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A Continuous Mining System Productivity Model in Terms of Equipment Reliability and Availability

by Francisco L. Viray, Ph.D.*

Introduction

There are numerous and complex reasons why coal production on a per-man-shift basis has been decreasing in the USA since 1969 despite the increased capacity of the machines working in the extraction cycle [1-4]. Whatever the reasons, increasing machine availability is a tangible area through which the declining production-per-man trend can be offset to some degree. In connection with this idea, it becomes necessary to develop mathematical models that can relate coal productivity with equipment reliability and maintainability. Specifically, the study quantifies the downtime in production due to failures of a system of equipment (called face equipment subsystem) made up of one continuous miner, two shuttle cars, one feeder-breaker and one proof bolter (see Figure 1).

Representative System

Figure 2 represents the subset of the entire mine system considered in this study. It boils down to the series reliability model shown in Figure 3 if the face equipment is lumped into a single group and treated as one element in the system. The availability of the portion of the system, shown in Figure 3, from the primary substation to point A has been analyzed by Hassan.[5] Therefore, this study concentrates on the face equipment subsystem.

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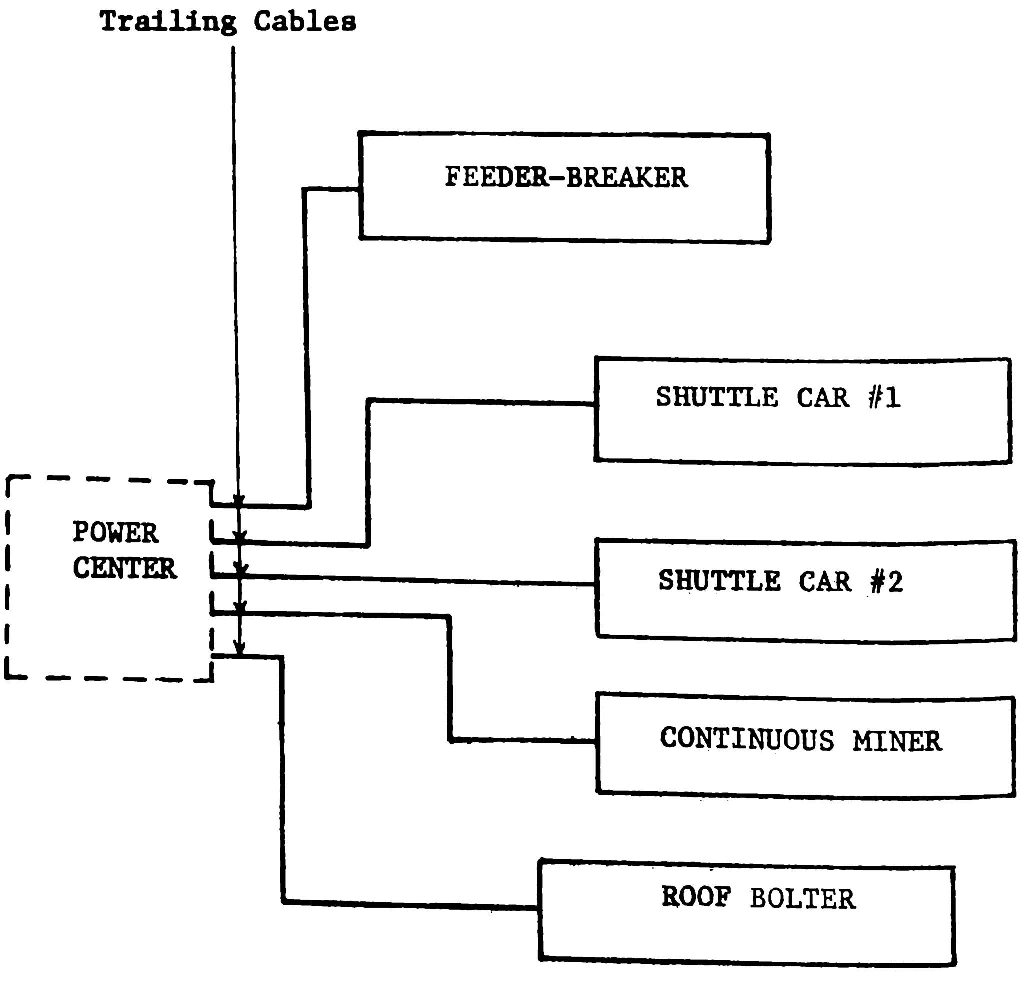

Figure 1 — Components of the Face Equipment Subsystem of the room-and-pillar underground coal mining system, using continuous mining method.

