4-1-2006

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Recommended Citation

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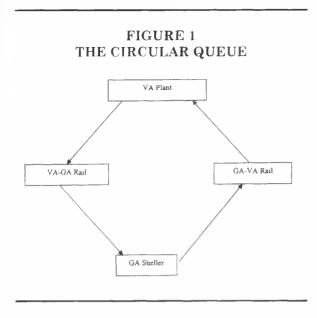James A. Pope
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ABSTRACT

A manufacturer leases rail cars to transport raw material from the supplier to the factory. The manufacturer must balance the costs of leasing rail cars versus stockouts (leading to plant closings) and inventory carrying costs. Using a model of circular queues and a simulation, the cost implications of leasing different numbers of rail cars are analyzed. It is concluded that stockout costs exceed the cost of excess inventory and capacity in the logistics system.

INTRODUCTION

Transporting raw materials to a production facility would seem to be almost trivial when the final product requires only one primary raw material. While the process is not as involved as a multi-level bill of materials system, there are still a number of variables with which one must deal, particularly in the logistics system. In this case, the raw material, peanuts, are transported from a sheller near Columbus, Georgia, to Portsmouth, Virginia, to be converted into peanut butter. The transportation is via railroad—a distance of about 700 miles. The manufacturer is currently required to lease rail cars, which are then moved from Georgia to Virginia full of raw, shelled peanuts, and

returned to Georgia empty. The question the plant manager faces on a regular basis is how many rail cars to lease?

Analytically, the system faced by the plant manager is a circular queueing system. As explained in Appendix A, this is a special case of a Jackson network (see Figure 1). In the usual queueing process, customers enter the system, are served and leave the system. In our case, the rail cars leased by the company moved in a continuous loop. The rail cars are "served'" in Georgia when they were loaded with peanuts, in Virginia when they are unloaded at the plant and en route in both directions. Appendix A describes briefly the analytical construction of the problem.

FIGURE 1
THE CIRCULAR QUEUE

There are numerous examples in the literature of analytic solutions to rail car scheduling (Cordeau, Soumis, and Derosiers, 2000; Lüübbecke and Zimmermann, 2003; and Sherali and Maguire, 2000). Although the objective here was to solve for the optimal number of rail cars, an analytical solution was not a practical option for several reasons. The first is the limitation of Jackson networks for predictive purposes (see Appendix A); the second is the nature of the data. The probability distributions of service times were empirical distributions. Using theoretical distributions would have made the problem computationally more attractive, but less realistic. Third, the company did not want to release cost figures. Therefore, results could only be stated as trade-offs in terms of numbers of rail cars and number of days the plant would be shut down. Given the results, however, the company could easily calculate the corresponding total costs. Finally, the company wanted the flexibility to test easily a variety of scenarios. For these reasons, it was decided to use simulation as the method of dealing with the problem. It was also easier to explain the process and results to the plant manager. Further, the plant manager could watch the outcomes develop as the simulation was running and could run the simulation with various scenarios.

THE PROBLEM

The peanut butter manufacturer in Virginia (VA) required an average of 180,000 pounds of peanuts per day to keep the line running. Rail cars carrying 190,000 pounds of peanuts each supplied the plant. The rail cars queued up at the plant waiting to be unloaded. Any time the queue was empty, the plant had to be shut down at a corresponding substantial cost. If there were too many rail cars in the queue, it could cause a problem, especially in the summer. Peanuts are a live organic product and could spoil if left sitting in the sun too long. Although the company could provide no specific data for this problem, management asked that the solution tell them the length of the queue at the plant and the mean number of days in the queue.

The peanuts are purchased from a sheller in Georgia (GA). The sheller buys raw peanuts from the farmers, shells them, and loads them in the hopper cars. Since the sheller maintains an inventory of peanuts, there is virtually no queue at the sheller except on weekends. A rail car arriving at the sheller is loaded and sent on its way. The plant in VA operates seven days per week; the sheller in GA operates five days per week. In other words, during the five days per week the sheller is operating, it is assumed that the queue time is zero. On the weekends, the queue time is one or two days, depending upon whether the rail car arrives on Sunday or Saturday. Except for the weekends, the company had no record of the sheller ever being a cause of delay.

