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Final Report: Coffee Shop Simulation Project

Introduction

A model was developed of a coffee shop in order to simulate changes in store operational scenarios and the resulting performance metrics. The operational scenarios investigated were changes in number of cashiers, number of tables, and customer arrival rates. The purpose of the study was to decide which operational scenarios would be beneficial to the coffee shop and to gain experience in modeling a dynamic system where individual entities interact with one another.

First, a baseline coffee shop model was established and characterized, 2 cashiers, and 6 tables. Key performance metrics that were used for store characterization were the following:

- Average time in register queue, average order to delivery time
    - Faster customer throughput means higher profits, and customers are more likely to enter a shop without a long line or long drink wait times
    - Affected by number of cashiers and register service time in relation to customer arrivals
- Number of lost customers
    - Lost potential customers mean lost profit
    - Affected by register queue length
- Number of reorders
    - More reorders allows the shop to gain additional profit on a customer occupying a table that could be filled by a new customer
    - Affected by number of tables and how busy the restaurant is
- Percent idle time, cashiers
    - A high percent idle time implies that a cutback in staffing may be advisable

Other interesting parameters tracked were number of customers, peak register line length, and peak drink group size.

Next, a series of questions about changing store operations were addressed. First, what would be the impact of removing a cashier? Would it increase the register queue wait time so much that potential customers would balk? Second, what would be the impact of doubling the number of tables in the restaurant? Would it significantly increase the number of re-ordering customers, and do so without otherwise affecting store performance? Finally, what if advertising were pursued that increased customer traffic by 20%? Would the store be able to handle the increased traffic without customer loss? Also, with the increased traffic, would it still be safe to remove a cashier?

All of these questions were answered by changing parameters in the coffee shop simulation model. It turns out that removing a cashier is acceptable, as is tolerating a 20% increase in customer traffic, but doing both at the same time causes unacceptable wait times and hence customer loss. Finally, it was shown that increasing the number of tables does in fact result in increased re-orders without significantly impacting other store performance metrics.

Background

Several models of restaurants and other customer service shops have been developed and analyzed in the past. Therefore, prior to starting model development, a literature search was performed. Many of the studies and articles associated with prior work dealt with efficiently setting up restaurants (positioning of preparation areas, access to store, etc) or effectively serving fast-food customers. Reference [2] does a thorough job investigating how a variety of scenarios impact performance of a fast-food restaurant. Reference [1] performs an analysis similar to my project, though (as in [2]) customers are all presumed to be "take-out" customers. In developed coffee shop model, the possibility of customers staying and affecting the system (for instance, by putting off other potential stay-in customers, or by ordering a second time) was taken into account. A coffee shop is a unique type of place in that people travel through it in many different manners: quickly taking coffee to go or sitting for a short while, sitting to enjoy a drink, staying and working after finishing the drink, or even staying and ordering another drink. This project was meant to combine the characteristics of the restaurants modeled in previous studies and tack on the additional behavior unique to a place such as a coffee shop.

System Description

The coffee shop is open between the hours of 6:00 am and 10:00 pm. Two cashiers work at the cash registers and take orders from customers, who enter the store and join a FIFO queue which splits off to the two cashiers. Cash register service times are uniformly distributed, ranging from 1 to 2 minutes. Drinks are prepared by two baristas, whose drink preparation times are also uniformly distributed, ranging from 1.5 to 5 minutes.

Customers are of two types, stay-in or take-out. Upon receipt of their order, a stay-in customer will sit at a table (if available) for an amount of time given by a random variable uniformly distributed between 5 and 60 minutes. If there are no empty seats upon a stay-in customer's drink receipt, the customer will leave. Take-out customers always leave immediately upon receipt of their order.

During their stay at a table, a stay-in customer may get up and order another beverage, conditional upon several things. First, the store cannot be very busy (the register line must contain less than 3 people). Also, the customer must have been sitting for at least 30 minutes, which gives them time to finish their first drink. Finally, not all customers are prone to ordering a second beverage – only half of the stay-in customers will re-order even if the previous 2 conditions are satisfied.

Alternatively, if the store becomes too crowded, lingering customers (those who have been at a table for more than 30 minutes) may leave the store. Specifically, if there are more than 10 people in the register and drink lines, combined, lingering customers will leave. Finally, if a potential customer arrives and observes that the register line contains more than 20 people, the customer will balk at how busy the store is and leave immediately.

