Analysis on the Number of Hotel Delivery Robots Based on Queuing Theory

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Abstract: The purpose of this paper is to investigate the problem of order queue congestion caused by random arrival of orders during peak hours when hotels use robots for delivery, to optimize customer waiting time. This can determine the optimal number of robots while ensuring service quality and controlling the total cost of robots. This study selects a four-star hotel in South Korea as a case study and constructs a cost model for the order queuing system during peak hours based on queuing theory. This model comprehensively measures the application effectiveness of different numbers of robots by calculating the waiting cost per unit time of customers and the total cost per unit time of robots. To meet the diverse needs of different hotels in cost control and service quality, the model also introduces different weights, which can adjust for the differences in cost and service quality preferences of different hotel types. The research results indicate that as the number of robots increases, the total system cost shows a trend of first decreasing and then increasing. In the initial stage, adding robots can effectively reduce customer waiting time and thus lower overall waiting costs. However, when the number of robots reaches a certain critical value, the total system cost will begin to rise, mainly due to the increase in costs caused by too many robots. By identifying the lowest point of system cost and researching the optimal number of robots, the best balance between service quality and cost expenditure has been achieved. This study not only provides theoretical support for hotel managers to develop robot quantity scheduling plans during peak hours, but also promotes the application and development of robot delivery services in the hotel industry to a certain extent.

Keywords: Hotel Robots; Queuing Theory; Number of Robots; Robot Delivery; Random Orders

1. Introduction

Room service refers to delivering items to guests' rooms, which is costly [1, 2]. Hilton New York has discontinued room service, [3]. With the popularization of robot technology, many hotels have introduced robots to complete room delivery, and Aloft Cupertino and Hangzhou FlyZoo hotels are typical cases [4, 5]. Robot delivery services have advantages such as all-day operation, reduced labor costs, and maintaining social distancing, but the high costs and low service efficiency limit robots' widespread application [6-9]. Henn-na Hotel adjusted its robot strategy due to inadequate service [10]. Service quality is the key to a hotel's competitive advantage [11]. But when the number of robots is insufficient, the random arrival of orders will increase customer waiting time and reduce customers' satisfaction. There are only three existing studies on the number of robots in hotel, including two papers from the Lee's team and one paper from Liu's team [12-14]. Although they have made some progress in the research on the number of robots, they have not fully considered the handling of random orders and instead conducted research based on fixed known orders. The Lee's team suggested manually handling sudden orders, but this would result in a heavy workload during peak periods, while the Liu's model lacks flexibility [12-14]. Therefore, further research is needed on the optimal number of robots when orders randomly arrive during peak hours to balance service quality and cost, to more effectively respond to the demand for sudden orders.

The hotel robot delivery system can be abstracted as a queuing system, combined with queuing theory to optimize the number of robots and reduce customer waiting time. Queuing theory is widely used in fields such as transportation scheduling, healthcare, banking, and warehousing, which helps to arrange resources rationally, reduce waiting time, and improve service quality [15-17]. This paper regards the hotel robot delivery system as a queuing system with orders as "customers" and robots as "service mechanism". Based on the multi service mechanism queuing model (recorded as M/M/C queuing model) and the model of Lee's team's research the waiting time of customers throughout the entire process is calculated [12]. By separating order queue time and customer waiting time, a customer waiting cost model is established, and the optimal number of robots is determined based on the total hotel cost. By adjusting the weight, this paper further optimizes the number of robots to meet the needs of cost control and service quality in different hotels.

