakdown of the terms:

1. Protein Nitrogen
Measures the nitrogen content in proteins, which can be used to estimate protein concentration.
Common Methods:
- **Kjeldahl Method –** Digests proteins, converts nitrogen to ammonia, then quantifies it.
- **Dumas Combustion Method –** A faster alternative that burns the sample and measures nitrogen gas.
- **Biuret or Lowry Assay –** Indirect methods based on protein-nitrogen reactions.

Application: Used in food, pharmaceutical, and biotech industries to quantify protein content.

2. Formaldehyde (CH_2O) Analysis
Toxic aldehyde used as a preservative, disinfectant, and in vaccine production (as an inactivating agent).
Common Testing Methods:
- Chromotropic Acid Test – Produces a purple colour in reaction with formaldehyde.
- Spectrophotometry (UV-Vis at 580 nm) – Quantifies formaldehyde levels.
- High-Performance Liquid Chromatography (HPLC) – Detects and quantifies trace amounts.
- Gas Chromatography (GC-MS) – Used for precise identification in pharmaceutical formulations.

Application:
Ensuring safe levels in vaccines, biological products, and industrial chemicals.
Monitoring contaminants in pharmaceuticals and environmental samples.

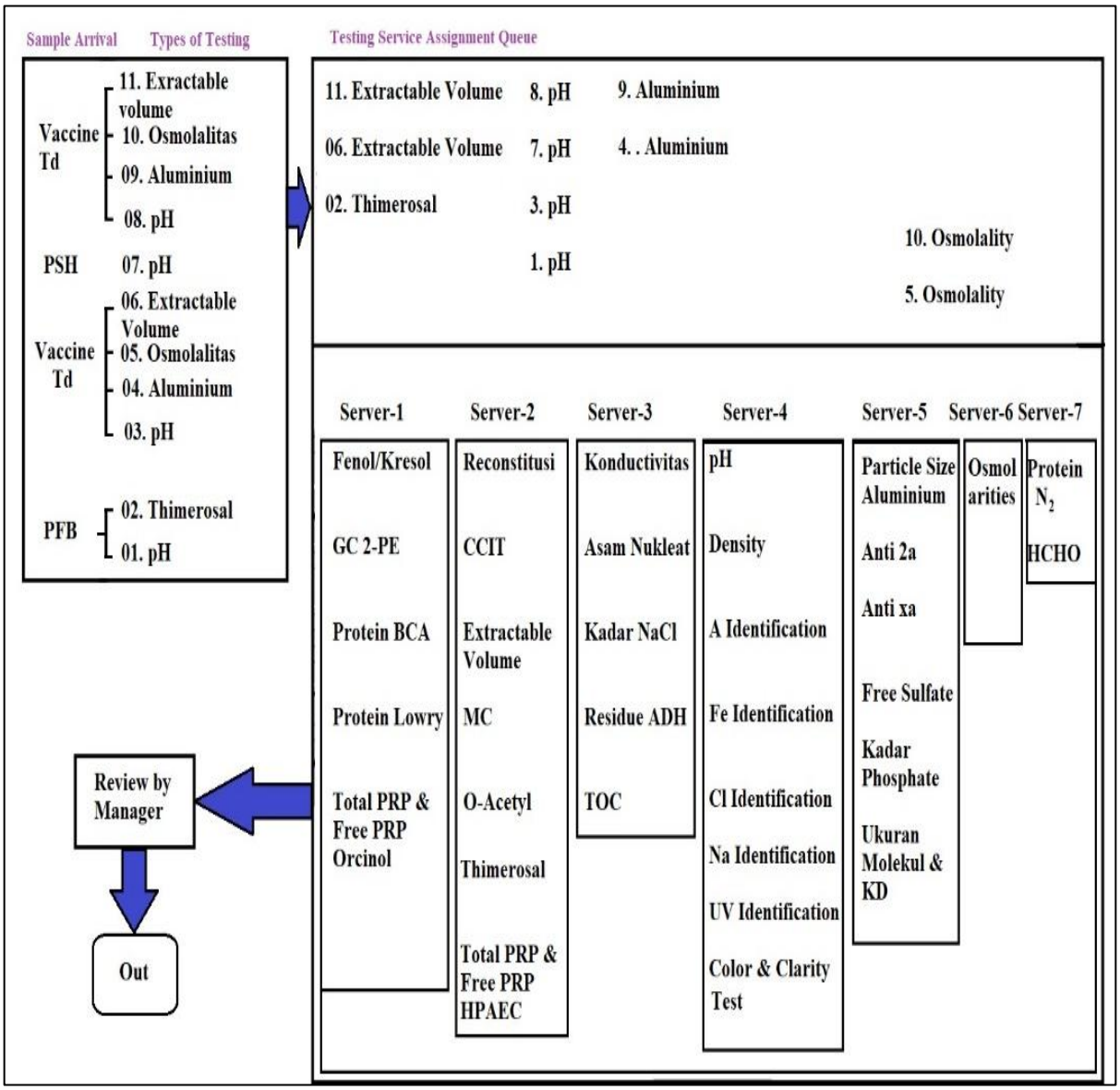

Fig.1 Flow Process of existing server arrangement

Table 2 Queuing System Performance

Measures of Queuing System Performance	**P_0**	**L_S**	**W_S**	**L_q**	**W_q**	**U**	**I**
(An already-running server)	0.0026	2.87	4.65 min	8.32	11.74min	0.35	0.72

Table 3 Queuing System Performance with Modified Server Arrangement

Performance Metrics for Queuing Systems	P_0	L_S	W_S	L_q	W_q	U	I
(Modified Server)	0.0028	2.48	2.23 min	6.54	5.35 min	0.33	0.74

Table 4 compares the performance of the current and modified server configuration. The updated queuing system's performance metrics show notable improvements:
L_S (The system's average number of tests) dropped from 2.87 to 2.48.
W_S (the average time spent by one test type in the entire system) is reduced from 4.65 minutes to 2.23 minutes.