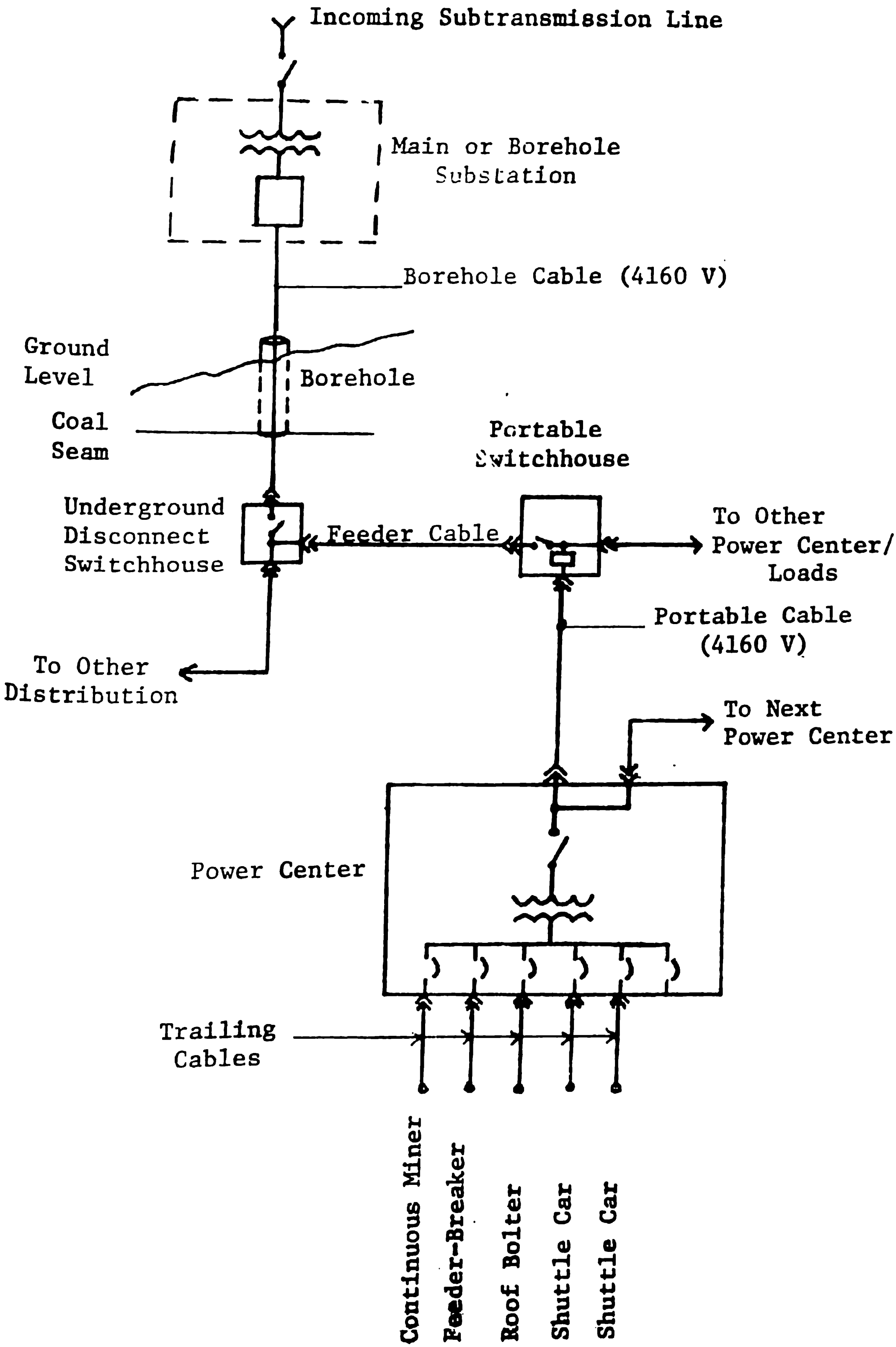

Figure 2 — A representative continuous mining system that is analyzed in this study.

