Mathematical Modeling for Demurrage Reduction in Coal Transportation for an Indian Thermal Power Plant

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Abstract

Competitive pressures on power plants have seen them attempting to reduce their operating expenses for profitable operations. In India, the plants use wagons of the Indian Railways to transport coal from the mines (in case of domestic coal) or from the ports (in case of imported coal). Once these loaded railway wagons have reached the power plant, they need to be unloaded and released within a stipulated time frame. If there is any delay beyond the stipulated time, the power plant has to pay penalty cost to the Indian Railways. In this paper, we describe an analysis of the underlying causes behind these delays. We use correlation analysis, queuing theory and simulation to mathematically model the coal arrival process in the company. The recommendation suggested by the study is currently under implementation.

Keywords: Simulation, Queuing, Transportation, Materials Handling

1. Introduction

There is an increasing pressure on the power plants to reduce their operating expenses for profitable operations. This has motivated the management to look closely at each facet of its operations. In India, one of the important components of cost in thermal power plants is the demurrage expense incurred by them in the coal receipt process. The plants use wagons of Indian Railways to transport coal from the coal mines (in case of domestic coal) or from the ports (in case of imported coal) to the plants. Once these loaded railway wagons have reached the power plant, they need to be unloaded and released within a stipulated time frame. If there is any delay beyond the stipulated time, the power plant has to pay a penalty cost, known as demurrage cost to the Railways. This paper aims to analyze the underlying causes behind this demurrage, understand the constraints in the process and model the process mathematically to arrive at solutions that can reduce the demurrage costs.

The electricity tariff in India is controlled by government regulations allowing only a limited profit margin for the power plants. This necessitates cost control as the only means to increase margins. The problem of escalating demurrage costs has a negative impact on the profitability of the power plant. The significance of the problem can be judged from the fact that Rs. 7 millions is generally lost by an average power plant per annum. This is money spent on a non-value added activity and if it could be avoided, there can be capital investments in other areas of plant operations.

The organization where this study was conducted is the power-generating agency supplying electricity to one of the important city in the Western India. It has a capacity of 390 MW, which is achieved through 4 power stations: three stations of 110 MW each and one station of 60MW. The plant is operating at an excellent PLF of 95.2 currently. This Plant capacity is augmented by another power plant at a nearby smaller town, with 2 gas turbines generating 100 MW. Thus, the total available capacity is 490 MW. This paper is organized as follows. The Section 2 discusses the literature survey of the application of queuing simulation model in coal transportation problems. In Section 3, we describe the coal receipt process and the reasons for demurrage. In section 4 we describe the modeling approach. We conclude the paper by describing the implementation process of the model in section 5.

2. Literature Survey

The problem of demurrage is a complex one. A lot of interrelated factors influence the final demurrage costs in the coal receipt process of a power plant. These factors include rake arrival schedules, changes in production scheduling, weather, deviation from delivery dates, coal quality and mechanical efficiencies. Traditionally this job has been assigned to experts, but standardization was desired to improve planning performance and allow for job rotation and the eventual retirement of experts. Observations and interviews are conducted, and a branch-and-bound model is chosen to structure the expert's knowledge. In assigning each job on the schedule, a tree structure is supposed and expert heuristics are used in the new branching and bounding processes by Fukumara and Yamakawa [1].

Earlier works dealing with demurrage have tended to focus on the development of a strategic model for a freight railway system operating in a given region. Chelst et al. [2] discuss a finite queuing system that can be used to model the coal unloading process. In this case, the model describes the relationship between the number of trains, queue throughput and queuing delays. In this case the queuing system built was a modified version of a standard single and multiple finite source queuing model, which allowed for server breakdowns.

Waters and Ash [3] describe a case of simulation of coal transportation and finding the optimal route. This study narrates the problem of transporting coal across Canada. A set of feasible routes are generated and described by a matrix. Once the routes have been generated demands are assigned to the links that must be used, then the assignment takes place for the alternative routes to the routes of lowest cost. This assignment is in order of total cost on a priority to using available capacity which minimizes the total cost. A strategic multi-modal freight network model is described by Fernández et al. [4] takes a short run approach and assumes that all the rail services offered are known and given. The network proposed includes several small sub-networks to represent yards operations and the concept of route sections is used to represent line operations. Allen et al. [5] describes use of three simple models to analyze the movement of coal in Cape Brenton

Development Corporation in Canada. In this case the company has doubled the through put of the system.

