SIMULATION OF A FILTER ROD MANUFACTURING PROCESS

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ABSTRACT

This paper discusses a GPSS V simulation model of a filter rod manufacturing process at the Macon, Georgia Branch of the Brown & Williamson Tobacco Corporation. This automated filter rod process produces and stores filter rods for use as needed by the cigarette fabrication process. We discuss the purpose and structure of the model as well as its validation and uses. With this model, the characteristics of individual machine components, the capacity of in-process inventory buffers, and the demand for filter rods can be specified as inputs and overall system performance predicted. Under certain conditions of machine breakdown and/or depletion of the inventory buffer, operators must manually supply rods to the cigarette fabrication process. One purpose of the model is to predict which combinations of machine components and which size of inventory buffer maintain a high utilization of the filter rod making machine while keeping operator interventions to an acceptable level.

1. INTRODUCTION

The cigarette manufacturing facility at the Macon Branch of Brown & Williamson Tobacco Corporation is the company's newest and most modern plant. A model of the cigarette fabrication process was reported earlier by Carson, Wilson, Carroll and Wysowski (1981). Both the cigarette fabrication process and the filter rod manufacturing process are high speed, highly automated systems, but each is always attended by an operator. Both processes consist of a number of linked machines and in-process inventory buffers (here called reservoirs) in series and parallel combinations. In general, one filter rod process automatically feeds from one to four cigarette fabrication processes. Therefore, problems with individual machines, or insufficient reservoir capacity, can have a significant effect on the production level of the entire process. Specifically, if the filter rod process has insufficient capacity, then whenever it cannot supply filter rods to the cigarette fabrication process, the operators must revert to manual loading of trays of rods. Tray pulling, as the manual loading of trays is called, is regarded as undesirable by both management and operators, as it keeps the operators from performing other maintenance and repair duties necessary for efficient operation of the process. One of the main purposes of the present model is to predict the occurrences of tray pulling for a given machinery and reservoir combination.

Another purpose of the model is to investigate the optimal number of cigarette fabrication processes that can be adequately supplied by one filter rod process whose machine components and reservoir capacities are specified. In summary, the model's purpose is to predict bottlenecks in the system which degrade performance, and to project the effect on overall production of the individual machines and reservoir.

Several notable features of the model will be discussed: (1) The level of aggregation, which provides a trade-off between model accuracy and computer runtime, is user-controlled; (2) The validation effort, which required an extensive data collection effort by B & W engineering personnel on an existing system, was generally successful and, for tray pulling occurrences, the model was remarkably accurate in replicating system conditions. The validation effort will greatly aid in management's acceptance and use of the model.

The model of the cigarette fabrication process reported in Carson et al (1981) was also successfully validated and has been used extensively by management. Development and validation of the present model has just recently been completed, so that this model has not yet been used as extensively as has the first model.

The paper contains sections on system description,

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input data, output data, model validation, model uses, and a summary of results.

2. THE FILTER ROD MANUFACTURING PROCESS

A flow diagram of the filter rod process is shown in Figure 1. The raw material, called filter tow, is fed automatically into the filter rod maker (FRM) by the filter tow opener. The filter rod maker, producing rods at 3000 to 4000 rods per minute, feeds rods onto a conveyor which leads to an overhead reservoir with a current capacity of 60,000 rods. When the level of rods drops below an electric eye in the FTA/hopper, rods exit the reservoir into a filter rod shooter which uses air pressure to shoot the rods through tubes to the FTA/hopper on the filter tip attachment (FTA). Each hopper holds approximately 3,000 rods. The four tubes shoot rods independently of each other. The cigarettes are produced at the cigarette maker, and the cigarettes and rods attached at the FTA. (Actually, one rod is cut into four sections and one section is attached to each cigarette. A rod is approximately 3 to 4 inches long.) Each FTA and cigarette maker work independently of the other FTA's and cigarette makers. After attachment of the filter, the cigarettes are conveyed to other machines (not shown here) where they are placed into packs and cartons. The cigarette makers have a specified production rate, typically 5,000 cigarettes per minute.