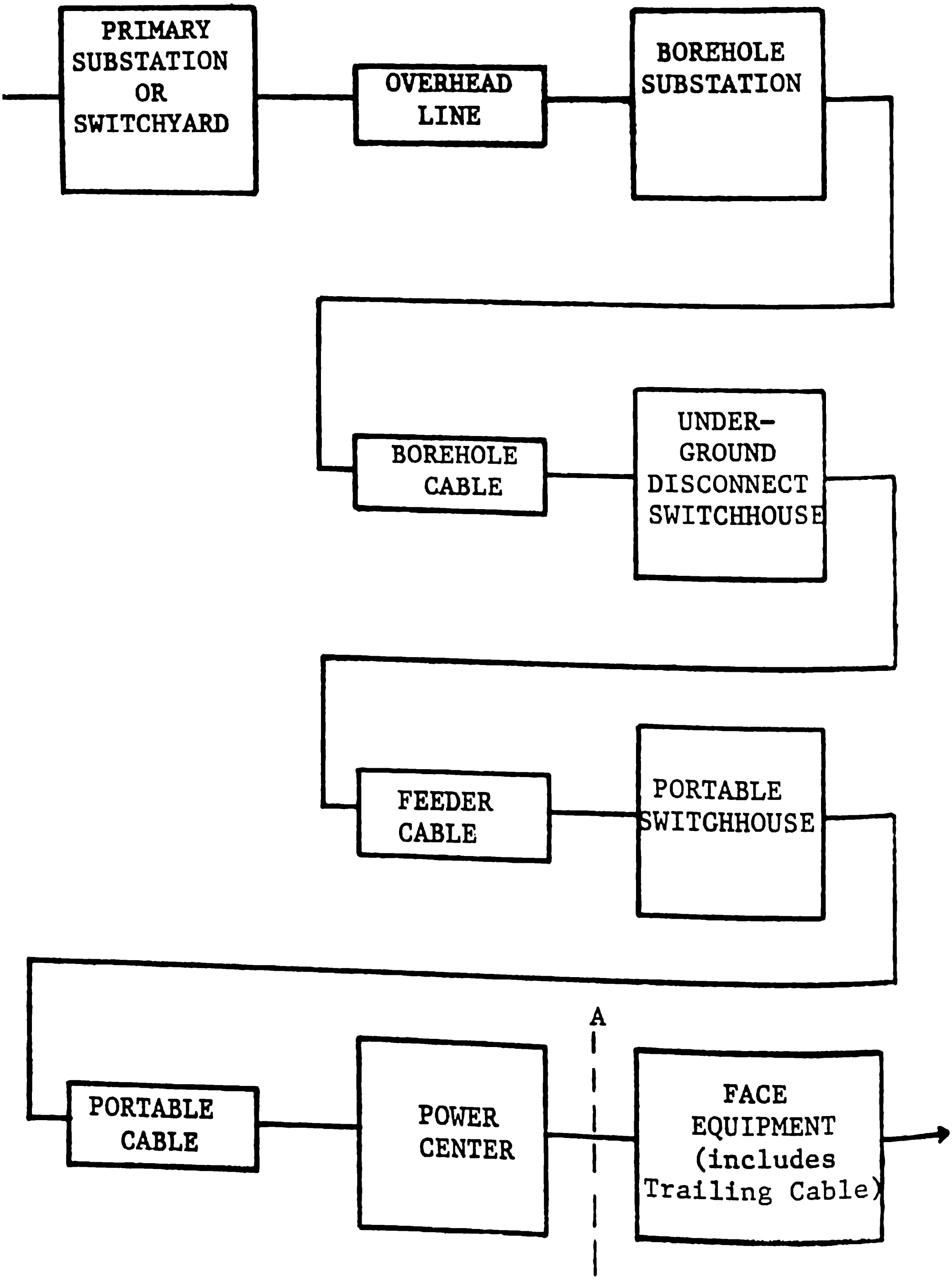

Figure 3 — The reliability block diagram of the representative continuous mining system shown in Figure 2.

Penalized Availability

The two shuttle cars shown in Figure 1 work in pairs such that the output material (or quantity on a per unit time basis) is dependent on whether only onc or both units are operating. The symbols used are defined as follows:

0_0 = output rate in quantity per unit time when both shuttle cars are operating

0_1 = output rate in quantity per unit time when only one shuttle car is operating

$k = 0_1/0_0$ — ratio of output rates = derating factor (1)

The total weighted output per unit time is given by

Total Output $= P_0(T)\,O_0 + P_1(T)\,0_1$

or, Total Output $= P_0(T)\,0_0 + P_1(T)\,k\,0_0$

or, Total Output $= P_0(T) + k\,P_1(T)\,0_0$ (2)

where $P_0(T)$ = average fraction of time that two shuttle cars are operating

$P_1(T)$ = average fraction of time that only one shuttle car is operating

T = total period of observation

The quantity inside the brackets in equation (2) is defined as the *average penalized availability* Ap(T); that is,

$$Ap(T) = P_0(T) + k\,P_1(T) \quad (3)$$

Availability Models

Figure 4 shows the process flow diagram in a continuous mining section. It has been depicted in such a way that the dependence of the output on the number of shuttle cars working is emphasized. Table 1 lists all the possible states of the face equipment subsystem, where X_i indicates that equipment i is good (unfailed) and X_i means it is bad (failed).

Availability models of the face equipment subsystem have been derived based on a simplified representation of room-and-pillar mining. Two types of repair policies are studied; namely, the independent repair policy and the first-come first-served (FCFS) repair policy. For each repair policy, three availability models are considered. They are: (1) a model where only certain failures of the roof bolter shut off production, Figure 5; (2) a model where any roof bolter failure interrupts production, Figure 6; and (3) a model where any roof bolter failure does not stop production, Figure 7.

The mathematical models describing all combinations of mining and roof support cycles coordination and repair policies are derived using the Markov model; and, the following assumptions for the face equipment subsystem shown in Figure 4 are used to derive such models.

1. The two shuttle cars are identical.
2. If the subsystem is unable to mine coal, no other failures can occur except for those that have already occurred and contributed to subsystem failure.

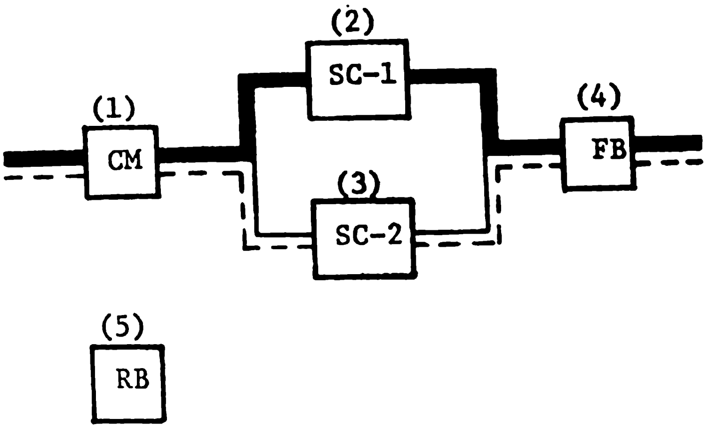

Figure 4. — Process flow in a continuous mining section.