In our case, we have looked the problem from the standpoint of our client, We also found that the client company was too small an organization compared with the Indian Railways and could really exercise no control over the arrival of the rakes from Indian Railways.

3. Coal Receipt Process

Coal is the main raw material for the Plant. The total coal requirement is around 4,600 tons per day. This may vary from season to season (for example, the plant runs at full capacity from April to October, whereas, November to March is a lean season). All Production Planning is usually done at a monthly level, wherein the volumes & variety (grade) of coal required per day as well as the supply locations are decided to take care of any seasonal or intra-week fluctuations. The receipts are planned and the stock is maintained in such a manner that there is never a stock-out, because the cost of a single stock-out is too high. Around 10 days of inventory is held at a minimum level.

There are 2 main types/ sources of coal: indigenous coal and imported coal. The coal supply process is described in the Figure 1. The domestic coal comes from the coalmines, located at a distance of approximately 1250 kilometers. The imported coal is mainly from Indonesia. It is unloaded at a port near to the power plant and then transported via wagons of Indian Railways. The ash content of coal is very important, and has a major impact on the production volume and quality. The Indian coal has an average ash content of 25%, as against 14% in case of South Africa coal and less than 2% in Indonesian coal. To achieve the volume and quality targets, a blend of coal is used at this company. This multiplicity requires receiving coal from different sources. As a result, the scheduling of receipts needs to be done after taking into account the production requirement of the plant, dispatch schedules of suppliers, transit time (all inclusive of travel and delays), variability in transit time, etc.

Insert Figure 1 about here

3.1 The Coal Movement

Coal is received in railway wagons. There are 3 inlet lines for receiving the railway rake (each having 56 to 58 wagons) and there is one outlet line reserved for rake to be sent back. Each wagon has a carrying capacity of 56 – 58 tons. This implies approximately 3,300 tons per rake. Thus, a daily requirement of 4,600 tons is covered through approximately 1.5 rakes. A process schematic is shown in Figure 2**.**

The Railways allow 10 hours free time for unloading. Any delay beyond this leads to demurrage charges payable towards Indian Railways. An additional constraint imposed by the Indian Railways is that the wagons cannot be interchanged across rake. This means that the same 58 wagons that came with a particular rake must go back with that particular rake. Thus, an unloading delay in even one wagon would delay the release of the entire rake, causing Demurrage costs.

Insert Figure 2 about here

As soon as a new rake arrives, the workers in the Locomotive Section take over the movement from the Railway employees. Coal Sampling is done before unloading. This is to check for grade quality and ensure that the correct grade has been received for the price paid. There are also two 100 MT weighbridges. Here, each wagon is weighed (and then tare weight subtracted) to arrive at the weight of coal received. Then the wagons are sent to the tipplers (two in number) for unloading. At this stage, if wet coal or large chunks in coal are detected (both of which may block the free tipping into the hopper), the problem is corrected manually (breaking large chunks etc.). After this, depending upon the Production Plan, the coal is either transferred directly to the Bunkers (for crushing) or to the Stock for later use. There are 6 Bunkers, where large coal pieces are crushed into smaller ones, and fine particles are separated. The crushed pieces are then sent to the Coal Mills before being fed into the Boilers. The Coal Mills are identified with the type of coal grade that they would store.

3.2 Reasons for Demurrage

The above description of the coal receipt process indicates clearly the factors that may lead to delays in release of rake thus resulting in demurrage costs.

The main factors are as follows:

1. Simultaneous arrival of rake
2. Variability in transit time (due to festivals, delays by Indian Railways etc.)
3. Stochastic time delays during unloading
    a. Quality of the coal: Wet coal might stick on the hopper
    b. Manual breaking of coal might be required (if large pieces)
4. Changes in consumption pattern across coal grades

Coal is released from either the stock or directly from the hopper, after checking the bunker level for each type of coal grade. Delay in a few wagons of a rake will lead to the whole rake getting delayed. Demurrage is caused broadly due to following:

1. High waiting time before unloading of a rake starts
2. Varying unloading time

Detailed problem causes are listed in Table1. The company records the approximate number of hours of demurrage attributable to each of the reasons.