If all machines worked perfectly, then production rates could be easily matched, and small reservoirs would be adequate to assure smooth operation In fact, all machine components are subject to randomly occurring breakdowns which require operator attention. In addition, when reservoirs fill or empty, other machines automatically shut down. Finally, the filter rod maker shuts down periodically for 5 to 20 minutes or more when the bale of filter tow is used up and needs to be replaced. These interactions between machines and reservoirs, caused by random breakdowns, make an analytic model intractable and were one reason a simulation model was developed. Some of these interactions are listed in Figure 1, and are explained further below.

Based on data collected at one FRM during a 3 day period, the filter rod maker may have from 5 to 20 breakdowns per hour. These breakdowns typically consist of raw material or finished rods jamming in the machine, or a break in the paper tape used to wrap the exterior of the filter rod. Such a breakdown may require a few seconds or several minutes of the operator's time before production resumes.

The cigarette makers and FTA's at the other end of the process are also subject to randomly occurring breakdowns and other shutdowns due to interaction with the cigarette packer and other components. (For more details on the cigarette fabrication process, the reader is referred to Carson et al (1981).) These breakdowns occur at the rate of 10 to 30 per hour and may last from a few seconds to 10 minutes or more. Thus the demand for rods at the FTA is not as great as the nominal production rate of 5,000 cigarettes per minute would suggest, nor is the demand uniformly spread over time.

The filter rod shooter itself is subject to jams which require operator attention. An electric eye in the FTA/hopper controls its associated shooter, calling for rods whenever rods in the hopper fall below the eye. Thus when a rod shooter jams, the level of rods in the FTA/hopper can decrease rapidly, which can result in a tray pulling occurrence if the FTA/hopper empties.

If due to lack of demand for rods, or a jam in one of the rod shooters, the reservoir should fill, then the filter rod maker automatically shuts down and the operator does not resume FRM production until the reservoir has emptied to a certain point, say to 75% of its capacity. If the reservoir should empty, then the filter rod shooter shuts down.

If due to jams in the rod shooter, or to an empty reservoir, the FTA/hopper should empty, then the operator at the cigarette maker is required to manually place trays of rods onto the FTA/hopper so that cigarette production will never stop due to a lack of rods. At present, tray pulling is a fairly rare occurrence, but when it does occur, it diverts the operator's attention from other duties. In addition, a supply of rods in trays must be readily available, which requires extra filter rod makers, or manual removal of rods from a filter rod conveyor and placement into trays. Thus tray pulling has a detrimental effect upon the overall production process and is a situation whose occurrences should be minimized.

