Discrete-Event Model of Mining Operations at the Waste Isolation Pilot Plant

Reid Kress, University of Tennessee[1]
Carla Mewhinney and Sue Downes, Sandia National Laboratories[2]

ABSTRACT

The goal of this effort is to develop a model of the mining operations at the Waste Isolation Pilot Plant (WIPP). This model includes all aboveground and belowground operations in sufficient detail to capture the essential elements of the movement of mined materials through the pilot plant. Essential elements include the following:

- The mining process
    - mining of the salt,
    - transportation of the salt in the underground
    - the hoisting operation, and finally,
    - the removal of the salt from the hoist at the surface;
- The times required to complete each step and;
- Critical resources and availability (personnel and equipment).

The modeling approach is to use the discrete-event simulation package, EXTEND™ [1], coupled with INDUSTRY™ [2] and employ a combination of personnel interviews, direct observation and data measurement, and analysis of archival data to develop the model[3]. Results include salt mining progress as expressed as a rate of removal per unit time, labor and equipment utilization, and average time to mine mains, entry ways, rooms and panels at WIPP. Results are compared to actual mining rates and experience. The model is capable of accurately predicting the mining progress on a weekly level. The model is also capable of identifying constraints in the process and to evaluate alternatives such as the impact of planned hardware acquisitions or different working schedules.

[1] University of Tennessee (during the time of this work and the writing of this paper)
[2] Sandia National Laboratories Carlsbad Programs Group, Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.
[3] Use of the Extend and Industry software does not imply endorsement.

BACKGROUND

Numerous manufacturing and process systems operate as discrete systems. Manufacturing systems such as job shops and production facilities, service organizations such as banks and fast food, communications routing controllers, and traffic flow are just a few examples from widely disparate fields. These systems cannot generally be modeled as continuous processes because their state changes instantaneously at separated points in time. As a consequence, discrete systems must be modeled using a discrete event approach. Many excellent background texts have been written on the subject of discrete event simulation and the interested reader is referred to Law and Kelton [3] or Banks, Carson, and Nelson [4] for two examples.

WIPP represents a unique type of mining because the mining operations are not driven by production of raw materials. At WIPP, the purpose of mining is to produce space for the storage of transuranic waste. WIPP does not generate revenue from the amount of raw materials brought to the surface, rather, the WIPP staff are driven by the goals of maintaining a high standard of safety and protection of the environment. As a result, like any other process model, a model of the WIPP mining process is defined by rates of machines and processes and also by availabilities of staff and resources; however, these availabilities may not be easily determined by simple collection of production and operational data. Although it may be difficult to accurately model the mining process at WIPP it desirable to do so for a variety of reasons including but not limited to the following. First, critical decisions need to made concerning the purchase of additional hardware to improve the efficiency of the mining operations. For example, one possible alternative is the possible replacement of individual trucks to transport muck in the underground with a continuously operating conveyor belt system. The efficacy of this proposed alternative can most easily be evaluated via a simulation. Second, critical decisions need to be made regarding choices of mining schedules. Some of the impact of going from one shift arrangement to another can be evaluated using a simulation of the process. Third, it is proposed to greatly increase the rate of arriving waste shipments in the future. One very pertinent question is, when will the rate of emplacement of waste in the underground exceed the mining teams' ability to produce space; thereby, creating impediments to the waste emplacement operations. These and other scenarios can be evaluated using an accurate model of the mining process at WIPP.

The organization of the remainder of the paper is as follows. The approach section describes the discrete-event approach to modeling the mining process at WIPP including a discussion of the steps in the real and modeled processes. The approach section also discusses fitting archival data for use as model inputs. The results section presents typical results of weekly mining progress and labor utilization including results collected to validate the model, and a simple what-if evaluation on surge storage capacity.

APPROACH

General Model Information

WIPP is planned to eventually have eight panels each consisting of seven rooms. There are four panels on the East side of the main drift numbered one through four starting with the northernmost panel. There are four panels on the West side of the main drift numbered five through eight starting with the southernmost panel. There are four main drifts each containing ~34,000 tons of salt; there are eight entryways, each containing ~7,000 tons of salt; and there are 56 rooms, each containing 14,000 tons of salt. This means that there are ~976,000 tons of salt that must be removed in order to complete mining operations at WIPP. (Panels 1 and 2 are completed to date.)