Insert Table 1 about here

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4. Modeling Approach

The logical approach of identifying the main causes of the problem and then finding source specific solutions was followed. A thorough study of the system revealed various causes of demurrage (as discussed in the previous section). The data maintained at the power plant also included the demurrage due to each of these reasons. Prior to identifying the important causes of demurrage it was important to establish if some causes were significantly correlated with each other. If this were true the importance of the factors involved would increase, as they now would be contributing to more demurrage.

Further the correlation of the existence of each of the problems with the total demurrage was established to isolate the main causes of the delay. The future methodology was determined by the results of this part.

4.1 Correlation between Factors

We found out correlation between the various factors. The results are shown in Table 2**.** There was no significant correlation between any of the factors, the highest correlation being 0.21 (between J and G). This suggests that each of the factors is independent of the other.

Then we found out the correlation of each of the factors with:

1. Demurrage hours
2. Loading time

Such an analysis would enable to us determine the factors that are primary causes for high demurrage and varying loading time

Insert Table 2 about here

4.2 Correlation with Demurrage

From the data available for the last 27 months, we calculated the average number of hours of demurrage per rake caused due to each of the reasons. The results obtained as per this calculation are presented in Table 3**.**

Insert Table 3 about here

Factor S (successive detention) has a very high correlation (R^2 = 0.85) with demurrage, which means that S is a chief factor causing demurrage. This is responsible, on an average, for around 8.5 hours of demurrage per rake. Demurrage due to successive detention suggests a resource constraint in the tippling section. Hence the possibility of decreasing the demurrage by increasing the capacity in the tippler section should be examined.

Another important reason for demurrage is B (outlet problem), which accounts for an average of 2.7 hours of demurrage per rake. This again has significant implications for the reductions of demurrage as it indicates that the outlet of the tippler is a bottleneck. There seem to be significant savings in demurrage possible by increasing capacity at the tippler section and making process improvements in this section.

The other factors have relatively low correlation with demurrage hours; only factors A, B and I have correlations more than 0.1. Thus by tackling factor S, the company can ensure lot lesser demurrage.

4.3 Correlation with unloading time

The factors that influence the unloading time the most are B, F and I. The amount of time taken for unloading has a direct bearing on the demurrage hours and hence tackling the factors that lead to an increase in the unloading time would see a drop in the demurrage.

Simulation

The company has no control over the operation of Indian Railways and while doing the simulation study, we decided to start our system from the point of coal arrival process from the point of receipt in the company**.** In order to determine whether the actual cause is the service or the arrival process we conduct two simulations, one where the arrival process is modified while another where the service process is improved. The marginal improvement in each of the cases can be taken to be indicative of the actual source of the problem. This means if the improvement is more when service process is improved the main problem cause is the service process.

4.4 Queuing Approach

The model chosen to fit the given situation was a G/N/2/∞ queue. The logic for each of these attributes is as follows:

Arrival Process

The actual rake-wise arrival times were taken from the logbook of the arrival point for the last 27 months. It was possible to assume the arrival distribution to be Poisson or Normal but the actual arrival process is fundamentally different from both these distributions. The underlying process here is that there are certain time zones in the day when the railway tracks are free. The arrivals are distributed in these times. Moreover, the arrival rate is superimposed by the demand pattern and availability at the mines. Another parameter than governs the arrival process is the random nature of the arrivals at the ports. The fitting of a single distribution is also made difficult by the fact that the arrivals take place in bundles of 56-58. It was not possible to capture all these parameters in any distribution and thus the actual arrival data was used. The distribution is shown in ***Figure 3.***

Insert Figure 3 about here

Service Rate

In queuing terms it is the average number of customers a single server can service in unit time assuming that it is busy all the time. In the context of the coal handling unit, it is the number of wagons that a coal tippler can empty in unit time given that there is no time when the tippler is not busy. This rate is governed by the tipplers and associated mechanisms. Assuming all these to be a single mechanical entity, the service rate can be assumed to be normally distributed over long periods of time. We have assumed that process improvement will not affect the variance of the unloading time. It can however be used to reduce the mean service times for the unloading process.

Number of servers

In the context of the Coal Handling systems the servers are the tipplers that are used to empty the wagons. We assume the number of tipplers (servers) to be two inspite of the fact that at some times only one tippler is in operation due to labor availability constraints. Fixing the number of tipplers also eliminated the option of adding additional tippers to overcome an overload problem. However, this option was not feasible because of plant layout and space constrains.