2. Mathematical Models Related to Hotel Delivery Robots

2.1 Problem Description

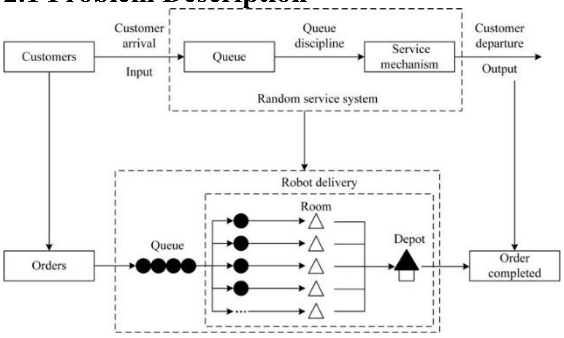

Figure 1. Queuing Model of Hotel Delivery Robot System

This paper aims to analyze the total cost of hotel robot delivery systems to determine the optimal number of robots during peak hours. During peak hours, a shortage of robots can lead to order delays and affect customer satisfaction. However, an excessive number of robots increases costs, wastes resources and burdens management. This paper regards orders as "customers" in the system, robots as " service mechanism", and abstracts the problem as an M/M/C queuing model with multiple service mechanisms. The specific corresponding relationship is shown in figure 1. To simplify the model, it is assumed that the robot undertakes single task delivery, with orders randomly arriving and following a Poisson distribution, without considering concurrent orders. The order adopts the First Input First Output queuing rule. After the robot completes the task, it returns to the depot to receive the next order. If there are no available robots, the orders need to wait. Assuming that the robot service time follows a negative exponential distribution and does not consider the impact of congestion during the delivery process.

2.2 Model Construction

2.2.1 Queuing model of hotel delivery robot system

λ represents the order arrival rate, following a Poisson distribution. μ represents the average service rate of a robot, following a negative exponential distribution. c is the number of robots. ρ is the system service strength, and when ρ <1, it will not form an infinitely long queue. L_s and L_q respectively represent the average number of orders and the average number of waiting orders. W_s and W_q represent the average stay time and average queue waiting time of the order. W_c is the actual waiting time of the customer. P_n and P_0 respectively represent the probability of n orders and the probability of no orders in the system. Based on the above analysis and assumptions, according to the relevant theories of queuing theory M/M/C models, the following equations (1) to (8) can be derived.

$$\rho = \frac{\lambda}{c\mu} \tag{1}$$

$$P_0 = \left[\ \sum_{n=0}^{c-1} \frac{(\lambda/\mu)^n}{n!} + \frac{(\lambda/\mu)^c}{c!}\left(\frac{c\mu}{c\mu-\lambda}\right)\right]^{-1} \tag{2}$$

$$P_n = \begin{cases} \frac{(\lambda/\mu)^n}{n!} P_0\ ,\ n \le c \\ \frac{(\lambda/\mu)^n}{c!c^{n-c}} P_0\ ,\ n > c \end{cases} \tag{3}$$

$$L_q = \sum_{n=c+1}^{\infty} (n-c) P_n = \frac{(\lambda/\mu)^c \lambda\mu}{(c-1)!(c\mu-\lambda)^2} P_0 \tag{4}$$

$$L_s = L_q + \frac{\lambda}{\mu} \tag{5}$$

$$W_q = \frac{L_q}{\lambda} \tag{6}$$

$$W_s = W_q + \frac{1}{\mu} \tag{7}$$

2.2.2 Model of average service time for delivery robots

To estimate the delivery efficiency of the robot, this paper uses the mathematical model proposed by Lee et al. to calculate the average delivery time per order for the robot [12]. The scenario description used by

Lee et al. is as follows: the first floor consists of a lobby and a robot depot, with the elevator on the left [12]. Robots can move from depot to elevator location and take the elevator to reach each floor's rooms, with only one row of rooms on each floor. There are three types of rooms in total, and the distance between each type of room is the same. The specific model diagram can be found in Lee et al.'s study [12]. Firstly, the time that it takes for the robot to move from the depot to the elevator is calculated by dividing the distance d_{ed} between the two by its horizontal movement speed (v_h), expressed as d_{ed}/v_h. Next, the time for the robot to wait for the elevator to arrive and enter or exit the elevator is represented as t_w and t_r respectively. The elevator running time is calculated based on the floor spacing (h) and elevator speed (v_v), expressed as $(n-1)h/v_v$. The time from the elevator to the room depends on the horizontal distance (d_{enm}) from the room to the elevator divided by the speed of movement, expressed as d_{enm}/v_h. The time for customers to retrieve items is expressed as t_c. The overall delivery time is the sum of the time for each step, as shown in equation (8).