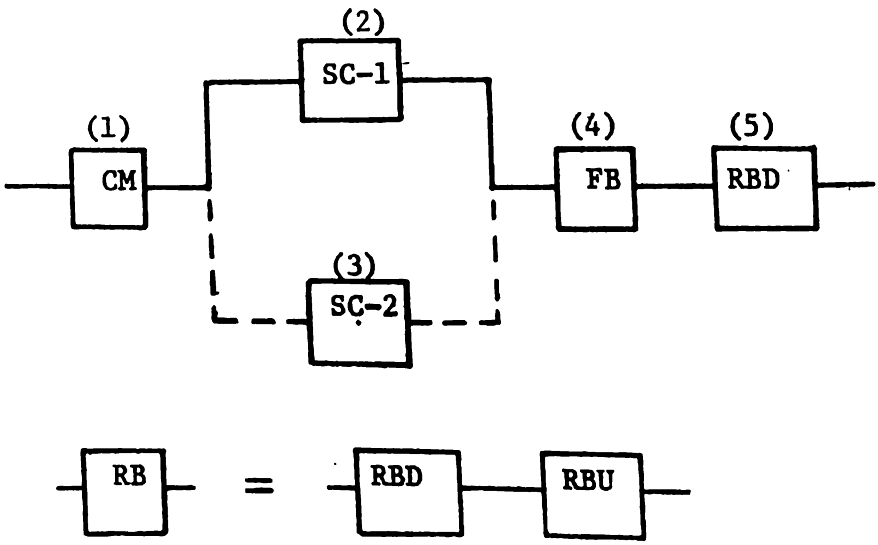

Figure 5 — Reliability block diagram for Model A; that is, only certain failures of roof bolter shut off production.

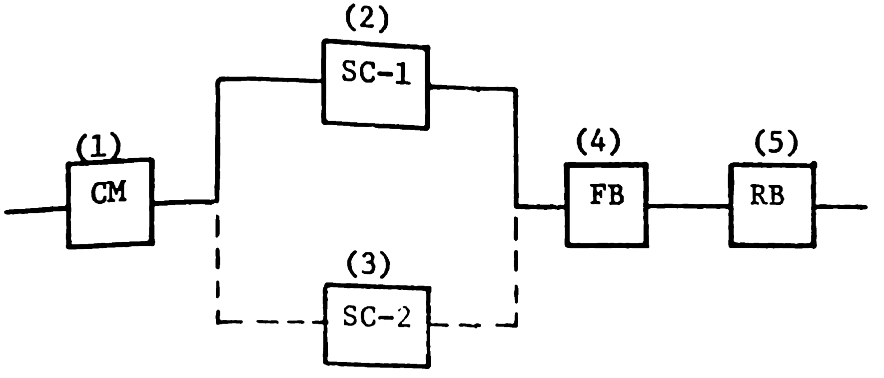

Figure 6. — Reliability block diagram for Model B; that is, any roof bolter failure interrupts production.

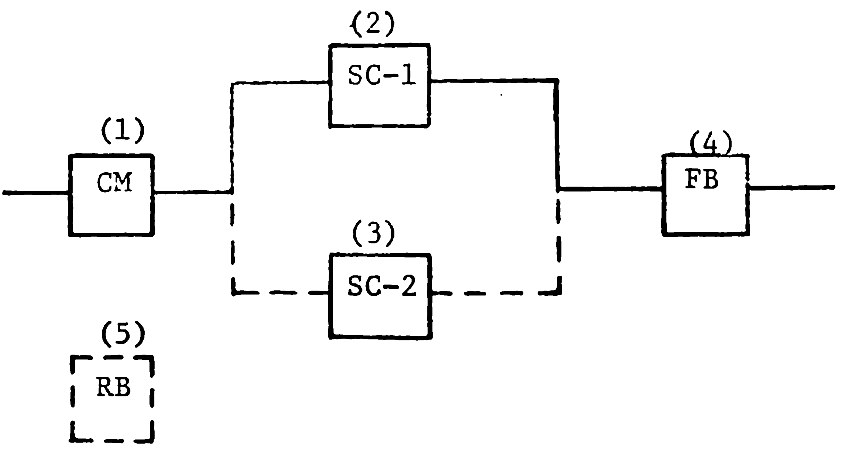

Figure 7. — Reliability block diagram for model C; that is, any roof bolter failure does not stop production.