Waiting Room size

In the context of this case it is the number of rakes that can wait on the four-railway track. One of the tracks is reserved for the locomotive and each of the other 3 rakes can hold 2 trains each. This means the actual waiting room size is 6. In practice, the tracks have never been fully utilized in the last two years. Therefore, we can assume the waiting room size to be infinite as the limit is rarely reached.

4.5 Model Description and Formulation

The simulation study was divided into two distinct parts, one each dealing with the effect of service capacity and arrival pattern. It is important to realize that the only variable factors in the model are the service rate (mean and variance) and the arrival distribution. The mean arrival rate is constrained by the total demand of coal by the power plant and the service process is constrained to be Normal by its intrinsic nature. Each the factors responsible for demurrage (as described in a previous section) can be allocated to one of these board causes for demurrage. The process and the malfunction related causes can be related closely to the mean service time while the scheduling and successive arrival problems are clearly due to the arrival distribution.

Effect of Improving the Service Time

The service time for a rake includes the time for actual unloading of the whole rake and the time lost due to external factors like system malfunction, coal quality and shift changes. This simulation studies the effect of improving system parameters to reduce the mean service time. The trade-off is between the investment made to reduce the service time and the corresponding impact on mean demurrage time.

The simulation model can be simplified as follows:

A_i: The Arrival time for i^{th} Rake

S_i: The time when i^{th} rake is ready to be dispatched to railways

μ_i: The mean unloading time per rake

σ_i: The Standard Deviation of the unloading time per rake

$$S_i - S_{i-1} \sim N(\mu_i, \sigma_i)$$

$$S_i = \text{Max}(A_i, \text{Large2}(S_1, S_2, S_3, \ldots S_{i-1})) + N(\mu_i, \sigma_i) \qquad \text{……(1)}$$

Where,

Large2 is a function that returns the second largest of the given values.

The output is measured in terms of the mean demurrage, D

$$D = \Sigma (S_i - A_i - 10) / n \text{ hours} \qquad \text{……(2)}$$

We simulate this over 1,000 runs of the whole system to get the mean Demurrage value in each case. We do this for values of μ_i ranging from 14 hours (current mean) to 6 hours. Using this study we can ascertain the marginal benefit from each hour of improvement in service time. Here we have not changed the variance in of the process. This is under the assumption that the large number of processes involved will mean that correcting a single process will not affect the variance greatly.

Effect of Improving the Arrival Pattern

The arrival of coal rakes currently is a highly random process which in effect is a convolution of many underlying processes. In this simulation we work with the assumption that the arrival pattern can be improved so as to fit into some standard distribution. The effect of this change is studied.

The departure time expression now becomes,

S_i = Max (A_i, Large2(S_1, S_2, S_3,…S_{i-1})) + X ……………………………………………(3)

Where, X represents different distributions for different cases of the simulation. Six cases were taken:

1. Deterministic: This simulation will give the ideal case for coal arrival process. There is no variance and the arrivals take place precisely when scheduled. This is certainly not possible to attain in practice but will give a lower bound to the demurrage costs.
2. Uniform (6 14): This represents the case where the arrival can occur uniformly in a given window of time. It basically is close to the case when there is no fixed time of arrival but the average number of wagons is fixed. This again is not very practical but gives a more realistic lower bound.
3. Exponential with parameter 1/14 per hour: This is one of the most random processes. The output here can be taken to be an approximation for the worst case scenario. In case the actual performance is worse than this, there is a problem with the system as such.

4. N(14, 4): This is what the current situation is expected to be closest to. The arrival process in the long run will approach normal and the mean and variance used are from the actual data.
5. N(12,4): This simulation would indicate the current system performance if some improvements in the unloading system are made to reduce the service time.
6. N(10,4): This simulation gives the next level of improvement in the service time.

The aim was to study the improvement that can be achieved if the arrival process was made orderly. The selection of these distributions was based on a gradient of randomness. This means that in case the arrival distribution was critical, there would be a huge difference in the demurrage for a deterministic arrival pattern and an exponential arrival pattern.

