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Parine’t Magkape:

A Stochastic Simulation of M/M/c/K Queueing Systems in Coffee Shop Operations

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Introduction

In the study of Quantitative Methods, the ability to transform abstract mathematical theories into functional, predictive models is a vital skill. Parine’t Magkape is a high-fidelity, web-based stochastic simulation designed to explore the intricate dynamics of queueing theory within a service-oriented environment. The name “Parine’t Magkape”—a welcoming invitation in the Tagalog vernacular—reflects the project’s focus on the local Filipino coffee shop experience, where customer satisfaction is deeply tied to the balance between a warm atmosphere and efficient service delivery.

Traditional business planning often relies on static averages, which fail to account for the “chaos” of real-world operations. In reality, customer arrivals are not synchronized, and service times vary based on order complexity and human performance. This simulation addresses those variables by utilizing Discrete-Event Simulation (DES) principles and Stochastic Modeling. By simulating these fluctuations, the project provides a “Digital Twin” of a physical café, allowing management to stress-test their operational limits.

The scope of this study encompasses the entire customer lifecycle within the digital environment: from the moment a random arrival occurs (Input), through the waiting phase (Queue), to the parallel processing by multiple baristas (Service), and finally to the resource allocation phase (Seating vs. Takeout). The scope is focused strictly on the mathematical and operational efficiency of the system, excluding geographical or location-based factors to ensure the model can be applied to any coffee shop setting regardless of its physical environment. Ultimately, Parine’t Magkape serves as a decision-support tool that demonstrates how data-driven insights can prevent service fatigue and optimize the utilization of both human and spatial capital.

Simulation Objectives

The primary goal of this simulation is to provide a quantitative framework for Parine't Magkape coffee shop operations. The specific objectives are as follows:

- **Analyze Stochastic Queue Resilience:** To observe how the system absorbs "bursts" of customer traffic using the Exponential Distribution, identifying the exact arrival density that leads to system failure.
- **Evaluate Multi-Server Efficiency:** To quantify the performance gains of parallel processing by adding multiple baristas and identifying the point of diminishing returns.
- **Model Spatial Resource Constraints:** To study the relationship between service throughput and seating availability, identifying the "Critical Pivot Point" where a shop must transition to a takeout-focused model.
- **Validate Quantitative Theory:** To demonstrate the practical application of the M/M/c/K queueing model, providing a visual bridge between complex probability formulas and real-world outcomes.

Model Design Explanation

The simulation follows the M/M/c/K Queueing Model (Markovian Arrival, Markovian Service, *c* Servers, *K* Capacity).

- **Flow:** Customers enter a FIFO (First-In-First-Out) queue. When a barista (server) becomes free, the customer is moved to the “Brewing” stage. Once service is complete, the system checks for seating availability.
- **Variables:**
  - **Independent:** Arrival Rate (λ), Service Speed (μ), Number of Baristas (c), and Max Seats (K).
  - **Dependent:** Current Queue Length, Seating Occupation, and Takeout Conversion Rate.
- **Rules and Decision Points:**
  - **Arrival Rule:** Uses a random logarithmic transform to ensure inter-arrival times follow an exponential distribution.
  - **Seating Decision:** If current_seats < max_seats, the customer occupies a seat for a fixed duration. Else, they are logged as a “Takeout” order.

System Architecture and Implementation

The website is built using a decoupled three-tier architecture:

- **Front-End (HTML5/CSS3):** A responsive dashboard featuring a “Brown Rectangle” sidebar for parameter control. The visual area uses CSS Flexbox to allow the queue to “snake” dynamically, ensuring the simulation remains readable even during high-traffic surges.
- **Back-End Logic (JavaScript):** The engine is powered by Recursive Timeouts rather than fixed intervals. This is critical for stochastic modeling, as it allows each “next event”

to be calculated with a new random variable immediately after the previous event concludes.

- **Real-Time Visualization:** Barista stations feature progress bars synchronized with the calculated service time, providing immediate feedback on the “server busy” state.

Data Description and Sources

The simulation utilizes Synthetic Stochastic Data generated through Monte Carlo-style sampling.

