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Throughput Analysis of an Amazon Go Retail under the COVID-19-related Capacity Constraints

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Abstract

The throughput of a finite-capacity queueing system is the mean number of clients served during a time interval. The COVID-19 outbreak has posed a serious challenge for many commercial establishments, including the retails, which have struggled to adapt to new working dynamics. Retails have been forced to adjust their service guidelines to comply with biosecurity protocols, ensuring to observe governmental and public health policies. A significant change for the retail market has been the capacity restrictions to ensure social distancing, i.e., a limitation on the number of customers simultaneously shopping in the store. Such a constraint has an impact on the throughput that can be achieved by a retail. This article assesses the impact of the capacity restriction measures on an Amazon Go-like retail performance through a throughput analysis under COVID-19-related capacity restrictions. For the assessment, we first retrieved real data from a retail located in Cartagena, Colombia. Two scenarios were considered: i) low demand and ii) high demand. Further, we built an Amazon Go-like, two-queue, M/M/c/K retail model with a CONWIP (Constant Work-In-Process) approach, considering biosecurity-based capacity restrictions due to the COVID-19 pandemic. The R package 'queueing' was used to set up the model, and an algorithm was created to go over each sampling period and find the hourly optimum capacity and throughput under the dynamic conditions of both scenarios (low and high demand). Results from the performance analysis show that, for some operational conditions, the optimum maximum throughput is achieved with capacities below the biosecurity-based capacity, while for some other operational conditions the maximum throughput cannot be achieved with the restrictions, as the optimum capacity lies beyond the biosecurity-based capacity. These results suggest that the maximum capacity definition should not be static. Instead, it should be done considering the retail's dimensions, the biosecurity policies, and the dynamic retail's operational conditions such as the demand and service capacity.

Keywords: Queuing Theory, Jackson Networks, Amazon Go Store, CONWIP, Throughput, COVID-19.

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1. Introduction

Retails are commercial establishments visited (each) by thousands of people daily. The literature has given special focus to the service dynamics taking place within supermarkets through a queueing theory perspective. The metrics to measure a retail's performance include the throughput, waiting times, queue length, and utilization, among others, with widespread use in quantitative studies. For instance, Jhala & Bhathawala [1] have studied the operational throughput of multi-server and single-server queueing systems through M/M/2 & M/M/1 queueing system models, respectively. Morabito & De Lima [2] approached the congestion and waiting times feacturing M/M/m & $M/M/1^m$ queuing models in the brazilean retail market. Moreover, Chai [3] performed an analysis and optimization of servers' number and layout to raise efficiency and lower operational costs. Throughput is arguably the most broadly used performance metric, which Sethi et al. [4] define as the number of effectively served customers per time unit, and it is a proxy measure of the system's efficiency.

With the COVID-19 outbreak, diverse economic sectors have been affected, including the retail market, which stands as a major player in the worldwide economy [4]. Some research works have studied the impact of the COVID-19 pandemic on the retail market. For instance, Vall Castelló & Lopez Casasnovas [5] analyzed the effects of confinement measures and infection rates on supermarkets' sales in Spain. Hepp et al. [6] characterized the overall economic impact of the restrictive biosecurity-based measures on the German retail market, while Ying & O'Clery [7] proposed an agent-based model to simulate transmission events within supermarket settings. According to Ying & O'Clery [7], from March 2020 on, supermarkets have undergone policies aiming to reduce the COVID-19 transmission risk, including setting changes, mandatory mask usage, social distancing, and restrictions regarding the number of customers simultaneously shopping within the supermarket.

This article assesses the impact of the biosecurity-based capacity restrictions due to the COVID-19 pandemic on Amazon Go-like retails. The throughput dynamic response is studied through an algorithm implemented in R, featuring an M/M/c/K queueing model undergoing a CONWIP approach. Under real operational conditions, retrieved from a retail store located on the north coast of Colombia, the throughput is assessed hourly as a function of the capacity, allowing to determine the optimum capacity, i.e., the capacity that maximizes the throughput, under the dynamic (time-varying) conditions of arrival rate and service rate. Then, results for optimum capacity are compared against the capacity threshold imposed by the biosecurity restrictions. The manuscript is organized as follows: Section 2 presents the methods used for the study, section 3 shows the simulation results for both case scenarios (low demand and high demand) and discusses their implications. Finally, the conclusions and future work are presented.

Nomenclature

$1/\lambda_t$	Mean time between arrivals
$1/\mu_t$	Mean self-service time
K	Biosecurity-based maximum capacity
C	Number of parallel servers
l	Length of store
w	Width of store
d	Social distancing magnitude

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2. Methods

The methods for this article comprise four stages: *i)* Data gathering; *ii)* Biosecurity-based capacity calculation; *iii)* System modeling; *iv)* Algorithm implementation and simulation. These steps are presented in detail below.