The steps in the mining process are the following. First, a continuous miner removes salt from the mine face. The salt is loaded onto haul trucks or load/haul/dump machines and taken to an underground hoist hopper. The salt is hoisted to the surface and emptied into waiting trucks that take the salt to an above ground storage location. Rates, cycle times, speeds, capacities, etc. are all known or can be directly measured although in many cases there are random perturbations to these nominal values that have a significant impact on the actual rate. To develop a model of this process, version 5.0.4 of EXTEND™ developed by Imagine That Inc. [1] was selected. For this application, EXTEND™ is coupled with its companion software INDUSTRY™ from Simulation Dynamics Inc. [2]. The libraries that are currently required are the following: Discrete Event, Flow, Generic, Items (DB), Plotter, SDI, and Utilities. No custom libraries or blocks are used. The model is bounded at the "borders" of WIPP. Mined material (salt) "enters" the model at the mine face in the underground. Salt progresses through the model as a stream (flow) with variable, model-determined rates although batched items can be used to model "batches of salt" during transportation and other activities, but this is not currently necessary. Salt leaves the model when it is placed in the aboveground storage area at the WIPP. The model is currently limited to mining operations at WIPP. It does not model the movement of waste to WIPP or through WIPP nor does it currently model the interactions between waste handling operations and mining. The steps in the mining process are described in greater detail in the following paragraphs. A summary of all of the input data values in included in the Appendix.

Details of the Continuous Mining Process Model

A continuous mining machine removes muck from the mine face. It has a rotating cutting head, which digs into the mine face and feeds muck out to a conveyor. The conveyor empties into a hauling truck or another conveyor. The rotating head can be driven up or down and the continuous mining machine advances when it can no longer cut into the mine face. An SME is a "Subject Matter Expert."

The input information required for the continuous mining model is summarized below:

- The rate for trimming was fit to archival data as a lognormal distribution.
- The rough-cut nominal rate was determined by discussion with SMEs.
- The ratio of time spent rough cutting or finish cutting is based on the mass of salt moved and was verified by discussions and direct observation and measurement.
- Equipment availability is taken from discussions with operating personnel.

Details of the Transporters (Haul Trucks and LHDs) Model

Muck is moved underground from the continuous miner to the hoist or to the hoist's storage (named the grizzly) or to other storage (e.g. surge) through the use of transporters. Two types of transporters are used: Haul Trucks and Load Haul and Dump (LHD) machines. The rate of salt transport with the transporters is defined by Eq. (1):

$$\text{Rate} = \frac{\text{Capacity} \times \text{Speed} \times \text{Number}}{\text{Distance}} \quad \text{(Eq. 1).}$$

Rate is given in units of Mass/Time. Capacity (amount of mass contained in a typical load) is specific to machine. Speed, in units of distance per time, is fit to archival data. Distance is taken from drawings of WIPP and varies with respect to the mine face location. Number is taken from discussions with personnel about typical mining operations.

Details of the Hoist Model

The hoist lifts salt from the underground to the aboveground. The hoist rate is determined by direct measurement and verified by discussions with operating personnel and also by calculations based on distance traveled, speed, and delays associated with acceleration, deceleration, loading, and unloading. The rate is given by Eq. (2) below:

$$\text{Rate} = \frac{\text{Capacity} \times \text{Avail.}}{\text{Typical Time for Round Trip}} \quad \text{(Eq. 2).}$$

Rate is given in units of Mass/Time. Capacity is a property of the hoist bucket and is a fixed mass. The typical time for a round trip was measured directly and taken from logbook information. Availability (Avail.) was obtained from discussion with SMEs and from logbook information.

Details of the Aboveground Trucks Model

Trucks move salt from the hoist dump to the aboveground storage. The rate for a truck is given by Eq. (3) below:

$$\text{Rate} = \frac{\text{Capacity} \times \text{Speed} \times \text{Number}}{\text{Distance}} \quad \text{(Eq. 3)}$$

Rate is given in units of Mass/Time. Capacity (amount of mass contained in a typical load) is specific to the trucks and taken from their specifications. Speed, in units of distance per time, is taken from discussions with SMEs. Distance is taken from drawings of WIPP and varies with respect to the mine face location. Number is taken from discussions with personnel about typical hauling operations.