TABLE 1 — Definition of states of the Face Equipment Subsystem

X_1 = CM; = SC-1; X_3 = SC-2; X_4 = FB; X_5 = RB

State Code	*State*	*Comments*
0	$X_1X_2X_3X_4X_5$	All equipment is good.
1	$\bar{X}_1X_2X_3X_4X_5$	Continuous miner is bad.
2	$X_1\bar{X}_2X_3X_4X_5 + X_1X_2\bar{X}_3X_4X_5$	One shuttle car is bad.
3	$X_1X_2X_3\bar{X}_4X_5$	Feeder-breaker is bad.
4	$X_1X_2X_3X_4\bar{X}_5$	Roof bolter is bad.
5	$\bar{X}_1\bar{X}_2X_3X_4X_5 + \bar{X}_1X_2\bar{X}_3X_4X_5$	Continuous miner and one shuttle car are bad.
6	$\bar{X}_1X_2X_3\bar{X}_4X_5$	Continuous miner and feeder-breaker are bad.
7	$\bar{X}_1X_2X_3X_4\bar{X}_5$	Continuous miner and roof bolter are bad.
8	$X_1\bar{X}_2\bar{X}_3X_4X_5$	Two shuttle cars are bad.
9	$X_1\bar{X}_2X_3\bar{X}_4X_5 + X_1X_2\bar{X}_3\bar{X}_4X_5$	Feeder-breaker and one shuttle car are bad.
10	$X_1\bar{X}_2X_3X_4\bar{X}_5 + X_1X_2\bar{X}_3X_4\bar{X}_5$	Roof bolter and one shuttle car are bad.
11	$X_1X_2X_3\bar{X}_4\bar{X}_5$	Feeder-breaker and roof bolter are bad.
12	$\bar{X}_1\bar{X}_2\bar{X}_3X_4X_5$	Continuous miner and two shuttle cars are bad.
13	$\bar{X}_1\bar{X}_2X_3\bar{X}_4X_5 + \bar{X}_1X_2\bar{X}_3\bar{X}_4X_5$	Continuous miner, one shuttle car, and feeder-breaker are bad.
14	$\bar{X}_1\bar{X}_2X_3X_4\bar{X}_5 + \bar{X}_1X_2\bar{X}_3X_4\bar{x}_5$	Continuous miner, one shuttle car, and roof bolter are bad.
15	$\bar{X}_1X_2X_3\bar{X}_4\bar{X}_5$	Continuous miner, feeder-breaker, and roof bolter are bad.
16	$X_1\bar{X}_2\bar{X}_3\bar{X}_4X_5$	Two shuttle cars and feeder-breaker are bad.
17	$X_1\bar{X}_2\bar{X}_3X_4\bar{X}_5$	Two shuttle cars and roof bolter are bad.
18	$X_1\bar{X}_2X_3\bar{X}_4\bar{X}_5 + X_1X_2\bar{X}_3\bar{X}_4\bar{X}_5$	One shuttle car, feeder-breaker, and roof bolter are bad.
19	$\bar{X}_1\bar{X}_2\bar{X}_3X_4X_5$	Only the roof bolter is good.
20	$\bar{X}_1\bar{X}_2\bar{X}_3X_4\bar{X}_5$	Only the feeder-breaker is good.
21	$\bar{X}_1X_2\bar{X}_3\bar{X}_4\bar{X}_5 + \bar{X}_1\bar{X}_2X_3\bar{X}_4\bar{X}_5$	Only one shuttle car is good.
22	$X_1\bar{X}_2\bar{X}_3\bar{X}_4\bar{X}_5$	Only the continuous miner is good.
23	$\bar{X}_1\bar{X}_2\bar{X}_3\bar{X}_4\bar{X}_5$	All equipment is bad.

Table 2 lists all the possible states for Model A (see Figure 5) and an independent repair policy, while Table 3 lists those for Model A and a first-come-first-served repair policy. The corresponding collapsed Markov diagram are shown in Figures 8 and 9; respectively. The transition probabilities, for constant hazard and repair rates, are defined in Tables 4 and 5.

The uncertainty and wide variation of hazard and repair rates data of the continuous mining equipment suggest that a sensitivity analysis on the availability and penalized availability functions is a worthwhile study. Since these two measures are dependent on steady-state probabilities, the sensitivity analysis treats the probabilities as the dependent variables or parameters. Therefore, the analysis is interested in how the probabilities vary (and consequently, the availability and penalized availability function) if the values of one or more parameters are changed. This analysis can be used to detect weak links in the subsystem. A set of representative data of mine failure and repair rates are all that are needed to derive the sensitivity equation(s).

The differential equations describing the system are derived[6] from Figures 8 and 9 and Tables 4 and 5. These equations yield the steady-state penalized availability of the system.

Table 2. — Definition of possible states of the Face Equipment Subsystem for Model A and Independent Repair Policy. States 4,7,10,11,14, 17, and 18 do not apply to Model B. States 4A and 10A do not apply to Model C.

X_1 = CH; X_2 = SC-1; X_3 = SC-2; X_4 = FB; X_5 = RB

State Code	*State*	*Comments*
0	$X_1X_2X_3X_4X_5$	All equipment are good.
1	$\bar{X}_1X_2X_3X_4X_5$	Continuous miner failed but is under repair.
2	$X_1\bar{X}_2X_3X_4X_5 + X_1X_2\bar{X}_3X_4X5$	One shutle car failed but is under repair.
3	$X_1X_2X_3\bar{X}_4X_5$	Feeder-breaker failed but is under repair.
4	$X_1X_2X_3X_4\bar{X}_5$	RBU submit of roof bolter failed but is under repair.
4A	$X_1X_2X_3X_4\bar{X}_5$	RBD subunit of roof bolter failed but is under repair.
5	$\bar{X}_1\bar{X}_2X_3X_4X_5 + \bar{X}_1X_2\bar{X}_3X_4X_5$	Continuous miner and one shuttle car failed but both are under repair.
7	$\bar{X}_1X_2X_3X_4\bar{X}_5$	Continuous miner and RBU subunit of roof bolter failed but both are under repair.
8	$X_1\bar{X}_2\bar{X}_3X_4X_5$	Two shuttle cars failed but both are under repair.
9	$X_1\bar{X}_2X_3\bar{X}_4X_5 + X_1X_2\bar{X}_3\bar{X}_4X_5$	Feeder-breaker and one shuttle car failed but both are under repair.
10	$X_1\bar{X}_2X_3X_4\bar{X}_5 + X_1X_2\bar{X}_3X_4\bar{X}_5$	RBU subunit of roof bolter and one shuttle car failed but both are under repair.
10A	$X_1\bar{X}_2X_3X_4\bar{X}_5 + X_1X_2\bar{X}_3X_4\bar{X}_5$	RBD subunit of roof bolter and one shuttle car failed but both are under repair.
11	$X_1X_2X_3\bar{X}_4\bar{X}_5$	Feeder-breaker and RBU submit of roof bolter failed but both are under repair.
14	$\bar{X}_1\bar{X}_2X_3X_4\bar{X}_5 + \bar{X}_1X_2\bar{X}_3X_4\bar{X}_5$	Continuous miner, one shuttle car and RBU submit of roof bolter failed but all are under repair.
17	$X_1\bar{X}_2\bar{X}_3X_4\bar{X}_5$	Two shuttle cars and RBU subunit of roof bolter failed but all are under repair.
18	$X_1\bar{X}_2X_3\bar{X}_4\bar{X}_5 + X_1X_2\bar{X}_3\bar{X}_4\bar{X}_5$	One shuttle car, feeder-breaker and RBU subunit of roof bolter failed but all are under repair.