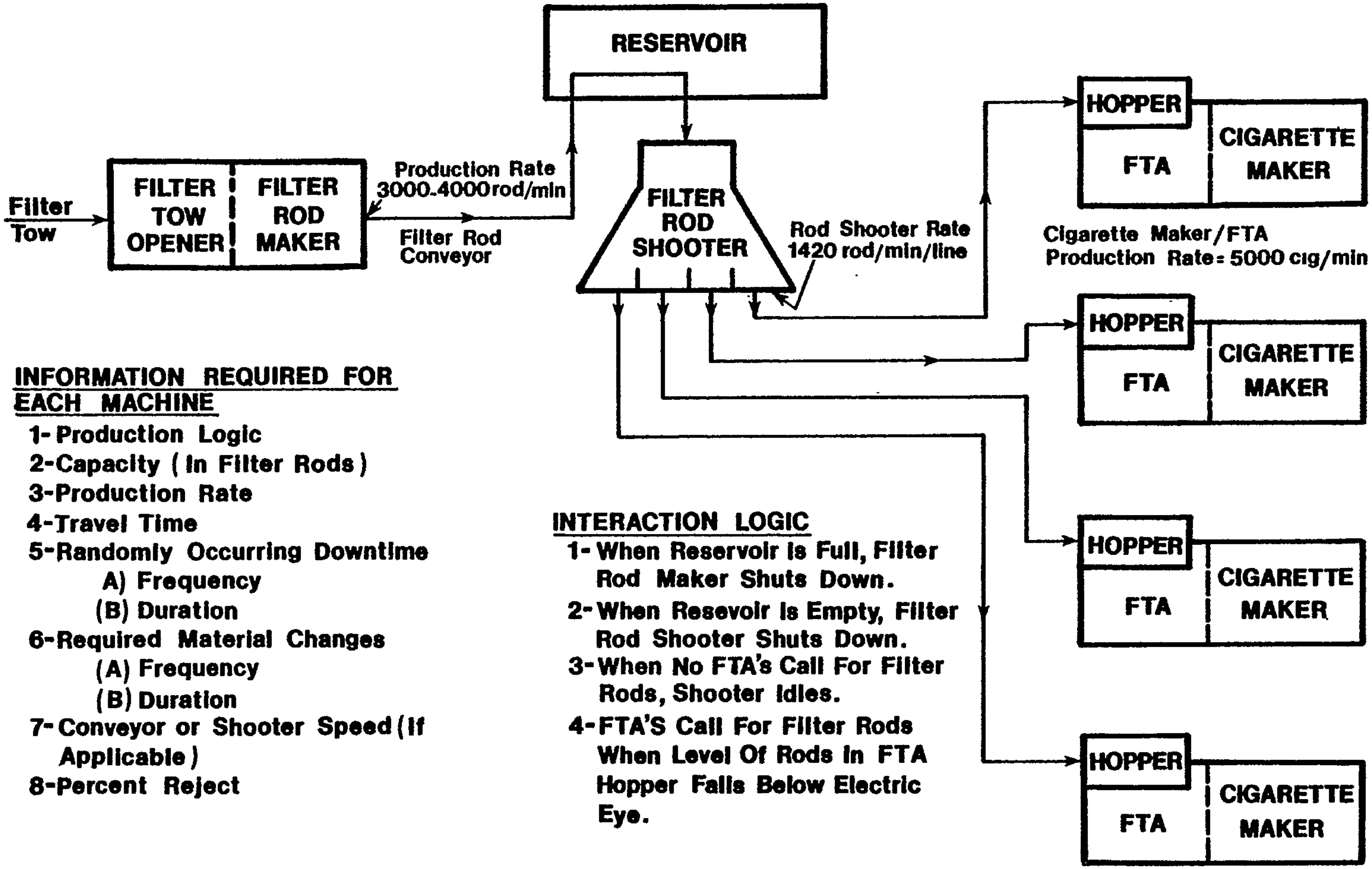
3. THE SIMULATION MODEL

A GPSS V model representing the key components in Figure 1 was developed for the filter rod manufacturing process. The model consists of distinct modules representing the following components explicitly:

1. FRM (filter rod maker)
2. Reservoir
3. One to four lines exiting the rod shooter
4. One to four FTA/hoppers.

A GPSS transaction in one of these modules represents a unit of rods, where the unit size (XB2) is controlled by the model user. The main purpose of having a unit size is to allow the user to control the level of aggregation and thus to control the trade-off between model accuracy and computer runtime. Unit sizes as large as 100 (XB2=100) gave negligible decrease in accuracy, but resulted in considerably smaller runtimes than modeling each rod individually (XB2=1). Runtimes were roughly inversely proportional to unit size. A four hour runlength with a unit size of 100 runs in a few seconds on the CDC CYBER.

The model user has the capability to specify all input paramteres, including



INFORMATION REQUIRED FOR EACH MACHINE

1- Production Logic
2-Capacity (In Filter Rods)
3-Production Rate
4-Travel Time
5-Randomly Occurring Downtime
    A) Frequency
    (B) Duration
6-Required Material Changes
    (A) Frequency
    (B) Duration
7-Conveyor or Shooter Speed (If Applicable)
8-Percent Reject

INTERACTION LOGIC

1- When Reservoir Is Full, Filter Rod Maker Shuts Down.
2- When Resevoir Is Empty, Filter Rod Shooter Shuts Down.
3- When No FTA's Call For Filter Rods, Shooter Idles.
4- FTA'S Call For Filter Rods When Level Of Rods In FTA Hopper Falls Below Electric Eye.

FIGURE 1 : FLOW DIAGRAM - FILTER ROD MANUFACTURING PROCESS

1. Number of FTA/hoppers and cigarette makers;
2. Production rate of FRM and each cigarette maker;
3. Capacity of reservoir, each FTA/hopper, and a tray of rods;
4. Size of a bale of filter tow;
5. Shooting speed of rod shooter, and transit time through line to FTA/hopper;
6. Average runtime (or distribution of runtime) for the FRM, the reservoir, the rod shooters, and cigarettes makers;
7. Average downtime (or distribution of downtime) for randomly occurring downtimes for the FRM, the reservoir, the rod shooters, and cigarette makers;
8. Initial contents of all reservoirs and initial condition of all machines at time 0.
9. Runlength, and mode (explained below).