Data Fitting for Input to Mining Model

Some of the input data distributions were taken from fits on actual rate and time data using the software package STAT::FIT [5]. This package will analyze a data set and determine an optimal distribution for the data from numerous different statistical distributions. For example, the hoist data sets for October 4, 1999 through December 31, 1999 were analyzed with STAT::FIT. Forty-seven points from the A Shift (Afternoon Shift) data set were analyzed and they were found to fit well to a lognormal distribution. Mathematically, a lognormal distribution is given by Eq.(4) taken from reference [1]:

$$f(x) = \frac{1}{(x - \min)\sqrt{2\pi\sigma^2}} \exp\left(\frac{[\ln(x - \min) - \mu]^2}{2\sigma^2}\right) \quad \text{(Eq. 4),}$$

where

min	=	minimum of x,
μ	=	mean of the included Normal,
σ	=	standard deviation of the included Normal.

The hoist lognormal distribution had a mean of 50 Tons/hr and a standard deviation of 10 Tons/hr. Note that a lognormal distribution is typical for this type of process where the activity takes a nominal amount of time (the mean), rarely takes much less, and occasionally takes much more time [3].

RESULTS

Results are presented in a model animator as mining progresses through a layout of the WIPP underground. Analytical results are given as average times to complete an entry, a main, a room, or a panel as well as tons of salt mine in a given time period (e.g. per week). Tonnage can be converted to feet using the formula given in Eq. (5) below:

$$x_{\text{Advance}} = \frac{\text{Mass}}{\rho A_{\text{Cross Section}}} \quad \text{(Eq. 5) .}$$

Results, in terms of time to complete mining a particular area, from a typical run without any additional storage (surge) are given in Table 1 on the next page.

Table 1. Results for a Baseline Run of the Mining Model

WIPP Area	Average Time To Complete
Main	2285 hr
Entry	466 hr
Room	942 hr
Panel	8200 hr

The amount of salt placed in the aboveground storage as a function of time for a typical run is shown in Figure 1. This figure was generated assuming that new panels were started every 10000 working hours.

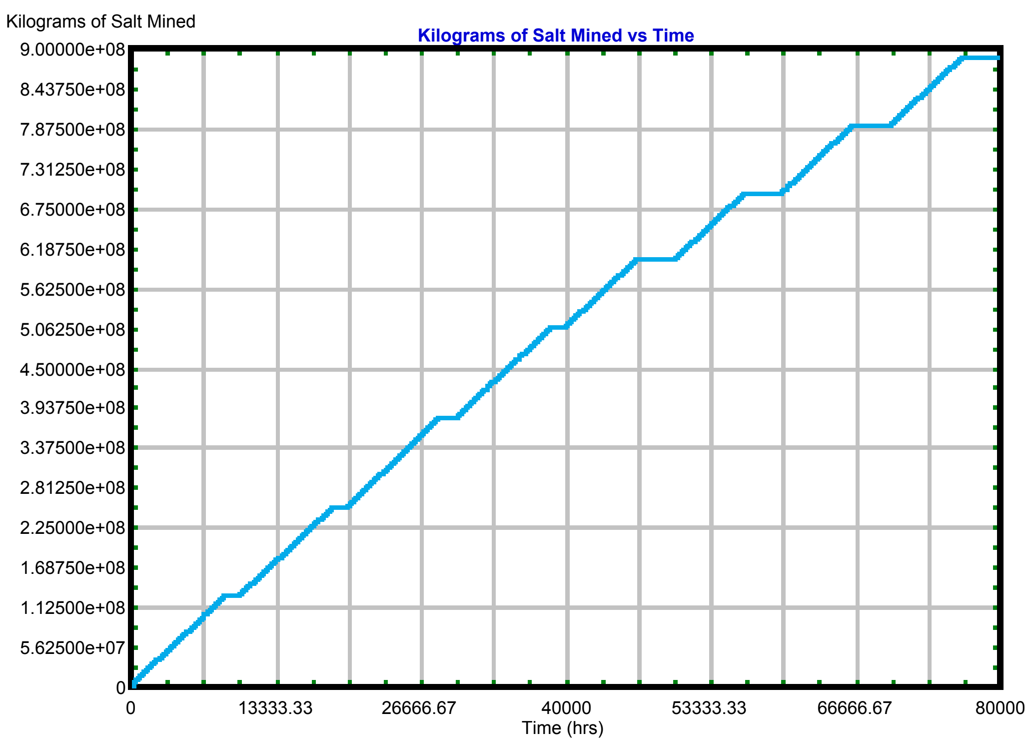

Figure 1. Kilograms of salt placed aboveground as a function of time.