4.6 Model Validation

Data Sources

All process data was obtained from the Power Plant – primarily form Daily Log Books of operations and from the Accounts office. Historical data was collected for the following:

1. Coal Receipt data
2. Day-wise / grade-wise receipts
    a. Arrival & Release Date/ time
    b. Deviations from Original Plan
3. Demurrage costs incurred
4. Time Study for all physical work practices related to receipt, unloading and release of rake
5. A review of the normal causes for delay
6. All relevant data of Indian Railways
    a. Transit time trends
    b. Normal causes of delays

Solution Methodology

The company records the approximate number of hours of demurrage attributable to each of the reasons. The list of reasons is given in Table 1. Using the data available for the last 27 months, the average number of hours of demurrage per rake caused due to each of the reasons was calculated. As discussed in the Approach section, a study of interdependence between factors and also the correlation with the demurrage was conducted.

Based on the preliminary analysis stated above, the two simulations were designed. The first one was to check for possible improvements if the tippler system could be improved and the associated faults eliminated by better engineering design or process. The result here was a graph depicting the marginal improvement in the demurrage time with every hour of reduction in mean service time, everything else remaining the same. The model has been described in a previous section. The resultant output is given in Figure 4. The decreasing marginal improvement as we decrease the mean unloading time is expected and can be intuitively explained. The graph can be used to determine the investment in the system to get maximum benefits per unit cost, given the cost of demurrage and the cost of system improvement.

The second simulation was meant to determine the impact of changing the arrival pattern. As has been described in pervious sections, different distributions were tried to get a gradient of randomness in the input parameter, the arrival distribution. The results are shown in ***Table 4.*** We noted that the impact of a change is randomness of the arrival process was very little on the demurrage hours. This may sound counter-intuitive but if we consider the fact that the unloading capacity is a constraint, it will be clear that there is unlikely to be significant change in the demurrage if the arrival process is made more streamlined as at all times there will be a queue.

5. Implementation Issues & Conclusion

The results indicate that there would not be much advantage in focusing too much effort towards coordination with Indian Railways. There is a need to conduct detailed work-study and time study of all the internal processes related to coal receipt at the power plant. An analysis of this information will give the root causes behind delays in any of the sub-processes. Once the basic causes are identified, the output of our model (which gives the tradeoff between investment and reduction is demurrage) can be used to arrive at the decision of allocating funds in the most optimum manner.

The in the first stage of implementation, a presentation was made to the top management of the power-plant explaining the main features of the simulation and the results. It was emphasized that the internal process needs to be improved and that the data needs to be continuously analyzed to understand the approach for further improvement. After a certain level of internal process improvement, there will be a scope of process improvement by changing the arrival process also. It was thus agreed the simulation package will be installed at the power-plant and the data continuously updated. This would enable them to run the simulation and generate updated results.

This was followed by getting the lower level managers acquainted with the system as they are the people who will finally operate the system. A demonstration was held on the power plant premises attended by the data operators and the operations managers. The mathematics behind the model was explained in brief so that they could make any fine adjustments if needed. Emphasis was laid on the operating aspects of it and the group was given a complete tour of the system developed. Integration with their current data collection software was also explained.