$$ts_{nm} = 2\left(\frac{d_{enm}}{v_h} + \frac{(n-1)h}{v_v}\right) + 2tw + 4tr + tc + 2\frac{d_{ed}}{v_h} \tag{8}$$

Considering that there may be different service times for robots to deliver to different floors, this paper uses the average time to represent the time required for robots to deliver an order. By summing up the total operation time of each task served by the robot in each room and dividing by the total number of rooms, as shown in equation (9).

$$E(ts_{nm}) = \frac{\sum_{n=2}^{N}\sum_{m=1}^{m_n} ts_{nm}}{\sum_{n=2}^{N} M_n} \tag{9}$$

μ is the number of deliveries per unit time of the delivery robot (also known as the average service rate of a robot), which is the reciprocal of the average delivery time of a delivery by the robot, as shown in equation (10).

$$\mu = \frac{1}{E(ts_{nm})} \tag{10}$$

2.2.3 Customer waiting time analysis and calculation model

This section focuses on the process of robot delivery orders in hotels and analyzes its time composition. It shows in figure 2 the analysis from the perspectives of robots and customers, with hotels and customers as the main part, and robots and orders as intermediaries. The time required for the robot's perspective includes waiting in order queue, delivery, receive, and order completion time. The customer perspective includes waiting time before delivery, waiting time during delivery, and receiving time. Calculate the average customer waiting time W_c as shown in equation (11), where T_c is the average service time of the robot.

$$W_c = W_q + \frac{1}{2\mu} - \frac{T_c}{2} \tag{11}$$

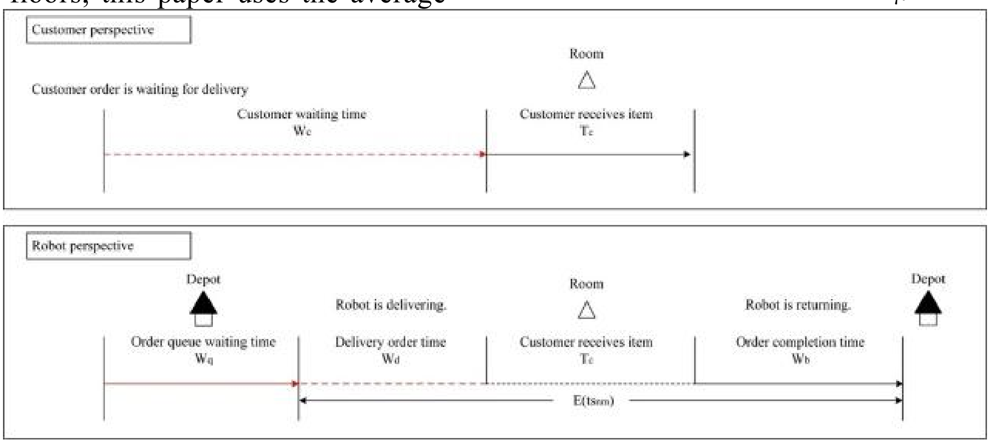

Figure 2. Time Composition Diagram

2.2.4 Analysis model for quantity demand of hotel delivery robots

During peak hours, due to insufficient supply of robots, some orders must queue, which prolongs customer waiting time and increases customers' waiting costs, expressed as F_c. Therefore, in economic analysis, it is necessary to calculate the cost of customer loss.

Assuming that the loss cost is equivalent to the customer's unit time room rate at the hotel, this measures the opportunity cost of customer waiting. This paper constructs a waiting cost model for customer per unit time in a hotel robot logistics system, as shown in equation (12).

$$F_c = \lambda \times W_c \times Z_c \tag{12}$$

According to Little's law, $\lambda \times W_c$ is the number of customers waiting in the system.