Figure 2 shows the average mass of salt mined each week versus time for a simulated campaign of mining all eight panels.

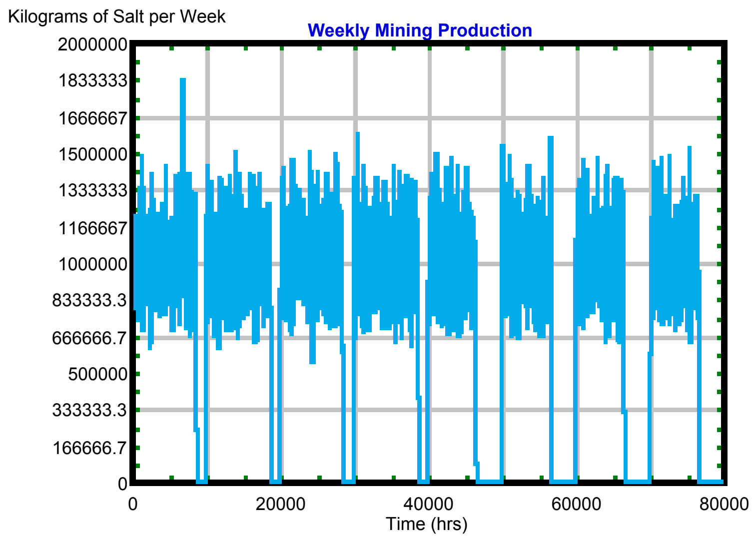

Figure 2. Average kilograms of salt mined per week assuming no surge location.

Figure 3 illustrates a typical plot of the utilization of different laborers. The upper plot is the utilization of mine crews, truck drivers, and hoist operators. The lower plot is the utilization of transporter drivers.

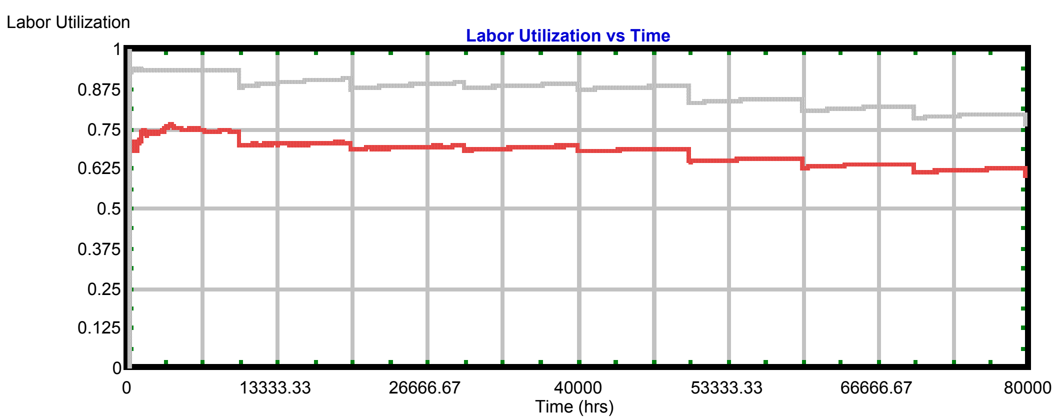

Figure 3. Typical labor utilization (Top = mine crews, truck drivers, and hoist operators. Bottom = transporter drivers.)

Other results include comparisons between alternatives. For example, Table 2 shows the mean time to complete various areas with and without a location for storing surge. (Surge is excess mine capacity; i.e., the continuous mining machine can mine salt faster than the hoist can remove salt from the underground.)

Table 2. Mean Times to Complete Mining an Area Based on Surge Storage Size.

	Average Time To Complete the Area (Hours)			
Surge (kg, tons)	Main	Entry	Room	Panel
0, 0	2285	466	942	8200
45360, 50	2160	452	893	7781
90720, 100	2103	424	852	7439
136080, 150	1997	397	820	7117
181440, 200	1887	375	791	6855

More details of the surge capacity what-if evaluation are shown in Figure 4.