Figure 1: Coal Supply Process

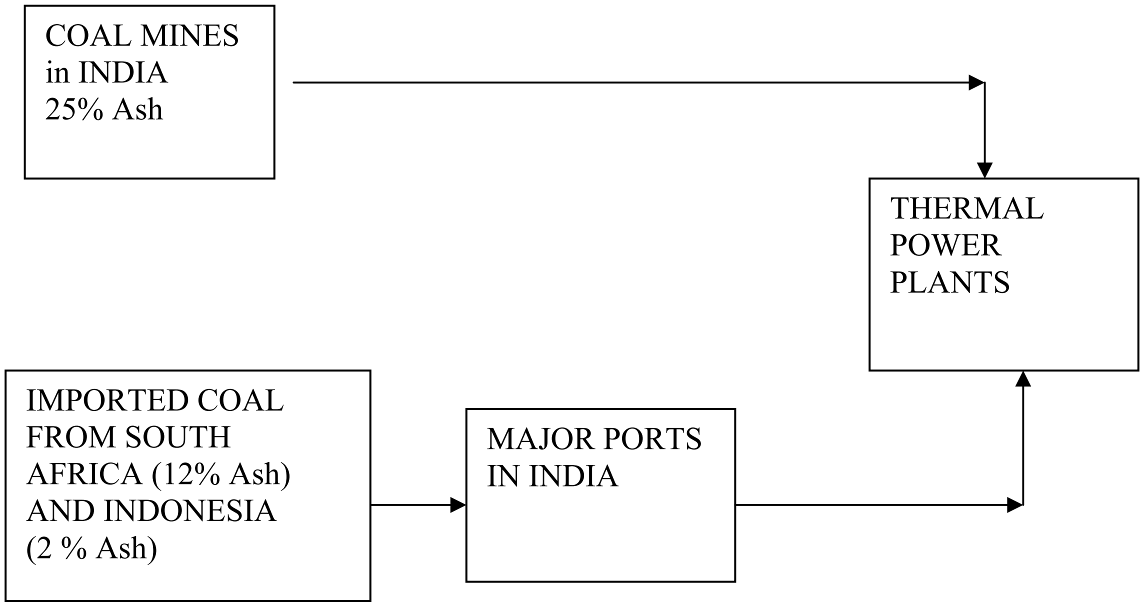

Figure 2: Schematic Diagram for Coal Receipt Process at CEC

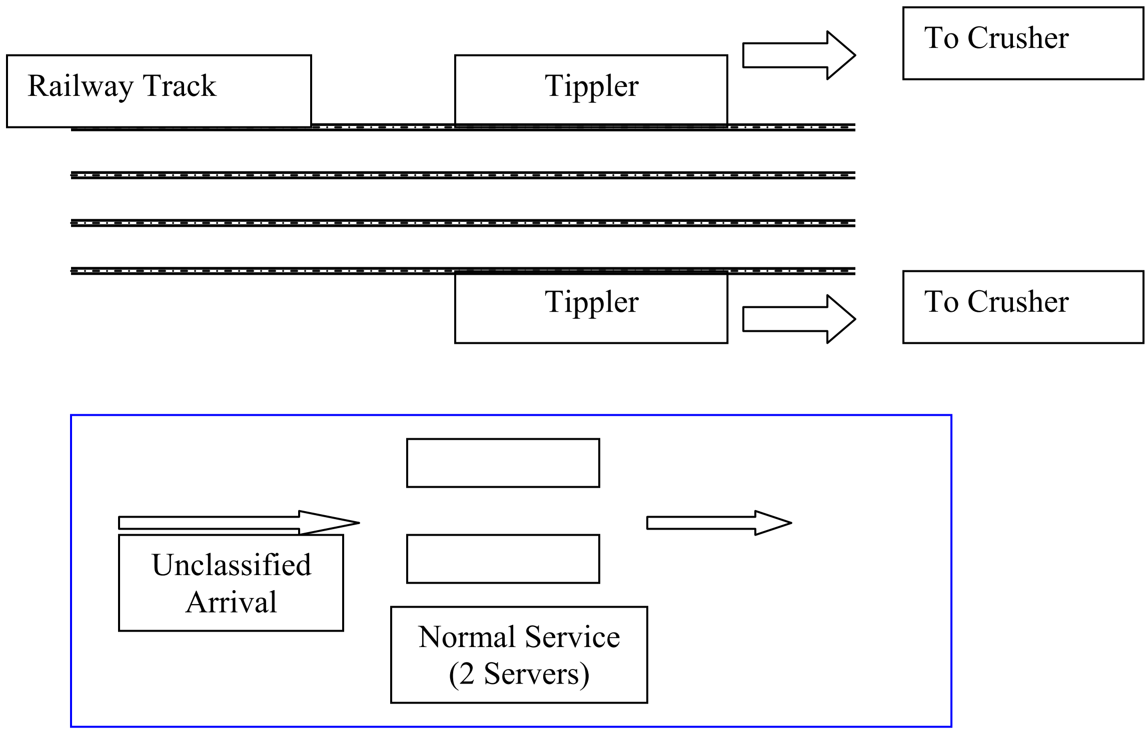

Table 1: Demurrage causes as Identified by CEC

A	: Receipt in quick succession
B	: Outlet problem
E	: Oversized coal
F	: Due to outage of one tippler / Due to outage of stream of a tipple
G	: Derailment
I	: Too much wet and sticky coal
J	: Low Ambient temperature
N	: Failure of electrical power system / Major electrical tripping
O	: Granulator problem; includes mechanical and electrical problems.
Q	: Empties could not be turned-out / No room on I/C lines / AYM did not allow even though line was clear.
R	: Rain continue at the time of unloading which made coal more wet and sticky
S	: Successive detention
T	: Locomotive / Dozer trouble

Others : These are other miscellaneous reasons that cause demurrage. These occur very infrequently.