To summarize, the customer lifecycle is as follows:

- Arrives at shop, waits in FIFO queue (if necessary) for a free register
- Moves to register to place order
- Moves to drink group to wait for drink
- If "stay-in" and a table is available, sits at table.
    - If still re-order conditions are met, orders another drink.
    - If crowd-out conditions are met, leaves store

- • If max stay time conditions are met, leaves store
- Otherwise, leaves store

Approach

The coffee shop simulation model was developed as a C++ console application. Performance statistics were automatically generated for the baseline operational scenario and each of the alternatives by simulating 30 days' worth of coffee shop operations. Some simplifying assumptions were made in generating the simulation model: in particular, then travel time between different parts of the store is assumed to be negligible, and cashiers and tables were assumed to be identical. An illustration of the coffee shop model implementation is shown in Figure 1 below.
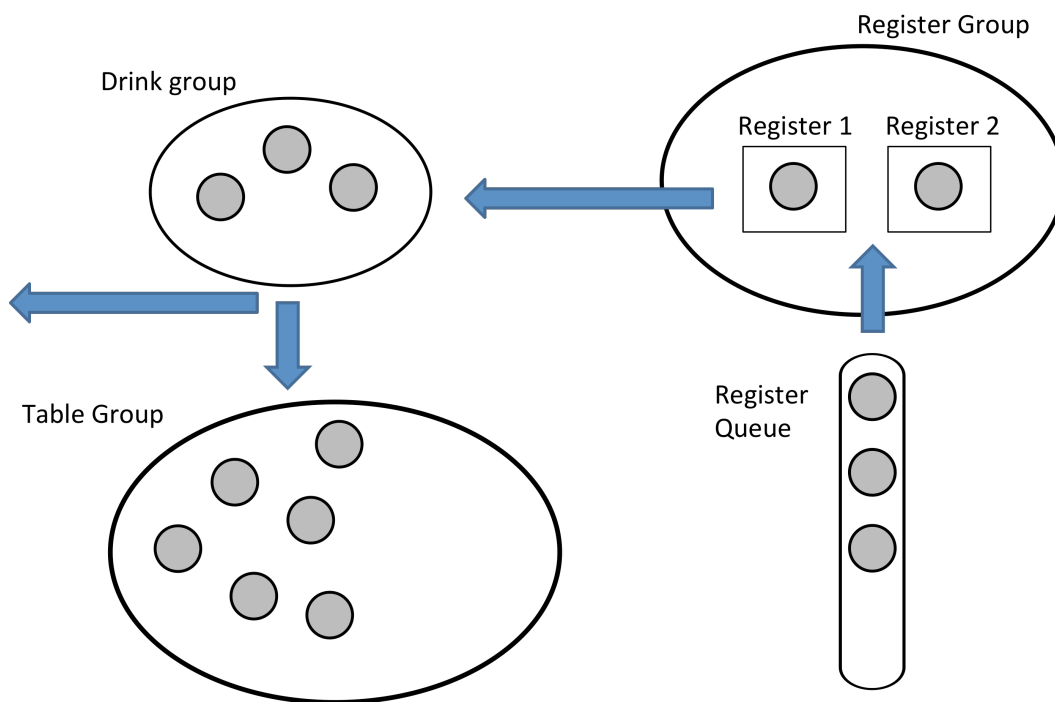

Figure 1 Coffee Shop Model Diagram

Customer entities were modeled and grouped into aggregate entities based on their activity as they flowed through the shop. Customers entering the store were added to a register queue (if needed), and once they reached a register, were moved to a register group while being served by one of the cashiers. Next, customers were moved to a drink group while waiting for their drink to be delivered to them. Finally, stay-in customers who could find a table were moved to the table group, where they stay for a length of time, and all other customers exit the store. Customer entities are associated with several attributes which were used to compute performance metrics of the coffee shop, as shown below:

Consumer Entity Class: *Customer*	
Represents customers arriving at the coffee shop	
Attributes	**Description**

stay_in	Boolean representing whether the customer is a stay-in or take-out customer (randomly decided upon arrival)
reordered	Boolean representing whether the customer reordered a drink
reorder_candidate	Boolean representing whether the customer may potentially reorder a drink (randomly decided upon arrival)
t_arrive	Time customer arrived at the coffee shop
t_start_reg	Time customer started being served at register
reg_depart_time	Time customer finished being served at register
t_drink_receipt	Time customer received their drink order
latest_t_leave	Time a stay-in customer will leave provided they don't get crowded out or decide to order another drink

The stochastic process for customer interarrival times was modeled as a piecewise homogenous Poisson process. In the modeling and simulation community, arrivals are often modeled as this type of process, where the probability of x arrivals in an interval λ is given by

$$P(x) = \frac{\lambda^x e^{-\lambda}}{x!} \; for \; x = 0, 1, 2, \dots$$

Poisson processes have inter-arrival times which are described by exponentially distributed random variables. The mean inter-arrival time, μ, for the coffee shop was selected to reflect the busier and slower times of day typical of a coffee shop, as shown in the table below.