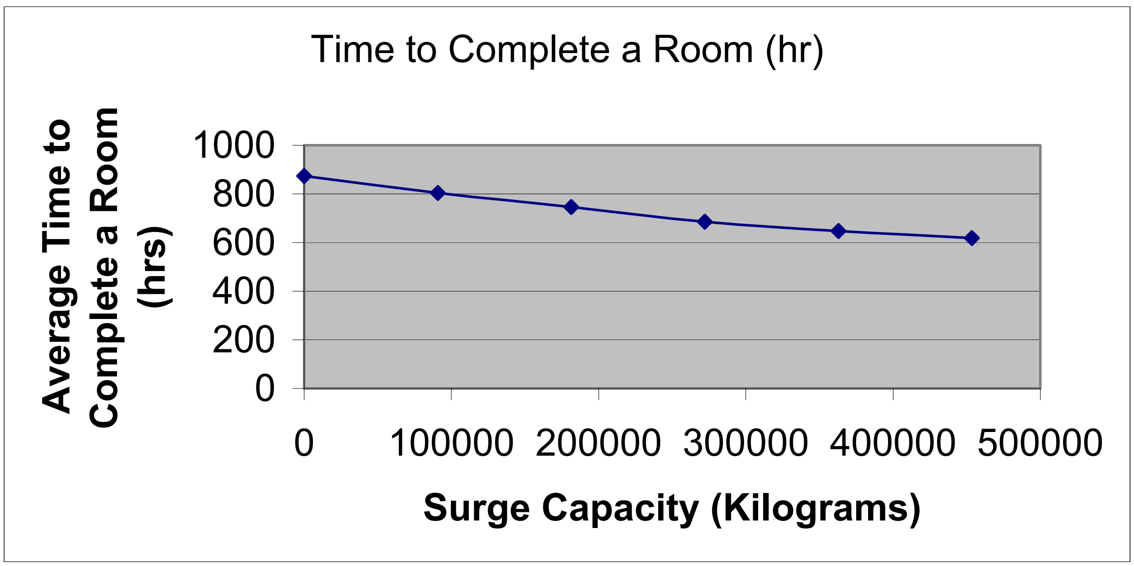

Figure 4. Average time to complete a room as a function of surge capacity.

WIPP personnel have only begun to use the model to evaluate alternatives such as the surge analysis described above. Several uses have been proposed. For example, one use proposed is to evaluate the impact of different work schedules and shifts. Another use is to examine the replacement of underground haul trucks with a conveyor. This analysis would include the impact of limited passageways in the underground affecting truck transportation and also include downtime for maintenance of a conveyor system. Finally, a study to evaluate the impact of accelerated waste delivery schedules on available storage space when different mining strategies are employed is planned.

CONCLUSIONS AND FUTURE WORK

The model is capable of accurately predicting the mining progress on a weekly level. The model is also capable of identifying bottlenecks in the process and to evaluate alternatives such as the impact of planned hardware acquisitions or different working schedules. Future efforts might include using the model in studies to evaluate alternatives, using the model to determine bounds on equipment availability below which a further reduction in availability will impact mining schedule, and coupling the model with an optimizer to match model production rates with actual production rates possibly even on a day-by-day schedule.

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APPENDIX: INPUT DATA SUMMARY

Table A.1 is a summary of the model inputs and the source of the input information for the discrete-event model of mining at WIPP.

Table A1. Input data of discrete-event model of mining at WIPP.

Item Description	Value	Source(s)
Number of Rooms/Panel	7	Given and well known
Number of Panels	8	Given and well known
Total Number of Entry Ways, Mains, and Rooms	7*8+8+8 =72	Given and well known (4 Mains are modeled as 0