L_q (the average number of test types in the queue) decreased from 8.32 to 6.54
P_0 (the probability of an empty system) increased from 0.0026 to 0.0028.
U Server utilization represents the fraction of time the server is busy serving customers It shows how effectively the server is being used.
I represent the probability that the server is idle, i.e., no customers are being served at that moment.

Table 4 Compares the performance of the current and modified server configuration.

Performance Metrics for Queuing Systems	**P_0**	**L_S**	**W_S**	**L_q**	**W_q**	**U**	**I**
(Present server)	0.0026	2.87	4.65min	8.32	11.74 min	0.35	0.72
(Updated Server)	0.0028	2.48	2.23 min	6.54	5.35 min	0.33	0.74

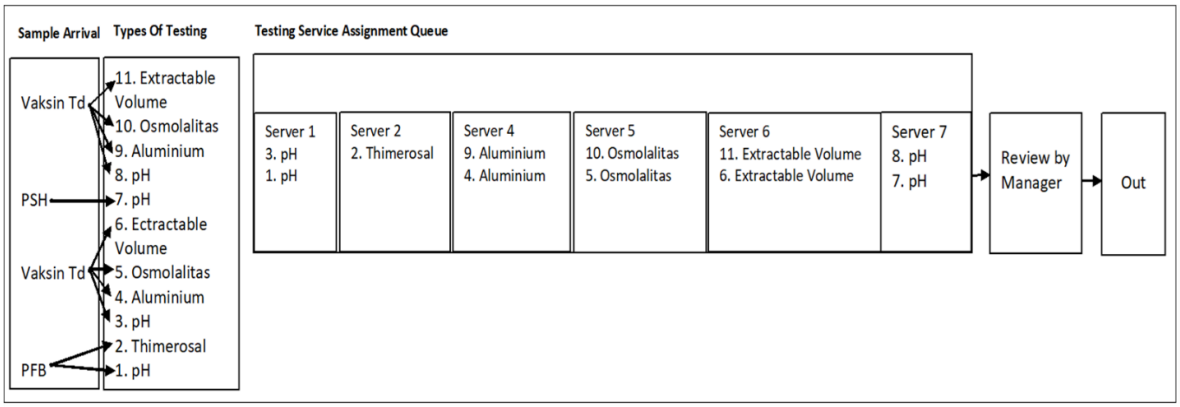

Fig. 2 Flow Comparison of Performance of serve process of modified server arrangement

DISCUSSION OUT

Previously, the server queue discipline followed the Service in Random Order (SIRO) method, where each server independently determined which test to perform first, regardless of arrival order or QC processing time. The modified server system, however, implements a Priority Services (PRI) queue, where the manager oversees the test queue, assigning available servers while considering test efficiency and QC time constraints. With the PRI queue, the delay rate is reduced to 0%, indicating greater control over the testing workflow. More regulated testing allows management to better oversee sample test types, ensuring that servers focus on service delivery without needing to coordinate test order. This improved control enables managers to directly regulate the time required for testing and enhance the efficiency of service operations. The system's average number of tests (Ls) shows a significant improvement. The improved server queue system reduced the system's average number of tests from 2.87 in the original server queue system to 2.48. This enhancement implies that a more streamlined procedure is produced by the upgraded system's increased effectiveness in handling the testing workload.