Table 3. —Definition of possible states of the Face Equipment Subsystem for Model A and FCFS Repair Policy. States 4,7,10,10B,11,14,14B, 17,17B,18, and 18B do not apply to Model B. States 4A and 10A do not apply to Model C

$$X_1 = CM;\ X_2 = SC\text{-}1;\ X_3 = SC\text{-}2;\ X_4 = FB;\ X_5 = RB$$

State Code	*State*	*Comments*
0	$X_1X_2X_3X_4X_5$	All equipment are good.
1	$\bar{X}_1X_2X_3X_4X_5$	Continuous miner failed but is under repair.
2	$X_1\bar{X}_2X_3X_4X_5 + X_1X_2\bar{X}_3X_4X_5$	One shuttle car failed but is under repair.
3	$X_1X_2X_3\bar{X}_4X_5$	Feeder-breaker failed but is under repair.
4	$X_1X_2X_3X_4\bar{X}_5$	RBU subunit of roof bolter failed but is under repair.
4A	$X_1X_2X_3X_4\bar{X}_5$	RBD subunit of roof bolter failed but is under repair.
5	$X_5X_4\bar{X}_3X_2\bar{X}_1 + X_5X_4X_3\bar{X}_2\bar{X}_1$	Continuous minor and one shule car failed but only shuttle car is under repair.
7	$\bar{X}_5X_4X_3X_2\bar{X}_1$	Continuous minor and RBU submit of roof bolter failed but only RBU subunit of roof bolter is under repair.
8	$X_1\bar{X}_2\bar{X}_3X_4X_5$	Two shuttle cars failed but only one is under repair.
9	$X_1\bar{X}_2X_3\bar{X}_4X_5 + X_1X_2\bar{X}_3\bar{X}_4X_5$	Feeder-breaker and one shuttle car failed but only shuttle car is under repair.
10	$X_1\bar{X}_2X_3X_4\bar{X}_5 + X_1X_2\bar{X}_3X_4\bar{X}_5$	RBU subunit of roof bolter and one shuttle car failed but only shuttle car is under repair.
10B	$\bar{X}_5X_4\bar{X}_3X_2X_1 + \bar{X}_5X_4X_3\bar{X}_2X_1$	RBU subunit of roof bolter and one shuttle car failed but only RBU subunit of roof bolter is under repair.
10A	$X_1\bar{X}_2X_3X_4\bar{X}_5 + X_1X_2\bar{X}_3X_4\bar{X}_5$	RBD subunit of roof bolter and one shuttle failed but only shuttle car is under repair.
11	$\bar{X}_5\bar{X}_4X_3X_2X_1$	Feeder-breaker and RBU subunit of roof bolter failed but only RBU subunit of roof bolter is is under repair.
14	$\bar{X}_3X_2\bar{X}_5X_4\bar{X}_1 + X_3\bar{X}_2\bar{X}_5X_4\bar{X}_1$	Continuous miner, one shuttle car and RBU subunit of roof bolter failed but only shuttle car is under repair.
14B	$\bar{X}_5X_4\bar{X}_3X_2\bar{X}_1 + \bar{X}_5X_4X_3\bar{X}_2\bar{X}_1$	Continuous miner, one shuttle car and RBU subunit of roof bolter failed but only RBU subunit of roof bolter is under repair.
17	$\bar{X}_5X_4\bar{X}_3\bar{X}_2X_1$	Two shuttle cars and RBU subunit of roof bolter failed but only RBU subunit of roof bolter is under repair.
17B	$\bar{X}_3\bar{X}_5X_1\bar{X}_2\bar{X}_4$ (or $\bar{X}_2\bar{X}_5X_1\bar{X}_3X_4$)	Two shuttle cars and RBU subunit of roof bolter failed but only one shuttle car is under repair.
18	$X_1\bar{X}_2X_3\bar{X}_5\bar{X}_4 + X_1X_2\bar{X}_3\bar{X}_5\bar{X}_4$	One shuttle car, feeder-breaker and RBU subunit of roof bolter failed but only shuttle car is under repair.
18B	$\bar{X}_5X_1\bar{X}_2X_3\bar{X}_4 + \bar{X}_5X_1X_2\bar{X}_3\bar{X}_4$	One shuttle car, feeder-breaker and RBU subunit of roof bolter failed but only RBU subunit of roof bolter is under repair.