Hotels use robots for delivery to improve service quality, which incurs operating costs and maintenance costs during operation. The more robots there are, the higher the cost of purchasing them. Therefore, it is necessary to construct a unit time total cost F_r model, as shown in equation (13).

$$F_r = c \times Z_r + \rho \times c \times Z_y \tag{13}$$

The total cost of using delivery robots in hotels and customer waiting costs show a contradictory trend. The optimal objective of the hotel robot delivery system is achieved when the sum of customer waiting costs and total hotel costs is minimized. A corresponding robot quantity objective function can be established, as shown in equation (14). F is the total cost per unit time of the system, Z_c is the customer waiting cost per order unit time, Z_r and Z_y are the unit purchase and operating costs of the robot, respectively.

$$F = \omega_1 \times F_r + \omega_2 \times F_c = \omega_1 \times \rho \times c \times Z_y + \omega_1 \times c \times Z_r + \omega_2 \times \lambda \times W_c \times Z_c \tag{14}$$

3.Case Analysis

3.1 Case Background

Lee et al. described a four-star hotel in South Korea with a total of 117 rooms: standard rooms on floors 2-8 (room spacing of 4 meters), deluxe rooms on floors 9-12 (room spacing of 5 meters), and suites on floors 13-15 (room spacing of 8 meters) [12]. The distance from the warehouse on the first floor to the elevator is 6 meters, and the distance between floors is 4 meters. The average time for the robot to complete a single task is calculated to be 8.2 minutes, and the average service rate μ per hour is 7.3 times. According to Liu et al.'s study, the unit service cost of robots is $1 per hour, with an annual maintenance cost of $800, so the operating cost is $1.02 per hour [14]. The cost of purchasing a robot is $10000, and it is calculated at $0.27 per hour based on five-year depreciation. The waiting cost for customers is calculated based on full occupancy, with standard room, deluxe room, and suite prices of $184, $208, and $290, respectively. The cost per hour of waiting is approximately $8.51. This paper assumes an hourly order arrival rate of 30 orders.

3.2 Numerical Results and Analysis

3.2.1 Analysis of the optimal number of robots

Based on the above parameter settings, Matlab2022a was used to establish a simulation program to calculate the system objective function and various indexes under different numbers of robots through the hotel robot number model, as shown in table 1. figure 3 shows that with the increase in the number of robots, the customer waiting cost first decreases and then stabilizes, while the total system cost first decreases and then gradually increases. In this section, $\omega_1 : \omega_2$ is 0.5:0.5. When the number of robots reaches a certain level, the customer waiting cost stabilizes. The total hotel cost increases mainly due to the increase in the number of robots, which leads to an increase in the total system cost. During the peak hours, according to Lee et al.'s method in 2020, about 5 robots can complete these tasks, but the customer waits for 0.144 hours on average, when the system cost is the highest. According to this paper's method, when the number of robots is increased to 9, the total cost is the lowest (F=10.025), the customer waiting time is 0.053 hours, and the average stay time for orders is 0.137 hours. The service intensity ρ=0.457 indicates that the robot can meet the order requirements well and maintain appropriate idle time.

3.2.2 Analysis of the optimal number of delivery robots considering changes in weight

Through analysis, it was found that the optimal number of robots showed significant changes under different weight ratios, as shown in figure 4. When the weight of ω_1 is low and the weight of ω_2 is high (e.g. 1:9), the system needs more robots to ensure high service quality. On the contrary, when the weight of ω_1 increases and the weight of ω_2 decreases (e.g. 9:1), the system tends to reduce the number of robots to lower costs. When the weights are balanced (e.g. 5:5), the optimal number of robots is at an intermediate level (about 9), indicating that the system has found a balance point between cost and service quality. Hotels can dynamically adjust these two weights according to their own strategic goals, optimize number of robots and improve customer satisfaction.