Time of Day	Start	End	μ
Early Morning	6:00 AM	7:30 AM	2 min
Peak Morning	7:30 AM	9:30 AM	1.2 min
Late Morning	9:30 AM	11:30 AM	1.5 min
Mid Day	11:30 AM	1:30 PM	2 min
Early Afternoon	1:30 PM	3:00 PM	3 min
Late Afternoon	3:00 PM	5:00 PM	6 min
Early Evening	5:00 PM	7:00 PM	3 min
Evening	7:00 PM	9:00 PM	2 min
Late Evening	9:00 PM	10:00 PM	6 min

The shop is busiest in the morning and evening (it peaks at about 50 customers/hour) and slowest in the late afternoon. This reflects the fact that many customers come in to get their morning coffee before work and as a pick-me-up during mid-day, and the fact that many people come in to relax or do work in the evening. These estimated customer arrival rates were based on limited observations of a coffee shop in the author's hometown and conversations with some shop employees.

Results

In the modeled coffee shop, there are 2 places where bottlenecks occur. First, the register line can become too long if the customers are arriving at the store at a rate much faster than they can be served by the cashiers. Second, if the cashiers take customers' orders at a faster rate than the baristas can prepare drinks, the group of people waiting for their drinks will become quite large. The length of time between drink order and delivery time is a function of both how fast the drinks can be made and how and how many people are waiting for their drinks already.

Baseline Model Performance

- Average time in register queue: 0.2 minutes
- Average order to delivery time: 1.6 minutes
- Peak register line length: 4 customers
- Peak drink group size: 7 customers
- Number of lost customers: 0
- Percent idle time, cashier(s): 69.8%
- Number of customers: 433
- Number of reorders: 31

The baseline model of the coffee shop has neither of these problems. The average wait time for a customer is only 0.2 minutes, and the greatest number of people waiting for their drink at any given point in time is 7. Even so, the average amount of time any customer spends waiting for their drink is only 1.7 minutes. No customers are lost. However, the cashiers are idle for almost 70% of the time the store is in operation. For this reason, the first alternative explored was to remove 1 cashier and analyze the change in performance metrics.

Scenario 1: Removing a cashier

- Average time in register queue: 3.5 minutes
- Average order to delivery time: 1.0 minutes
- Peak register line length: 14 customers
- Peak drink group size: 3 customers
- Number of lost customers: 0
- Percent idle time, cashier(s): 38.3%
- Number of customers: 434
- Number of reorders: 31

Removing a cashier from the coffee shop has the obvious primary effect of increasing customer wait time. While the baseline model had an Average time in register queue of less than a minute, removing a cashier results in an Average time in register queue of 3.5 minutes. Still, the register queue never gets so long that potential customers start to balk at how busy the store is, though it peaks at a length of 14 customers. Also, notice that the peak drink group size of 3 customers is lower than in the baseline scenario. This is because the cashier controls the input rate of customers to the drink group. Since there is one less cashier, fewer customers can be processed per unit time, so baristas usually have enough time to make preceding customers' drinks before the next customer arrives. Finally, as would be expected, the sole remaining cashier is quite busy – only idle for 38.3% of the shop's operating day.

Though money could be saved on employee wages by removing a cashier, it must be carefully considered whether the experience of increased wait time will discourage customers from coming to the store in the first place, even if the line isn't yet at the assumed length required for customers to balk. In a real operational trade study, someone studying this question would likely gather further data relating to customer sensitivity to wait time and run the simulation with a stochastically modeled balking condition reflecting the more additional data.

Scenario 2: doubling the amount of tables

- Average time in register queue: 0.2 minutes
- Average order to delivery time: 1.7 minutes
- Peak register line length: 4 customers
- Peak drink group size: 8 customers
- Number of lost customers: 0
- Percent idle time, cashier(s): 67.2%
- Number of customers: 450
- Number of reorders: 54

As expected, doubling the amount of tables has little impact on any of the store performance parameters save for the number of re-orders. Since customers only get up and re-order a drink when the shop is quite empty, the coffee shop operates more or less in the same manner as the baseline scenario. However, the number of reorders increased by approximately 20. Hence, if the store has room to comfortably add more tables, it will likely result in increased profits due to customers re-ordering.