The travel time between the sheller and the plant (and the return trip) varied widely. The rail cars were sent from the sheller to a rail yard, where they waited until a northbound train was formed. When they reached Virginia, they were once again taken to a rail yard, where the train was broken down. The peanut cars then had to wait for a switching locomotive to take them to the plant. It was assumed that the rail cars arrived at the destination server in the same order in which they left the source server. In other words, no passing was allowed. The travel

times both ways varied according to the following empirical probability distribution, with the average (mean) time in both directions equal to 7.9 days (see Table 1). Since a simulation was used instead of an analytical solution, there was no need to attempt to fit the data to a theoretical probability distribution.

The rate of consumption of the peanuts at the plant depended upon the availability of machines, workers, other raw materials as well as the master schedule provided by company headquarters. The output of the plant was measured in cases of peanut butter. Each case required eighteen pounds of peanuts. The consumption of peanuts and production of peanut butter varied randomly according to an empirical probability distribution with mean consumption equal to 181,260 pounds (see Table 2).

Since the plant manager thought in terms of cases produced, this is how production is entered into the simulation program. It is a simple matter to convert from cases produced to total pounds—the unit of measure for shipping the peanuts. The third column represents the method of eliciting probability estimates from the plant manager. The manager was asked to state the number of days that the plant would most likely have the associated production level in any given two week period. This information was verified from plant production records. The second and fourth columns are those actually used by the simulation.

TABLE 1
RAIL TRAVEL
PROBABILITY DISTRIBUTION

Days	Probability
5	0.01
6	0.18
7	0.27
8	0.25
9	0.13
10	0.09
11	0.03
12	0.04

TABLE 2
PEANUT CONSUMPTION
PROBABILITY DISTRIBUTION

Average Cases	Production Pounds	Days per 14 Days	Probability
0	0	0.0	0.0
1,000	18,000	0.0	0.0
2,000	36,000	0.14	0.01
3,000	54,000	0.28	0.02
4,000	72,000	0.28	0.02
5,000	90,000	0.42	0.03
6,000	108,000	0.56	0.04
7,000	126,000	0.84	0.06
8,000	144,000	0.98	0.07
9,000	162,000	1.40	0.10
10,000	180,000	1.96	0.14
11,000	198,000	2.24	0.16
12,000	216,000	2.10	0.15
13,000	234,000	1.82	0.13
14,000	252,000	0.84	0.06
15,000	270,000	0.14	0.01

THE SIMULATION

At the time this research was conducted, the company was using twenty-five rail cars. Although the plant manager was satisfied with 25 cars from the point of view of keeping the factory operating, it was of interest to know if it would be economical to reduce the number of cars. In consultation with the plant manager, it was decided to run simulations for ten through twenty-six rail cars. This would yield seventeen data points for plotting the graphs. The company could then calculate the trade-offs. For each number of rail cars, a sample of size 30 was generated. Each of the 30 items in each sample

was generated by a simulation of 2000 days—slightly over five years.

Both Banks and Carson (1984) and Thesen and Travis (1992) emphasize the importance of minimizing initial bias. Banks and Carson (1984) state that there is no analytical method for doing so, but suggest setting the initial conditions as close to reality as possible. To this end, the rail cars were evenly distributed at the plant and the sheller. The plant had sufficient inventory of peanuts to avoid running out before new shipments arrived, and new shipments could be made from Georgia without the initial wait for empty cars. The initial conditions slightly increased the queue sizes at the two locations, but over 2000 days, the effect would be minimal. Since the system stabilizes so quickly, there was no need to distribute cars en route.

The simulation was written in third generation software of a specific simulation software. This choice was made to provide flexibility for the plant manager, and to provide easy portability of the software to workstations at the plant. Each run generated a number of statistics including the following data: (See Figure 2).