Table 2: Correlations across Factors

Correlations across factors

	A	B	E	F	G	I	J	N	O	P	Q	R	S	T	OTH
A	1.000	-0.088	-0.078	-0.067	0.016	-0.048	0.065	-0.012	0.039	0.034	0.023	-0.024	-0.024	0.022	-0.040
B		1.000	-0.154	-0.147	0.005	-0.087	-0.003	0.029	-0.067	-0.037	-0.104	-0.070	-0.023	-0.082	-0.061
E			1.000	0.018	0.022	-0.001	-0.015	-0.010	-0.029	-0.012	-0.021	0.047	-0.021	0.010	-0.039
F				1.000	-0.025	-0.002	0.004	0.026	-0.026	-0.012	-0.039	-0.023	-0.018	0.024	-0.040
G					1.000	-0.024	-0.004	-0.009	-0.010	-0.004	-0.011	-0.007	0.035	-0.011	-0.012
I						1.000	-0.014	0.013	-0.005	-0.012	-0.022	0.062	0.028	-0.036	-0.013
J							1.000	-0.006	0.210	-0.002	-0.007	-0.004	0.005	-0.007	-0.007
N								1.000	-0.010	-0.005	-0.014	-0.003	-0.027	-0.014	-0.015
O									1.000	-0.005	-0.015	-0.009	0.063	0.033	-0.015
P										1.000	-0.006	-0.003	-0.035	0.056	-0.006
Q											1.000	-0.011	0.051	-0.017	-0.012
R												1.000	-0.025	-0.010	0.005
S													1.000	-0.040	0.020
T														1.000	-0.018
OTH															1.000