Scenario 3: Increasing the arrival rates by 20%

- Average time in register queue: 0.3 minutes
- Average order to delivery time: 2.2 minutes
- Peak register line length: 5 customers
- Peak drink group size: 11 customers
- Number of lost customers: 0
- Percent idle time, cashier(s): 62.4%
- Number of customers: 538
- Number of reorders: 35

The next theoretical scenario considered was an advertizing campaign resulting in an increase in customer arrival rates by 20%. As seen above, the average time each customer spends in the register queue only modestly increases, to 0.3 minutes from 0.2 minutes in the baseline scenario. The peak register line length also only sees an increase of 1 customer. This is because the 20% increase did not result in customer inter-arrival rates significantly higher than the average register service time. However, since the drink preparation time is a bit higher than the register service time, we do see a slight increase in the peak size of the group of customers waiting for their drink, from 7 in the baseline scenario to 11. Again, this is because the cashiers control the input rate of customers to the baristas making the drinks. For the same reason, the average order to delivery time is up from 1.6 minutes to 2.2 minutes. Finally, the percent idle time of cashiers is slightly decreased due to the increased traffic that they see in this scenario.

Scenario 4: Increasing the arrival rates by 20% and removing 1 cashier:

- Average time in register queue: 7.9 minutes
- Average order to delivery time: 1.0 minutes
- Peak register line length: 20 customers
- Peak drink group size: 3 customers
- Number of lost customers: 16
- Percent idle time, cashier(s): 28.3%
- Number of customers: 523
- Number of reorders: 26

The final scenario considered was the same as scenario 3, but with one less cashier. As is expected, the cashier percent idle time drops even lower, to 28.3%, as customer are arriving faster than in the baseline scenario and there is only 1 cashier serving. This does mean that the shop is effectively utilizing their sole cashier, who is busy most of the time, but the bottleneck that results does produce a loss in 16 customers, and the average wait time is up to almost 8 minutes from 0.2 minutes in the baseline scenario. Also, as this model assumes that cashier efficiency stays the same regardless of how busy or tired they are, which probably not the case in real life. In this case, it would be useful to consider the relative cost of lost customers vs. how much it costs to employ another cashier for busy parts of the day.

Performance Summary for All Scenarios					
Statistics	Baseline	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Average wait time	0.2	3.5	0.2	0.3	7.9
Average order to delivery time	1.6	1	1.7	2.2	1
Peak register line length	4	14	4	5	20
Peak drink group size	7	3	8	11	3
Number of lost customers	0	0	0	0	16
Percent idle time, cashier(s)	69.8	38.3	67.2	62.4	28.3
Number of customers	433	434	450	538	523
Number of reorders	31	31	54	35	26

References

[1] Curin, S. A., Vosko, J. S., Chan, E. W., and Tsimhoni, O. 2005. Reducing service time at a busy fast food restaurant on campus. In Proceedings of the 37th Conference on Winter Simulation (Orlando, Florida, December 04 - 07, 2005).. Winter Simulation Conference, 2628-2635.

[2] Farahmand, K. and Martinez, A. F. 1996. Simulation and animation of the operation of a fast food restaurant. In Proceedings of the 28th Conference on Winter Simulation (Coronado, California, United States, December 08 - 11, 1996). J. M. Charnes, D. J. Morrice, D. T. Brunner, and J. J. Swain, Eds. Winter Simulation Conference. IEEE Computer Society, Washington, DC, 1264-1271.

[3] Steven L. Jaynes , John O. Hoffman, Discrete event simulation for quick service restaurant traffic analysis, Proceedings of the 26th conference on Winter simulation, p.1061-1066, December 11-14, 1994, Orlando, Florida, United States.

[4] Gregor Hohpe, "Your Coffee Shop Doesn't Use Two-Phase Commit," IEEE Software, pp. 64-66, March/April, 2005

[5] Joo Seong-Jong, Stoeberl Philipp A., Fitzer Kristin, Measuring and benchmarking the performance of coffee stores for retail operations. In Benchmarking: An International Journal, p. 741-753. Emerald Group, Publishing Limited, 2009.

Constants		
Name	**Role**	**Value**
T_OPEN	Time the coffee shop opens for business [min]	360
T_CLOSE	Time the coffee shop closes for business [min]	1320
STAY_MIN	Minimum amount of time a stay-in customer will sit at a table [min]	5
STAY_MAX	Maximum amount of time a stay-in customer will sit at a table at once [min]	60
REG_MIN	Minimum service time at a register [min]	0.3
REG_MAX	Maximum service time at a register [min]	2
DRINK_PREP_MIN	Amount of time it takes a single barista to prepare the simplest drink order [min]	0.3
DRINK_PREP_MAX	Amount of time it takes a single barista to prepare the most complicated drink order [min]	3
DRINK_PREP_MINMAX	If there are multiple baristas, the minimum amount of time it takes to prepare the most complicated drink order [min]	1.5
LINGER_TIME	Amount of time before a customer will potentially order another drink or leave if the store gets too crowded [min]	30

Parameters	
Name	**Role**
num_cashiers	Number of cashiers working at registers at the shop
num_baristas	Number of baristas preparing drinks at the shop
num_tables	Number of tables available to customers at the shop