- Average length of each queue
- Mean number of days in each queue
- Number of days the plant was shut down for lack of raw materials

FIGURE 2
DISPLAY OF ONE SIMULATION RUN

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            PEANUT TRANSPORTATION SIMULATION RESULTS

Day = 2000    Number of cars in the system =        25
                 Length of Portsmouth queue =        15
              Scheduled for production today =    162000
                   Amount left in lead car =     62000
     Length of Portsmouth-Georgia Rail queue =        5
                  Length of Georgia queue =         0
     Length of Georgia-Portsmouth Rail queue =        4
           Cumulative days out of material =         0
------------------------------------------------------------
               AVERAGE STATISTICS FOR 2000 DAYS

        Number of rail cars in system      =    25
        Average queue length at Portsmouth =    8.2 rail cars
        Mean Days in Portsmouth queue      =    8.7 days
        Average rail queue length, P-G     =    5.6 rail cars
        Mean Days in P-G rail queue        =    8.4 days
        Average queue length at Georgia    =    0.3 cars
        Average rail queue length, G-P     =    5.8 rail cars
        Mean Days in G-P rail queue        =    8.9 days
        Total Days out of material         =    0 days (0.0%)
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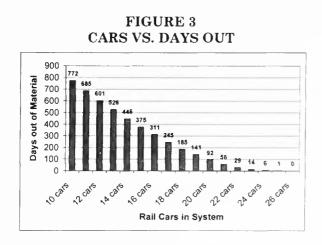
THE RESULTS

As already stated, the actual system was being operated with twenty-five rail cars at the beginning of the study. This was the "way they had always done it," but the new plant manager wanted to challenge that assumption. The results from the simulation with 25 cars were used to validate the system (Fishman, 1973). The days out, queue length in Virginia, and average time in the queue in Virginia were consistent with actual observations at the plant and with data provided by the plant manager for the twenty-five car case.

Figure 3 shows the average number of days out of 2000 the plant would be shut down for each number of rail cars in the system. It varies from 772 (38.6 percent of the days) for ten rail cars to 0.4 (rounded to zero on the graph) for twenty-six. The 95 percent confidence interval ranges from ±28.59 for the average 772 days with ten rail cars to ±2.21 for the average 0.4 with 26 rail cars. Decreasing the number of days the plant must close has a cost, however. Although the actual cost of leasing rail cars was not known, the queue at VA serves as a surrogate. This is because as long as the cars are moving, they are being productive. When they are in the queue at the plant, they and their contents are in inventory and are thus simply adding to carrying costs.
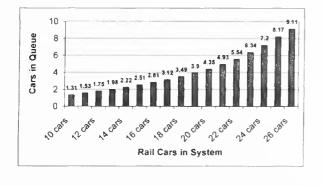
As shown in Figure 4, the average number of cars in the VA queue (at the plant) ranges from 1.31 when ten cars are in the system to 9.11 when 26 cars are in the system. In percentage terms, the queue ranges from 13.1 percent of the ten rail cars in the system to 35 percent of the 26 cars in the system. While the number of cars in the system went up by 260 percent, the average number of cars in the queue went up by 595 percent. In other words, the increase in the cost of holding inventory at the plant has been more than twice as much as the cost of leasing rail cars. These two costs together must be traded off against the cost of closing the plant for lack of materials.

FIGURE 3
CARS VS. DAYS OUT

As shown in Figure 6, the average time on the GA-VA rail route (or queue), for example, increases slightly as the number of cars in the system increases. This is caused by the rule that cars may not pass each other. Otherwise, the average time would remain the same for all cases. In similar fashion, under the fill rule at Georgia (fill a car as soon as it arrives), the average queue length there increases slightly from 0.2 to 0.4 cars as the number of cars in the system increases from 10 to 26. This is because the supplier works only five days per week; so, with more cars in the system, the weekend queue becomes longer.

FIGURE 4
LENGTH OF VA QUEUE

FIGURE 5
DAYS IN VA QUEUE

FIGURE 6
DAYS IN GA-VA QUEUE

The average time spent in the VA queue shows similar results. As shown in Figure 5, the average number of days per rail car spent in the VA queue ranges from 2.65 days for 10 cars to 9.63 days for 26 cars. Since the GA queue and the transit times are relatively constant no matter how many cars are in the system, the average rail car spends approximately thirteen percent of its time in the VA queue when ten cars are in the system and approximately thirty-four percent when 26 cars are in the system. The average time spent en route is the same in both directions since they are driven by identical probability distributions.
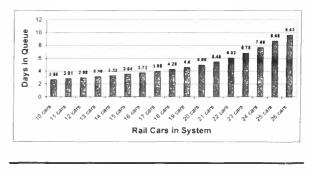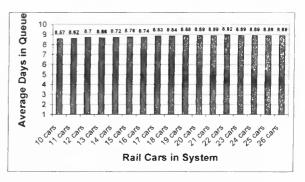
RECOMMENDATIONS

Without actual cost figures, it appears that twenty-five or twenty-six is, in fact, the best number of cars to lease. More than twenty-six would be unnecessary since the plant would almost never shut down with twenty-six in use. To make a decision, the company should inject actual costs into the calculations and make the trade-offs. Management must be careful to include all the relevant costs. The cost of the rail cars must include not only the cost of leasing that number of cars, but must also include the cost of holding the additional peanut inventory in the queue at the plant.