2.1. Data Gathering

The validation data was retrieved from a primary source (i.e., a traditional retail) through direct quantitative recording. Data was recorded for one-hour periods during two 12-hour shifts. Two case scenarios were measured: *i)*

a typical low-demand day; *ii)* a typical high-demand day. The retail store from which data was retrieved is located in Cartagena, on the north coast of Colombia. The store has a walking area of $20\ m \times 20\ m$. The data gathered for both case scenarios are available at https://github.com/iportnoy1/Amazon-Go-like-Data.

2.2. Biosecurity-based Capacity Calculation

As previously mentioned in subsection 2.1, the walking area of the store is $20\ m \times 20\ m$. Additionally, due to international public health guidelines, a $1.5\ m$ social distance is to be observed within supermarket facilities [8]. The biosecurity-bases capacity threshold is then calculated with the following equation [9], [10]:

$$K = \frac{l\ w}{d^2} \tag{1}$$

Where l and w are the walking area's length and width, respectively, and d is the social distance to be observed. Using equation (1) with the abovementioned store dimensions and person-to-person distance yields a biosecurity-based capacity threshold of $K = 177$ customers.

2.3. System Modeling

The system was modeled as an M/M/c/K queueing system, as depicted in Fig. 1. In the model, arrivals and service times follow an exponential distribution. Furthermore, there are C parallel servers, and the capacity, K, is finite. Despite having C parallel servers, there are no customer queues, as they serve themselves (self-service model) while being tracked in real-time, and the list of products is automatically recorded as customers place them in the shopping cart. This shopping dynamic is similar to that featured by the M/M/∞ queue model, operating also like a self-service model [11], although the number of customers is finite and limited to K.

2.4. Algorithm Implementation and Simulation

Here, we describe the algorithm implemented in R (Version 3.6.2) to assess the hourly optimum capacity for both case scenarios. The R package "queueing" was used to set up the model, fitting it to an M/M/c/K queue system. The proposed algorithm conducts simulations (in both scenarios) with the M/M/c/K model for each sampling period, $t = 1,2,\dots,12$, using the operational conditions corresponding to each period. Furthermore, for each iteration, t, the algorithm simulates the queueing system for different capacities, using the following values: $k = 1,2,\dots,200$. Therefore, this iterative procedure allows going over a wide operational region (i.e., $\forall\ (t,k)\ |\ t \in [1,2,\dots,12]\ \&\ k \in [1,2,\dots,200]$), assessing the throughput achieved at each condition. The algorithm further plots the results period-wise, showing the throughput vs. capacity curves at each period t. Additionally, for each period, the optimal capacity (i.e., that leading to the maximum throughput) is recorded, and the algorithm creates yet another plot to show the time-evolution of the optimum capacity throughout the 12-hour shifts (for both scenarios). The source code and the datasets are freely available at https://github.com/iportnoy1/Amazon-Go-like-Data.
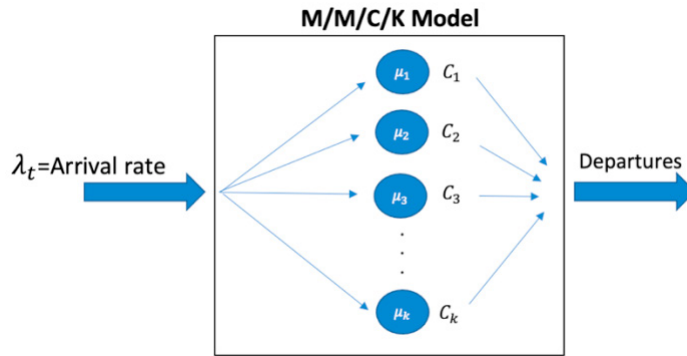
M/M/C/K Model

Fig. 1. Flowchart of the M/M/c/K model for the Amazon Go-like store.

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3. Results

After carrying out the simulations using the iterative procedure described in subsection 2.4, the period-wise Throughput vs. capacity curves and the Optimum Capacity vs. time curves were obtained. Fig. 2 shows the period-wise Throughput vs. capacity curves for the high-demand scenario, while Fig. 3 shows these curves for the low-demand scenario. In Figures 2 and 3, the vertical green line represents the optimum capacity, while the vertical red line represents the biosecurity-based capacity threshold.