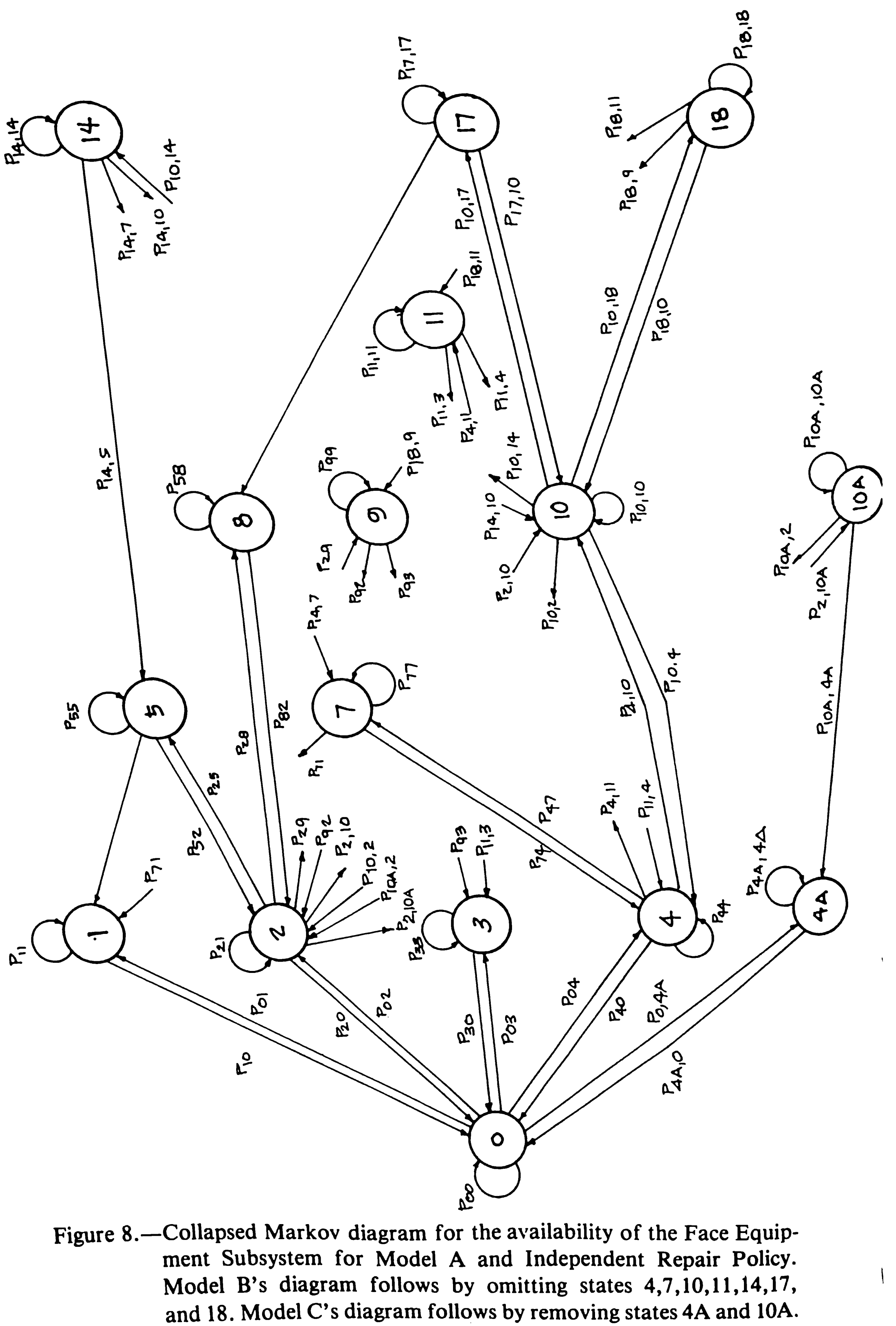

Figure 8.—Collapsed Markov diagram for the availability of the Face Equipment Subsystem for Model A and Independent Repair Policy. Model B's diagram follows by omitting states 4,7,10,11,14,17, and 18. Model C's diagram follows by removing states 4A and 10A.