To gain insight into what the decisions should be, the authors independently contacted a rail car leasing company. Hopper cars of the type used by the peanut butter manufacturer would cost $325 per month on a five-year lease or $340 per month on a three-year lease. This includes maintenance, a liner to keep the peanuts clean, and a hatch to allow unloading from the top of the hopper car. Each car would cost, assuming a five-year lease, $3900 per year to lease. Twenty-five cars would cost $97,500 per year. Since twenty-five cars is a relatively small number for the leasing company, there are no price breaks for a problem of this magnitude. In the simulation results, the annual cost of the rail cars would range from $39,000 for ten cars to $101,400 for twenty-six cars. These data are representative of what the manufacturer may have paid, and are not their actual costs. But, since the cost of shutting down and restarting a continuous process factory is high no matter what the product, and marginal cost of the extra rail car is so small ($3900), and given the constraints of transporting the peanuts via rail, there is no reasonable scenario under which the plant manager should reduce the number of rail cars.

Another area where the plant manager could cut costs is in the peanut inventory carried in the queue at the Portsmouth plant. The number of rail cars in the queue and their average stay are both around 8.5. Since each rail car holds

190,000 pounds, and the spot price of raw peanuts is about $390.00 per ton, each car holds about $37,050 worth of peanuts. Using the generally accepted U.S. average inventory carrying cost of 35 percent of the cost of the peanuts per year, it would cost approximately $302 to carry the inventory in each rail car for the 8.5 days. Since the firm uses about 300 rail cars full of peanuts per year, the inventory holding cost amounts to about $90,595 per year. Relative to the annual turnover for the plant, this is a very small amount. Even if the holding cost were tripled to 100 percent, it would be a relatively small amount. In addition, given the variability in transit times via rail, reducing the queue at the Portsmouth plant would also increase the probability of a plant shut down for lack of material. The marginal cost of carrying the extra inventory is not large enough to justify taking this additional risk.

RESEARCH EXTENSIONS

The simulation opened additional doors for research. The company could, for example, switch from rail cars to trucks. This, in fact, was proposed to the company by a trucking firm. Although trucks carry a much smaller load (44,000 pounds), they make the trip much faster and with less variation since they travel directly from the sheller to the plant without going through the switching yards. The trucking company claimed they could supply the plant with ten trucks. The plant manager did not want to consider this option since the unloading facility was designed specifically for rail cars, and switching to trucks would have required a considerable capital investment. The simulation model was used to test the claim of the trucking company and it was found that ten trucks did, indeed, yield about the same results as twenty-five rail cars.

Also proposed was using a rail-truck combination to use trucks as a back-up to avoid running out of material. Several factors caused this option to be rejected. One is that the rail transit times are entirely under control of the railroad, and the variation is caused by delays in the

switching yard. Getting information about arrival times would be difficult to impossible within a time frame in which one could mobilize truck transportation unless one kept one or two trucks on stand-by. Keeping trucks on stand-by would be more expensive than simply adding additional rail cars to the system.

Another option would have been to allow different decision rules for loading cars at the Georgia facility. A queue could be allowed to form in Georgia and a rail car filled and released only when a rail car is emptied in Virginia (a type of kanban approach); or a maximum could be set on the number of rail cars filled and released per day in Georgia. This would keep the queue at the plant from getting too long. Although the queue at the sheller would grow in length (when the rail cars were empty), these rules would decrease the length of the VA queue and thus decrease the costs of holding peanut inventory and spoilage. As was shown previously, however, the potential gains from decreasing the Portsmouth queue length are minimal or even possibly negative. In addition, the process would be under the control of the sheller, which means there would be no guarantee that the rail cars would be loaded when the factory needed them. There also would be a cost to coordinating and communicating with the sheller and a cost of allowing empty rail cars to stay at their facility.