Table 1. Objective Function and System Metrics for Different Number of Robots.

c	ρ	L_q	L_s	W_s	W_q	W_c	F	F_c	F_r
5	0.822	2.756	6.866	0.229	0.092	0.144	5.542	36.687	21.114
6	0.685	0.679	4.788	0.160	0.023	0.075	5.812	19.020	12.416
7	0.587	0.215	4.324	0.144	0.007	0.059	6.082	15.063	10.572
8	0.514	0.071	4.181	0.139	0.002	0.054	6.352	13.837	10.095
9	0.457	0.023	4.133	0.138	0.001	0.053	6.622	13.429	10.025
10	0.411	0.007	4.117	0.137	0.000	0.052	6.892	13.301	10.096
11	0.374	0.002	4.112	0.137	0.000	0.052	7.162	13.250	10.206
12	0.342	0.001	4.110	0.137	0.000	0.052	7.432	13.225	10.328
13	0.316	0.000	4.110	0.137	0.000	0.052	7.702	13.225	10.463
14	0.294	0.000	4.110	0.137	0.000	0.052	7.972	13.225	10.598
15	0.274	0.000	4.110	0.137	0.000	0.052	8.242	13.225	10.733
16	0.257	0.000	4.110	0.137	0.000	0.052	8.512	13.225	10.868
17	0.242	0.000	4.110	0.137	0.000	0.052	8.782	13.225	11.003
18	0.228	0.000	4.110	0.137	0.000	0.052	9.052	13.225	11.138
19	0.216	0.000	4.110	0.137	0.000	0.052	9.322	13.225	11.273
20	0.206	0.000	4.110	0.137	0.000	0.052	9.592	13.225	11.408
21	0.196	0.000	4.110	0.137	0.000	0.052	9.862	13.225	11.543
22	0.187	0.000	4.110	0.137	0.000	0.052	10.132	13.225	11.678
23	0.179	0.000	4.110	0.137	0.000	0.052	10.402	13.225	11.813
24	0.171	0.000	4.110	0.137	0.000	0.052	10.671	13.225	11.948
25	0.164	0.000	4.110	0.137	0.000	0.052	10.942	13.225	12.083
26	0.158	0.000	4.110	0.137	0.000	0.052	11.213	13.225	12.219

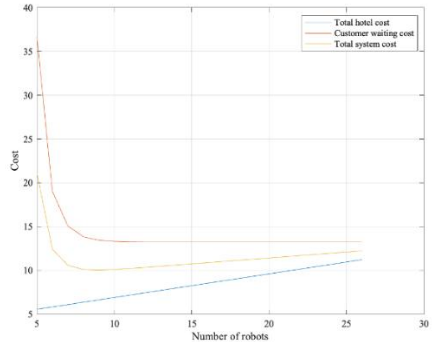

Figure 3. Relationship between Cost and Number of Robots

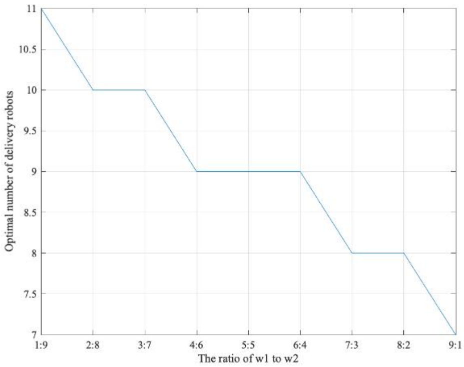

Figure 4. Changes in the Optimal Number of Robots under Different Ratios of ω_1 and ω_2

4. Summary

After the COVID-19, hotels widely use robots to replace tedious room service work. However, the three existing papers have revealed the limitations of robot services, particularly the lack of consideration for order randomness. This paper found through data analysis of a four-star hotel in South Korea that as the number of robots increases, the system cost shows a trend of first decreasing and then increasing as the number of robots increases. The marginal cost method can determine the optimal number of robots corresponding to the lowest total system cost. The results indicate that considering total system cost more effectively addresses the random arrival of orders and peak congestion, optimizing the relationship between hotel cost expenditures, customer waiting cost, and the number of robots. In addition, hotels can adjust weights according to their own business goals, achieving a balance between customer satisfaction and cost control, flexibly configuring the number of robots, and accurately. Future research can further optimize task allocation for random and scheduled orders, as well as the application of multi capacity robots.

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