The average time spent on a single type of test across the entire system (W_S) demonstrates a significant improvement. Under the current server queue system, each test took an average of 4.65 minutes, whereas with the updated system, this time was reduced to just 2.23 minutes. This decrease in testing time indicates increased productivity and a faster turnaround in the testing process

Additionally, with the redesigned server queue system, the average number of test types in the queue (Lq) dropped from 8.32 in the original server queue system to 6.54. This decrease means that tests in the queue are waiting less time, which enables more effective use of resources and a quicker testing procedure overall.

In the updated server queue system, the average wait time (Wq) for a test was 5.35 minutes, a considerable reduction from 11.74 minutes in the original server queue system. This decrease in waiting time suggests improved testing queue management, which will cut down on delays and increase process timeliness overall.

These gains have been facilitated by the suggested change to implement a Priority Services (PRI) queue system, in which the manager manages the test queue and allocates available servers according to QC time and test efficiency constraints. The testing process is better managed by putting this queue system into place, which enables managers to effectively prioritize tests and streamline the service workflow [23,24].

Implementing the suggested improvement plan won't result in a rise in the costs of human resources. Rather, it will maximize current resources and procedures without adding to costs. There shouldn't be an increase in the cost of human resources because the changes mostly entail rearranging and reallocating the current queue system rather than installing additional servers.

According to the performance study conducted before and after the revisions, the queuing system has benefited from the improvements in terms of decision-making efficiency. This suggests that improved setup and fewer bottlenecks have preserved or perhaps increased decision-making efficiency. These results are consistent with earlier studies on queuing systems, which have shown how important effective queue management is to improving system efficiency and performance. In order to decrease queue delays and boost efficiency, for instance, priority schedules and discipline with and without interruptions are crucial in transportation systems, according to a study by [25]. Improvements that are economical and resource-efficient fit well with the idea of Innovation focused on sustainability, which is presently gaining more traction in a variety of industries [26].

Additionally, a study by emphasized how crucial it is to use resources as efficiently as possible and cut down on wait times in the healthcare sector by implementing efficient queue management techniques. Their results demonstrated that, without a method for scheduling appointments, an efficient queue management system can aid in enhancing patient flow.

The suggested strategy gives administrators crucial information in the form of the "required" number of employees, enabling them to manage the queue in advance and reduce wait times through optimal yet flexible staffing.

CONCLUSION

The results of the queuing study show that the suggested changes to the bacterial vaccination quality control procedure, such as the implementation of a queue system for Priority Services (PRI), having led to notable gains in a number of performance metrics. Better use of testing resources, shorter wait times, and increased efficiency have all been shown with the redesigned server queue system. These results highlight the significance of efficient queue management in maximizing service performance and are consistent with previous studies regarding queuing systems. The paper adds to the body of knowledge already available on queuing systems and how to use them to enhance process efficiency. Regarding bacterial vaccination quality control, it offers a particular case study that emphasizes how crucial effective queue management is to improving system efficiency as a whole. The study illustrates the advantages of implementing a queue for Priority Services (PRI) system by contrasting the current server queue system with the suggested changed server queue system. on cutting down on wait times, optimizing the use of resources, and expediting the testing procedure. The article's conclusions have real-world applications in the pharmaceutical sector, especially when it comes to quality assurance in the manufacturing of vaccines. To increase the efficacy and efficiency of the quality control procedure, the study's suggested modified server queue system can be used in actual laboratory settings. Managers can prioritize tests according to their efficiency in tests, QC time, and urgency restrictions by putting in place a queuing system for Priority Services (PRI). This ensures that crucial tests are completed on time and maximizes the use of available resources. With the help of the suggested changes, managers will be able to effectively manage the testing queue and make prompt decisions based on test priority. This can speed up essential test response times considerably and help with timely decisions about vaccine batch release or additional research. Making decisions quickly is essential to guaranteeing vaccine efficacy and safety while preserving manufacturing efficiency. Advanced queueing models that take into account differing service durations Priority levels, arrival rates, and for various tests can be the focus of future study in the area of performance improvement through analysis of queuing in the bacterial vaccine quality control procedure.

Dynamic queuing models can be enabled by the integration of real-time data, and test scheduling and resource allocation can be optimized through optimization techniques. Further improving the effectiveness, Decision-making and responsiveness abilities of the procedures for quality control can be achieved by investigating. Using queuing analysis across multiple sites integrating Artificial intelligence and machine learning approaches, and carrying out comparison research. Future studies can help create more efficient and successful quality control procedures in the pharmaceutical sector by tackling these issues. Future studies might also look at the application of artificial intelligence (AI) and machine learning (ML), which are not covered in this work. By offering sophisticated data analysis and prediction capabilities, ML and AI integration could improve operational efficiencies and further optimize the system.

Data availability the raw data is kept private due to the delicate nature of the vaccine development process.

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