For a given number of rail cars, the probability distribution of travel times could be varied to see if there would be an advantage to negotiate more stable travel times with the railroad. Unfort-

unately, that did not seem to be even a remote possibility.

A random production rate was assumed for all simulations. This was reasonable given the plant operation at the time, but it may be possible to vary the production rate according to a plan and thus to adapt to the length of the queue at the plant. This was considered unlikely by the plant manager since that degree of control over the production rate would have required a major process improvement effort at the plant.

CONCLUSION

As stated at the beginning of the article, the typical queueing system consists of a stream of customers entering the system at either a constant or random rate. They are directed to one or more servers where the service rate is, again, either constant or random. The customers then leave the system. The literature for both theory and applications in these typical systems is quite rich. Circular queues, however, present a different scenario. Customers stay in the system and proceed from server to server infinitely. The literature on circular queues is fairly sparse, although applications in the "real world" are common in logistics systems including scheduled ocean transportation. It was shown that a relatively intractable problem theoretically can be solved using simulation. Although the solution is not optimal, as simulation results never are, it provides clear guidance to the decision maker. The results of this research demonstrate that simulation is a viable tool for dealing with circular queueing logistics problems.

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APPENDIX A

Queueing systems typically have one or more servers serving a stream of customers who enter an open system from the outside, are served, and then leave the system. The primary problem is to determine, given the appropriate cost and/or value functions, the number of servers one must have to process the customers in an optimal manner. Circular queueing systems, on the other hand, are closed network systems. They are a special case of Jackson systems (Ozekici, 1990). The system has a fixed number of customers who are served consecutively by two or more servers in an endless loop. The primary problem in this case is to determine the number of customers required to minimize the cost of server idle time plus the cost of the customers. Circular queues are relatively difficult to deal with analytically. In an early work, Cox and Smith (1961), for example, devote only three pages to the topic, and then only under constraining assumptions. Gelenbe, Pujolle, and Nelson (1987), give a more detailed analysis in their chapter on Jackson networks. The limitation of Jackson networks in this case is that they are robust in describing a system, but limited in predicting a system (Lipsky, 1992).

In the present case, the circular queue consists of four servers. Server one is a peanut butter manufacturer in Virginia. Server three is the vendor—the peanut sheller in Georgia. Servers two and four are railroads transporting the loaded rail cars from Georgia to Virginia and the empty cars back again. The peanuts are processed (shelled) in Georgia and then shipped to Virginia via rail car to be manufactured into peanut butter. Since they are moving through the system and being served, the customers are the rail cars. They were served (loaded) in Georgia, travel to Virginia full, served (unloaded) in Virginia, and returned to Georgia empty. The manufacturer in Virginia lease the rail cars. The problem is to determine the optimal number of rail cars to lease.

If the vector $k = (k_1, k_2, k_3, k_4)$ represents the number of customers (rail cars) at each of the N (N = 4) servers, then

$$K = \sum_{i=1}^{4} k_i = \text{total rail cars in the system}$$

The matrix of transition probabilities is as follows:

$$P[p_{ij}] = \begin{bmatrix} 0100 \\ 0010 \\ 0001 \\ 1000 \end{bmatrix}, \text{ where } p_{ij} \text{ is the probability of a customer moving from serving station } i \text{ to serving station } j.$$

The matrix P reflects the circular nature of the Jackson network. Given that a customer (rail car) is at a particular serving station, the next station to which it moves is deterministic; i.e., it moves there with probability 1. Since customers are not allowed to enter or leave the system, the system is closed.

The system may be diagrammed as in Figure A1:

k_i = number of customers in queue i including the customer being served.

p_{ij} = probability of a customer going from station i to station j.

μ_i = mean service time at server station i.

FIGURE A1

$$k_1 --\mu_1 \rightarrow p_{12} \rightarrow k_2$$
$$\uparrow \qquad\qquad |$$
$$p_{41} \qquad\qquad \mu_2$$
$$\uparrow \qquad\qquad \downarrow$$
$$\mu_4 \qquad\qquad p_{23}$$
$$| \qquad\qquad \downarrow$$
$$k_4 \leftarrow p_{34} \leftarrow \mu_3 --k_3$$

This is intended to be an overview of the theory and not a comprehensive view of the literature.

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