From Fig. 2, it is noticeable that, for the high-demand scenario, the optimum capacity is lower than the biosecurity-based capacity threshold for some periods ($t = 1, 6, 8, 9, 10, 12$). On the other hand, From Fig. 3, it is noticeable that the optimum capacity is always lower for the low demand scenario than the biosecurity-based capacity threshold. Results displayed in Figures 2-3 show that the optimum capacity (and therefore the maximum throughput) depends on the supermarket's operational conditions, such as the arrival and service rates, and the queueing system's setting. Thus, the optimum capacity is dynamic and can switch from being below or above the biosecurity-based capacity threshold during a time window. These facts imply that a supermarket's capacity could be defined considering the operational conditions along with the biosecurity restrictions.
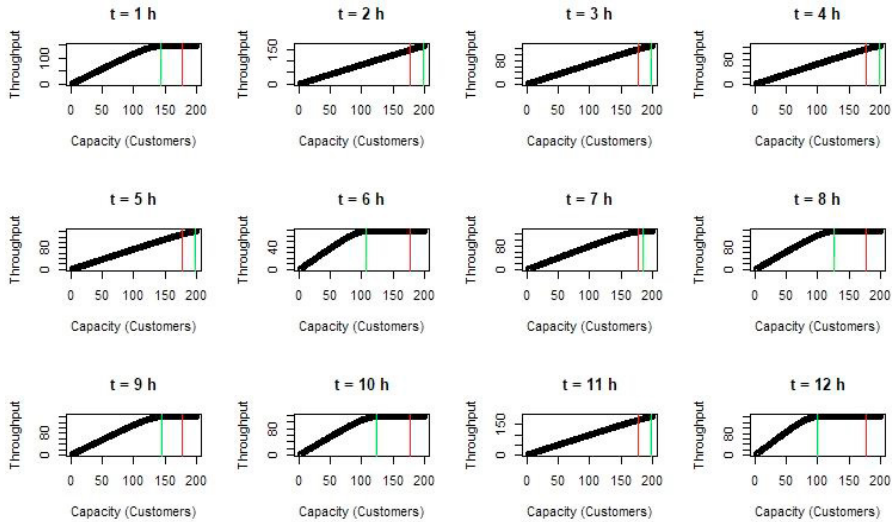
Fig. 2. Hourly Throughput vs. Capacity curves, High-Demand Scenario. Vertical green lines represent the optimum capacity, while vertical red lines represent the biosecurity-based capacity threshold.
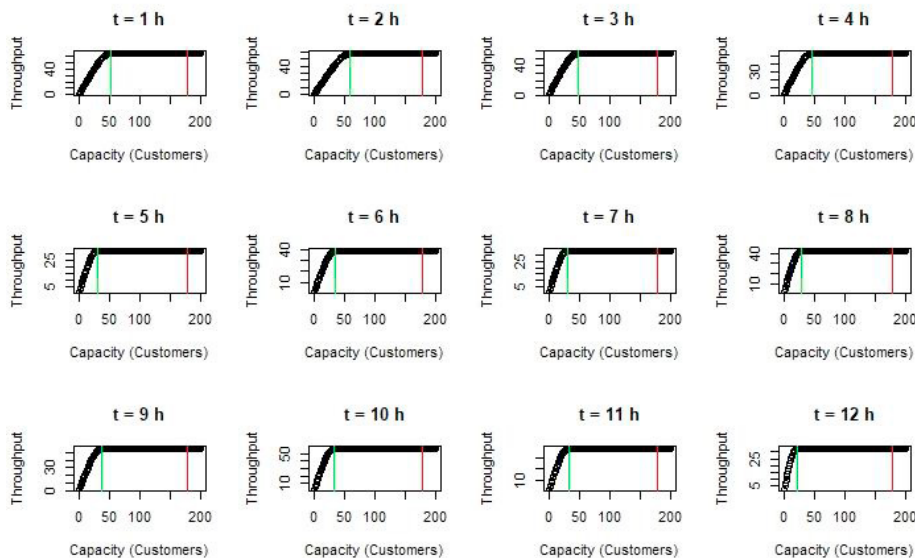

Fig. 3. Hourly Throughput vs. Capacity curves, Low-Demand Scenario. Vertical green lines represent the optimum capacity, while vertical red lines represent the biosecurity-based capacity threshold.

Considering the results, this article proposes the following thumb rule: if (for a given operational condition) the optimum capacity were determined using our proposed method yielding a value below the biosecurity threshold, it would be more cost-effective to use this optimum capacity instead of that biosecurity-based (see equation (1)). Otherwise, the supermarket's manager should stick to the biosecurity-based threshold, ensuring the public health policies compliance. Thus, this thumb rule, aided by the proposed method, constitutes a potential tool for a dynamic

decision-making scheme regarding the working capacity of supermarkets, maximizing throughput while observing the public health restrictions.

4.   Conclusions

The impact of Amazon Go-like supermarkets' capacity restrictions on their operational performance has not been fully assessed, considering dynamic (time-varying) arrival and service rates. This work implemented a model based on an M/M/c/K queueing system with time-evolving, exponential arrival and service rates. Furthermore, an iterative algorithm was implemented (in R) to assess the system's hourly performance going over a wide region of working capacity values. The algorithm yields, period-wise, the Throughput vs. capacity curves, as well as the maximum throughput, and the optimum capacity that achieves it.

The analysis was validated with real operational data from a supermarket located on the north coast of Colombia, considering two scenarios: low demand and high demand. Simulation results show that the optimum capacity can be below or above the biosecurity-based capacity threshold depending on the operational conditions. These results imply that, for some conditions, the maximum throughput can be achieved without violating the biosecurity restrictions.

The proposed analysis algorithm is a potential tool to determine in real-time the capacity to be used to maximize the throughput while complying with the biosecurity measures. This poses a paradigm change from a static to an adaptive working capacity.

The scope of this work is limited to systems with the studied configuration. Future works could extend this algorithm to supermarkets with different working settings, such as "fast casher", multiple-server systems, self-payment systems, among others.

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