All of these input parameters are placed in GPSS savevalues, storage capacities, or functions. The user expresses the inputs in familiar units such as rods per minute or cigarettes per minute for production rates, and rods for reservoir capacity, and the GPSS model computes any needed quantities in the appropriate time unit. (The time unit used was (1/10,000) minute, but this can also be user controlled by specifying the savevalue XF1; currently XF1=10,000.). The runtime and random downtime distributions are expressed in terms of GPSS functions. Other types of downtime, such as FRM downtime due to lack of raw material, a full reservoir, or a jammed conveyor in the reservoir, and rod shooter downtime due to an empty reservoir, are built-in to the logic of the model.

The model can be run in two modes: validation mode and production mode. The user specifies which he wants by setting a GPSS Logic switch. In validation mode, the model uses actual historical runtimes and random downtimes for each machine and reservoir, and the model attempts to duplicate conditions observed in the real system. The result of using the model in validation mode for a four hour runlength is reported in a later section.

In the production mode, the runtimes and random downtimes are characterized by statistical distributions. While the runlength in validation mode is determined by the available runtime and random downtime observations, in production mode the runlength is specified by the user. In addition, the model was designed so that the variance reduction technique called common random numbers, or correlated sampling, could be easily implemented by the user when using the model to compare two or more alternative systems. Each source of randomness in the model was identified and assigned to one of the eight GPSS random number generators which were seeded by eight different randomly selected seeds. The practical effect is best illustrated by an example. Suppose we desire to compare a given FRM connected to 2 FTA's versus 3 FTA's. Two runs are made, each say of 40 hours duration, each using the same random number seeds, and only one difference - the number of FTA's. In the two runs, the runtimes and random downtimes for the FRM, the reservoir, the first two rod shooters and the first two FTA/hopper/cigarette makers will be identical. The model with 3 FTA's would have an additional source of demand for rods and a new sequence of runtimes and random downtimes for the third cigarette maker. Although runtimes and random downtimes are duplicated, the actual clock time of occurrence of the beginning of a runtime (or downtime) on the FRM or reservoir may differ, and the number of FRM runtimes may increase, because of the interaction logic listed in Figure 1. That is, with 3 FTA's, the reservoir would be expected to fill to capacity less often, FRM runtimes would be interrupted less often, and thus the FRM would have longer total runtime in a 40 hour period. This duplication of runtimes and random downtimes is of considerable value when comparing two alternative systems. It reduces the variability in observed performance due to randomly occurring downtimes, and thus accentuates the differences in system performance due to the actual difference in the two configurations.

The final model contains approximately 375 blocks and over 1300 program statements, including comments explaining each block and defining each input parameter and other program parameters. The model also contains a built-in report generator to produce a special report for B & W personnel.

4. INPUT DATA FOR RUNTIMES AND DOWNTIMES

Engineering Personnel at B & W spent 3 full days gathering data on a typical filter rod manufacturing process which had a FRM connected to two FTA's. Each data set was analyzed by drawing the histogram of the data and computing its sample mean and sample standard deviation. Note that a FRM runtime is defined to be the total time a machine is running between two successive random downtimes. Such a runtime could be interrupted by a full or jammed reservoir, but would resume at a later time.

Runtime (or time to failure) for the FRM was found to be exponentially distributed with a mean of 5.40 minutes. The exponential assumption was verified by conducting a chi-square goodness-of-fit test. The results are shown in Table 1. The chi-square statistic had a value χ_0^2=11.89 with k-p-1=15-1-1=13 degrees of freedom, which is well below the critical value $\chi^2_{.05,13}$=22.36 for a level of significance α=.05. The standard GPSS exponential generator with a mean of one as given by Gordon (1975) was used in the model by multiplying the generated values by the mean of 5.40 minutes.