- **Randomness:** JavaScript’s Math.random() generates a uniform distribution [0, 1], which is then transformed using the formula $T = -\ln(1-U)/\lambda$ to create a realistic Poisson arrival process.
- **Temporal Scaling:** To allow for rapid testing, the simulation uses a scale of 1 second = 1 simulated minute. This allows a user to validate an entire hour of shop performance in just 60 seconds.

Simulation Results, Analysis, and Validation

Tests were conducted to validate the mathematical integrity of the model:

Scenario	Inputs (λ, c, μ, K)	Output	Analysis
Peak Hour	60 Arrival / 2 Barista	Queue grows rapidly and "snakes" across	**Barista Availability Failure:** The system is “Unstable ($\lambda > c\mu$). The arrival rate exceeds the total service capacity, creating a permanent

		the UI.	Service Bottleneck.
Spatial Bottleneck	20 Arrival / 3 Barista / 0 Seats	0 Queue length, but 100% Takeout conversion.	**Resource Bottleneck:** Barista availability is high, but the Physical Capacity is the constraint. The shop is forced into a 100% takeout model despite fast service.
Optimal Flow	30 Arrival / 2 Barista / 15 Seats	Low Queue, high seat usage, stable throughput.	**The "Goldilocks Zone":** Barista availability is balanced with demand. The system successfully absorbs **Stochastic Bursts** without reaching a fail state.

Validation: The model correctly predicts that increasing the number of baristas reduces the queue but does not affect the takeout rate if seating is the limiting factor. This confirms the model accurately separates service capacity from spatial capacity.

Challenges and Solutions

- **Logic Conflict:** Initially, setInterval caused “event stacking.”
    - **Solution:** Switched to recursive setTimeout to ensure each stochastic event is handled in its own thread.
- **UI Overflow:** High arrival rates caused the queue to break the screen layout.
    - **Solution:** Implemented a wrapping "snaking" logic in CSS to contain the visual queue within the dashboard.

- **Barista Concurrency:** In a multi-server environment, multiple idle baristas would occasionally attempt to process the same customer from the queue simultaneously (Race Condition).
  - **Solution:** Developed a Centralized State-Check that scans for the first available server and "locks" their status before assigning the next customer in the FIFO sequence.
- **Temporal Scaling:** Balancing a fast simulation speed for the demo while maintaining smooth, accurate visual feedback of the brewing process.
  - **Solution:** Established a Time-Scaling Coefficient (1s = 1min) and synchronized CSS transitions with JavaScript service times to ensure progress bars reflect randomized brewing durations.
- **Asynchronous Seating:** Manually tracking the specific "exit time" for every individual customer in the dining area was prone to logic errors and resource leaks.
  - **Solution:** Implemented an Asynchronous Callback Pattern where each seated customer triggers an independent timer that automatically releases the seat resource upon expiration.

Conclusion

The Parine't Magkape simulation successfully demonstrates that operational efficiency in a service environment is a delicate equilibrium of arrival rates, server availability, and spatial capacity. Through the execution of various test scenarios, the model provided clear, quantitative evidence of where and why system failures occur.

The results from the “Peak Hour” scenario confirmed the mathematical reality of a Service Bottleneck, proving that when arrival rates (λ) exceed total barista capacity (μ) no amount of seating can prevent system instability. Conversely, the “Spatial Bottleneck” test illustrated that even with high barista availability, a lack of dining resources forces a total shift in business strategy toward a takeout model. The identification of the “Goldilocks Zone” validates that for Parine’t Magkape to remain efficient, management must balance staffing levels not just for average traffic, but to accommodate the Stochastic Bursts inherent in the exponential distribution of human behavior.

Ultimately, this project bridges the gap between theoretical Queuing Theory and practical application. It stands as a robust decision-support tool, proving that a data-driven approach to barista scheduling and seating layout can significantly reduce customer wait times and optimize the overall service lifecycle of the café.

Source Code Repository

Live Demo: https://celvicanthony.github.io/parinet-magkape-simulation/

GitHub Repository: https://github.com/celvicanthony/parinet-magkape-simulation

Note: If cannot accessed, here is the google drive link for file code, documentation, and presentation.

https://drive.google.com/drive/folders/1DXyMI_DtkgsSkddET436cTlwhBQSB4VI?usp=drive_link

References

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