Errors are indpendent of each other

Table 3: Demurrage hours attributed to the various reasons

A	B	E	F	G	I	J	N	O	P	Q	R	S	T	OTH
4.90	4.73	3.50	4.63	3.00	4.84	4.67	3.47	4.33	1.50	2.77	5.00	12.42	2.86	5.03

Figure 3: Distribution of Inter Arrival Times of Rakes

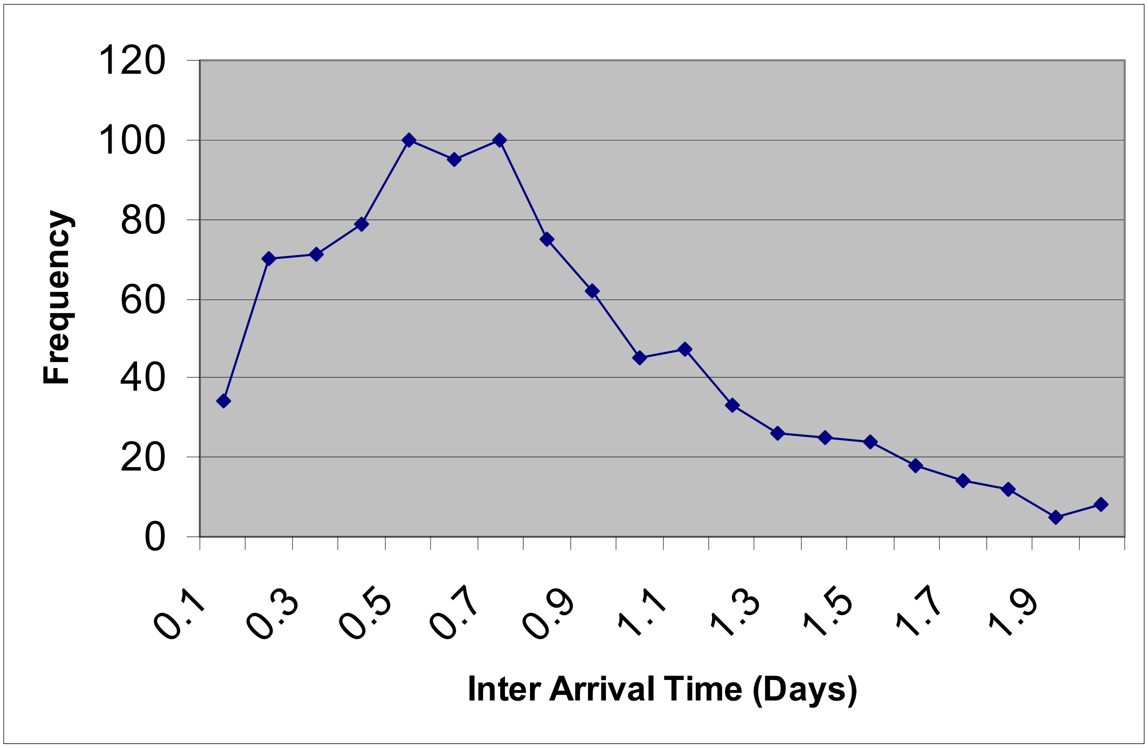

Figure 4: Marginal Benefit due to Service time improvement

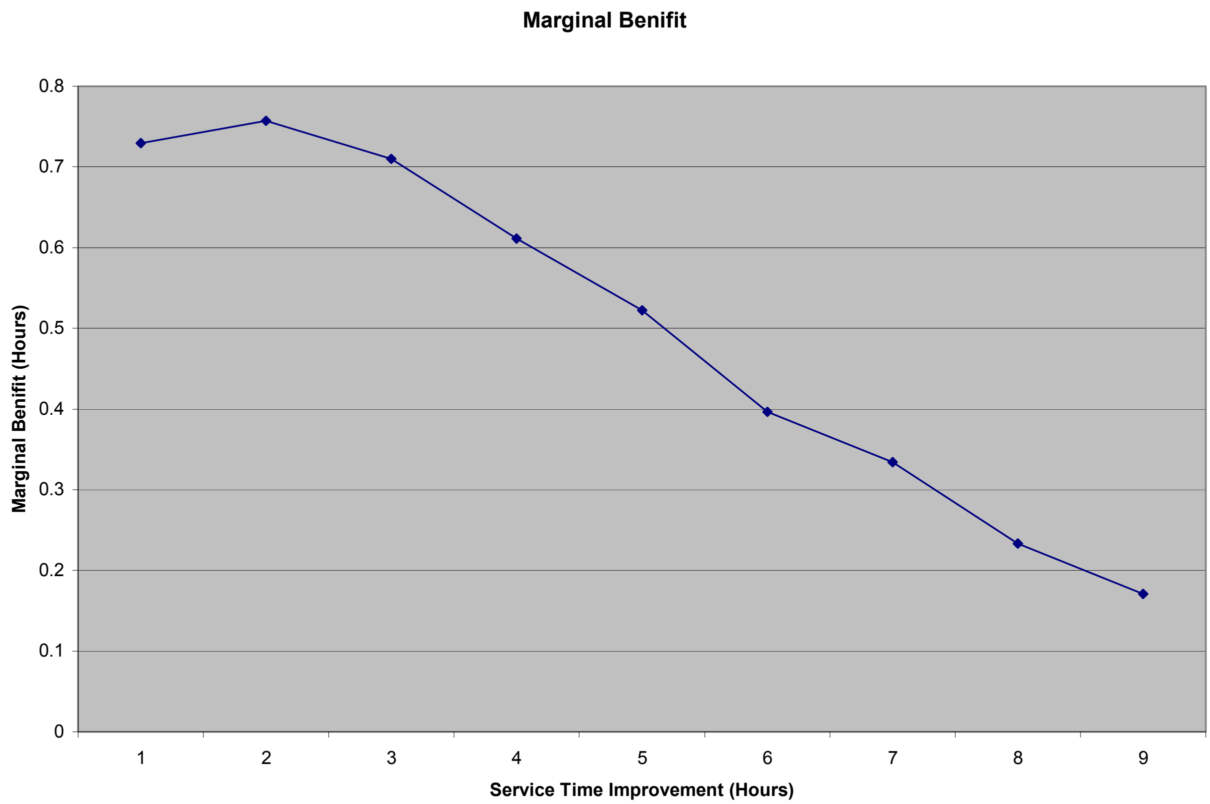

Table 4: Simulation of Arrival Process

Arrival Process	Mean Demurrage Time (Hours)
Deterministic	4.009
Uniform (6,22)	4.001
Normal (14.23)	4.028
Normal (12.23)	4.001
Normal (10.23)	4.020
Exponential	4.019

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