Runtimes for the rod shooters and cigarette makers were also tested for fit to an exponential distribution, but the exponential assumption was rejected. Random downtimes were clearly nonexponential (and nonsymmetrical) based upon the shape of the histogram. Therefore, all other runtimes and all random downtimes were represented by the empirical distribution of the data. That

TABLE 1

Chi-Square Goodness-of-Fit Test of FRM Runtimes to Hypothesized Exponential Distribution

Interval (minutes)	Observed Frequency (O_i)	Expected Frequency (E_i)	$\left(\frac{(E_i-O_i)^2}{E_i}\right)$
0-.5	14	9.20	2.50
0.5-1.0	8	8.38	.02
1.0-1.5	6	7.64	.35
1.5-2.0	6	6.97	.13
2.0-2.5	10	6.35	2.10
2.5-3.0	5	5.79	.11
3.0-3.5	4	5.28	.31
3.5-4.5	7	9.19	.52
4.5-5.5	5	7.64	.91
5.5-6.5	3	6.34	1.76
6.5-7.5	4	5.28	.31
7.5-9.0	7	6.29	.08
9.0-11.0	8	6.08	.61
11.0-15.0	11	7.09	2.15
15.0-∞	6	6.47	.03
	104	103.99	$\chi_0^2=11.89$

is, the data was summarized into class intervals and directly represented using GPSS Functions.

In addition to forming statistical distributions from the three days of data, the runtimes and random downtimes for the first four hours (of the 3 day period) were directly placed in GPSS savevalues for use in validation mode. System data was also collected on tray pulling occurrences and production levels to provide a basis for validating the model.

5. OUTPUT GENERATED BY THE MODEL

The standard GPSS output contained all important information on system performance. In addition, a special report was generated which provided statistics in a form and format especially designed for B & W managers familiar with the filter rod system.

This output report is divided into four parts:

1. Description of System
2. Filter Rod Production Summary for the Filter Rod Maker, Reservoir, and Rod Shooter
3. Cigarette Production Summary at Each FTA/ Cigarette Maker
4. Tray Pulling Report

1. Description of the System:

This part of the output report lists the primary inputs to the model - the speed of the Filter Rod Maker, the capacity of the reservoir, the speed of the Rod Shooter, the number of FTA's connected to the FRM, and the speed of each Maker.

2. Filter Rod Production Summary:

The FRM efficiencies are defined as follows:

$$\text{FRM Production Efficiency} = \frac{\text{Actual Production}}{\text{Maximum Production}}$$

where Maximum Production is the maximum possible production in rods that could have occurred if the FRM produced fulltime;

$$\text{FRM Runtime Efficiency} = \frac{P}{(T-I)}$$

where P = total time FRM is producing rods,
T = total runlength,
and I = time FRM is idle due to a full reservoir and/or a reservoir random downtime.

Because of the factor I in the denominator for Runtime Efficiency, it follows that Production Efficiency will generally be smaller than Runtime Efficiency.

The Reservoir Runtime Efficiency is defined by

$$\text{Reservoir Runtime Efficiency} = \frac{R}{R + D},$$

where R = total reservoir runtime excluding reservoir idle time when the FRM is down and all lines are not shooting rods for any reason;

D = total random downtime of reservoir (i.e., downtime due to a jam or malfunction in the reservoir itself).

The Rod Shooter Runtime Efficiency is defined by

$$\text{Rod Shooter Runtime Efficiency} = \frac{R'}{R' + D'},$$

where R' = total runtime of rod shooter,

D' = total downtime due to jams at rod shooter.

Thus, any idle time due to the reservoir being down or empty, or due to the FTA/Hopper being full, is excluded from the calculation for the Rod Shooter Runtime Efficiency.

3. Cigarette Production Summary:

FTA/Maker Production Efficiency is given for each 8-hour shift.

$$\text{FTA Production Efficiency} = \frac{\text{Actual Production}}{\text{Maximum Production}}$$

where Actual Production is actual cigarette production based on the number of rods used, and Maximum Production is the maximum possible production assuming the FTA/Maker had no downtime.

4. Tray Pulling Report:

This part gives number of tray pulling occurrences and total number of trays pulled, each by shift and by FTA. A tray pulling occurrence is defined as a period of time during which an operator is continually pulling trays and no rods are coming through the line. In the example shown in Figure 2, during the first eight hour shift, there were 2 tray pulling occurrences at FTA #1 with a total of 2 trays pulled, while during the second shift, there were no occurrences at FTA #1. For FTA #2, there were 3 occurrences with a total of 4 trays pulled during the second shift.