		mass; i.e. already mined)
Tons Salt/Room	12700800 kg, 14000 Tons	SME and direct calculation
Tons Salt/Entry	6350400 kg, 7000 Tons	SME and direct calculation (See note on overlap)
Tons Salt/Main	30844800 kg, 34000 Tons	SME and direct calculation (See note on overlap)
Hours Between Starting Panels	10000 Hours	Totally arbitrary/No basis
Hours Worked per Week	80 Hours	SME
Work Efficiency	0.80	Interviews with personnel
Nominal Round-Trip N-S Distance	1219.2 m, 4000 feet	Map of WIPP, e.g. DWG # 51-W-102-W
Incremental Round-Trip N-S Distance	304.8 m, 1000 feet	Map of WIPP
Nominal Round-Trip E-W Distance	304.8 m, 1000 feet	Map of WIPP
Incremental Round-Trip E-W Distance	61.0 m, 200 feet	Map of WIPP
Surface Truck Travel N-S Distance	381.0 m, 1250 feet	Calculation to match SME's cycle-time data
Surface Truck Travel E-W Distance	381.0 m, 1250 feet	Calculation to match SME's cycle-time data
Continuous Miner Nominal Rough-Cut Rate	362880-453600 kg/hr 400-500 Tons/hr	SME
Continuous Miner Rough-Cut Rate Distribution	Lognormal with mean of 362880 kg/hr (400 Tons/hr) and standard deviation of 90740 kg/hr (100 Tons/hr)	Fit to SME's data
Continuous Miner Nominal Trimming Rate	149721 kg/hr, 165 Tons/hr	SME and SME
Continuous Miner Trimming Rate Distribution	Lognormal with mean of 149721 kg/he (165 Tons/hr) and standard deviation of 45370 kg/hr (50 Tons/hr)	Fit to SME's data
Continuous Miner Nominal Availability	0.915	SME
Continuous Miner Availability Distribution	Random Uniform 0.90 to 0.93	SME
Continuous Miner Storage Capacity (Bunker)	7259.2 kg, 8 Tons	SME
Hoist Nominal Rate	90740 kg/hr, 100 Tons/hr	SME, SME, and direct calculation from

		measurements
Hoist Nominal Mechanical Availability	0.90	SME
Hoist Actual Availability	0.75	Direct calculation from interviews with SME, SME, and hoist operators
Hoist Actual Availability Distribution	Random Uniform 0.73 to 0.78	Direct calculation from interviews with SME, SME, and hoist operators
Hoist Rate Distribution for A (Afternoon) Shift	Lognormal with mean of 45370 kg/hr (50 Tons/hr) and standard deviation of 9074 kg/hr (10 Tons/hr)	Fit to hoist log data
Hoist Rate Distribution for D (Day) Shift	Lognormal with mean of 18148 kg/hr (20 Tons/hr) and standard deviation of 4537 kg/hr (5 Tons/hr)	Fit to hoist log data
Hoist Storage Capacity	127036 kg, 140 Tons	SME
Haul Truck Capacity	6352.8 kg, 7 Tons	SME
Haul Truck Nominal Speed	8046.7 m/hr, 26400 ft/hr	SME
Haul Truck Speed Distribution	Lognormal mean with mean of 8046.7 m/hr (26,400 ft/hr) and standard deviation of 804.7 m/hr (2640 ft/hr) Min = 20000, Max=30000	Fit to SME's data
Haul Truck Spotting Time	40 seconds	SME's data and direct measurement
Haul Truck Spotting Time Distribution	Random Uniform 32.5 s to 46.5 s	SME's data and direct measurement
Haul Truck Availability Distribution	Random Uniform 0.83 to 0.87	SME
Haul Truck – Number Operating	2 for 50% of time 3 for 50% of time	SME
LHD Capacity	3175.9 kg, 3.5 Tons	SME
LHD Nominal Speed	8046.7 m/hr, 26400 ft/hr	SME
LHD Speed Distribution	Lognormal mean with mean of 8046.7 m/hr (26,400 ft/hr) and standard deviation of 804.7 m/hr (2640 ft/hr) Min = 20000, Max=30000	Fit to SME's data
LHD Spotting Time	40 seconds	SME's data and direct measurement

LHD Spotting Time Distribution	Random Uniform 32.5 s to 46.5 s	SME's data and direct measurement
LHD Availability Distribution	Random Uniform 0.83 to 0.87	SME
LHD – Number Operating	1 for 60% of time 2 for 40% of time	SME
Surface Truck Capacity	29037 kg, 32 Tons	SME
Surface Truck Nominal Speed	16093 m/hr, 52800 ft/hr	SME
Surface Truck Spotting Time	40 s	SME
Surface Truck Spotting Time Distribution	Random Uniform 32.5 s to 46.5 s	SME's data and direct measurement
Surface Truck Availability Distribution	Random Uniform 0.83 to 0.87	SME
Surface Truck – Number Operating	2	SME