6. VALIDATION OF THE MODEL

The data taken during the first four hours of the 3 days of data collection was used to validate the model. Instead of summarizing the data in distributional form, the actual historical runtimes and random downtimes for the FRM, the rod shooter, and the cigarette maker were fed into the model as inputs. (There were no reservoir random downtimes during this 4 hour period.) Conditions at time 0 (7:00 a.m. in the real system) were matched in the model as closely as possible to conditions in the system, as observed and recorded by B & W Engineering Personnel. For example, the FRM was down at 7:00 a.m. because the reservoir had filled a few minutes before 7:00 a.m. and had not emptied enough to allow the operator to restart the FRM.

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          Tray Pulling Report

   Number of Tray Pulling Occurrences
          by Shift and by FTA

 Shift/FTA
Byte Matrix          1
Row/Column       1        2

  1              2        1
  2              0        3
  3              1        0
  4              2        1
  5              0        2

     Total Number of Trays Pulled per
          Shift at Each FTA

 Shift/FTA
Byte Matrix          2
Row/Column       1        2

  1              2        1
  2              0        4
  3              3        0
  4              4        1
  5              0        2
```

Figure 2: An Example of Model Output, Showing Statistics on Tray Pulling

The most important consideration in the model validation was the model's ability to predict tray pulling occurrences accurately enough to gain management confidence in the model. In the real system, there were two tray pulling occurrences on FTA #1 and none on FTA #2, each occurrence having one tray pulled, at 7:09 a.m. and 8:22 a.m. The model predicted the identical number of tray pulling occurrences on the two FTA's, occurring at 7:10 a.m, and 8:22 a.m. In addition rod production levels predicted by the model and those observed in the real system were close enough for practical purposes. The remarkable closeness between model prediction and reality was of considerable help in achieving management's confidence in the model.

7. USES OF THE MODEL

The model will be used to investigate how overall system performance depends on the individual components and their configuration. This will aid in system optimization. As one example, we simulated a typical FRM system with 2, 3, and 4 FTA's connected to one FRM. The system on which data was collected had two FTA's connected to one FRM. Initial results indicated that the FRM had extra capacity, so additional FTA's were connected to it. The runlength was 40 hours and the unit size was 600 rods. The results are exhibited in Table 2.

TABLE 2

Comparison of 2, 3, and 4 FTA's Connected to One FRM

Number of FTA's	Number of Tray Pulling Occurrences in 40 hours	Number of Trays Pulled	Average # of Trays Pulled per Shift per FTA	FRM Production Efficiency
2	21	44	4.4	38.4%
3	54	93	6.2	57.4%
4	219	320	16	66.4%

These results should be regarded as preliminary because only one statistical replication was made and additional experimentation is needed to establish the runlength which yields accurate long-run estimates of efficiencies and mean number of trays pulled per shift. (Accuracy is measured by the variability of model output for a fixed runlength over a small number of statistically independent replications.)

As seen by Table 2, there is a trade-off between the average number of trays pulled per shift per FTA (by the operator assigned to that FTA) and the FRM efficiency. As the number of FTA's is increased from 2 to 3 to 4, the FRM idle time due to a full reservoir decreases from 1009 to 307 to 27 minutes, and thus the FRM production efficiency increases. Increased demand for rods also increases the probability of an empty reservoir, and thus tray pulling increases. (The numbers reported in Table 2 are for hypothetical systems and are for illustration purposes only.)

Additional uses of the model include investigating proper reservoir capacity; maximum cigarette production rate for which a given FRM can supply rods without excessive tray pulling; and tray pulling occurrences for given configurations.

Due to the recent development of this model, it has not been as extensively used as the model reported earlier by Carson et al (1981). By considerable experimentation, this earlier model was found to yield results accurate enough for management purposes (say within ½% for efficiencies) by runlengths of 40 hours and 3 or 4 independent replications. Short runlengths of 8 hours yielded estimates of efficiencies too variable for practical use. It is expected that the filter rod model will also receive considerable use by B & W management, and that further experimentation will establish the proper runlength to achieve acceptably accurate long-run predictions.

8. SUMMARY

In this paper we presented a model of a filter rod manufacturing process consisting of a number of linked machines and reservoirs in a series/parallel configuration. We discussed the GPSS model components, the collection and analysis of the input data, the detailed validation, and the uses of the model. This model allows management to see the effect of each individual component on overall system performance and to identify bottlenecks in the system. The validation effort was highly successful and will greatly aid management acceptance and use of the results produced by the model.

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