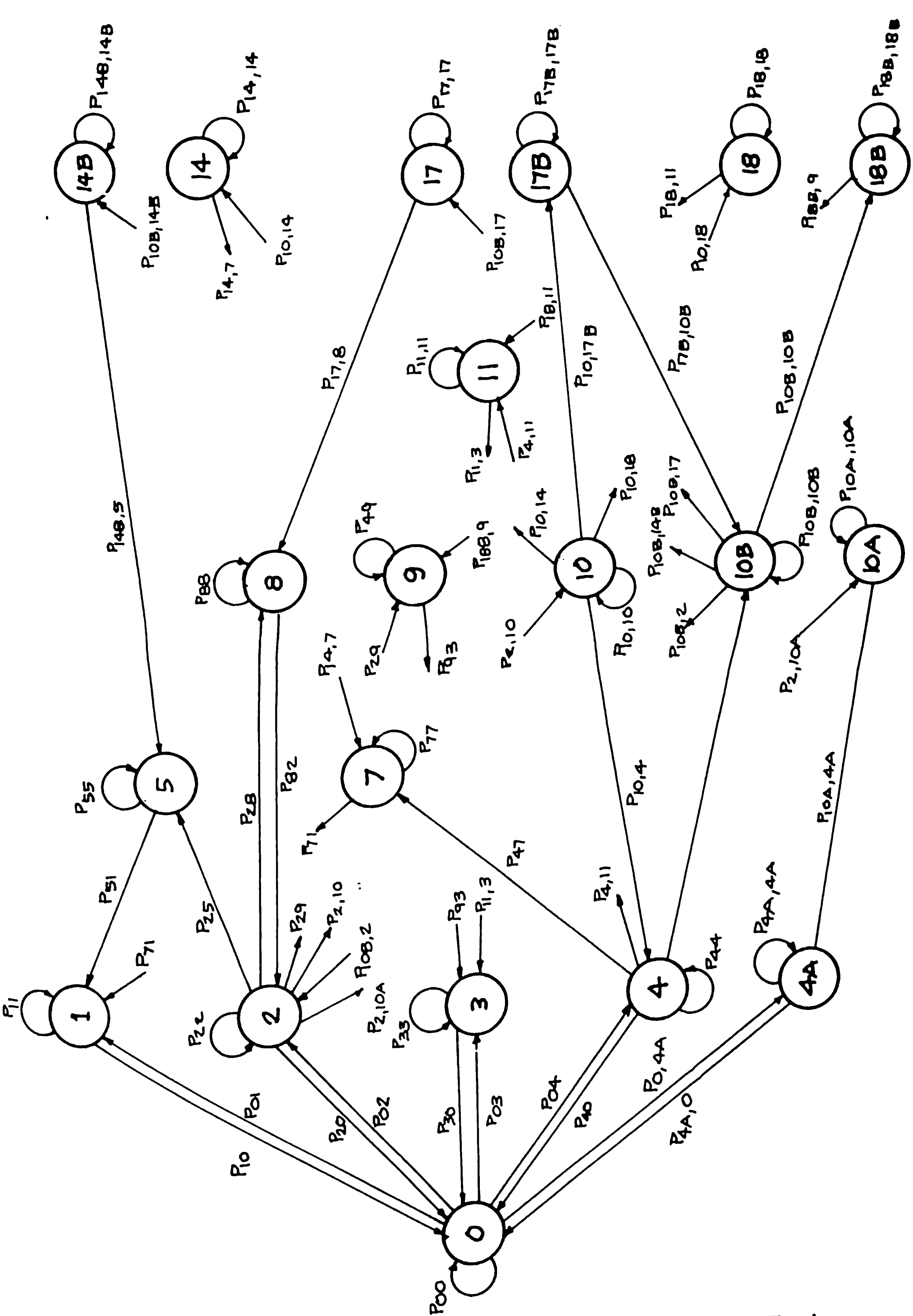

Figure 9.—Collapsed Markov diagram for the availability of the Face Equipment Subsystem for Model A and FCFS Repair Policy. Model B's diagram follows by omitting states 4,7,10,10B,11,14,14B,17,17B, 18, and 18B. Model C's diagram follows by removing states 4A and 10A.

$P_{00} = 1 - (P_{01} + P_{02} + P_{03} + P_{04} + P_{0,4A})$

$P_{01} = \lambda_{CM}\Delta t$

$P_{02} = 2\lambda_{SC}\Delta t$

$P_{03} = \lambda_{FB}\Delta t$

$P_{04} = \lambda_{RB}\Delta t$

$P_{0,4A} = \lambda'_{RB}\Delta t$

$P_{11} = 1 - P_{10}$

$P_{10} = \mu_{CM}\Delta t$

$P_{22} = 1 - (P_{20} + P_{25} + P_{28} + P_{29} + P_{2,10} + P_{2,10A})$

$P_{20} = \mu_{SC}\Delta t$

$P_{25} = \lambda_{CM}\Delta t$

$P_{28} = \lambda_{SC}\Delta t$

$P_{29} = \lambda_{FB}\Delta t$

$P_{2,10} = \lambda_{FB}\Delta t$

$P_{2,10A} = \lambda'_{RB}\Delta t$

$P_{33} = 1 - P_{30}$

$P_{30} = \mu_{FB}\Delta t$

$P_{44} = 1 - (P_{40} + P_{47} + P_{4,10} + P_{4,11})$

$P_{40} = \mu_{RB}\Delta t$

$P_{47} = \lambda_{CM}\Delta t$

$P_{4,10} = 2\lambda_{SC}\Delta t$

$P_{4,11} = \lambda_{FB}\Delta t$

$P_{4A,4A} = 1 - P_{4A,0}$

$P_{4A,0} = \mu'_{RB}\Delta t$

$P_{55} = 1 - (P_{51} + P_{52})$

$P_{51} = \mu_{SC}\,\Delta t$

$P_{52} = \mu_{CM}\Delta t$

$P_{77} = 1 - (P_{71} + P_{74})$

$P_{71} = \mu_{RB}\Delta t$

$P_{74} = \mu_{CM}\Delta t$

$P_{88} = 1 - P_{82}$

$P_{82} = 2\mu_{SC}\Delta t$

$P_{99} = 1 - (P_{92} + P_{93})$

$P_{92} = \mu_{FB}\Delta t$

$P_{93} = \mu_{SC}\Delta t$

$P_{10,10} = 1 - (P_{10,2} + P_{10,4} + P_{10,14} + P_{10,17} + P_{10,18})$

$P_{10,2} = \mu_{RB}\Delta t$

$P_{10,4} = \mu_{SC}\Delta t$

$P_{10,14} = \lambda_{CM}\Delta t$

$P_{10,17} = \lambda_{SC}\Delta t$

$P_{10,18} = \lambda_{FB}\Delta t$

$P_{10A,10A} = 1 - (P_{10A,2} + P_{10A,\,4A})$

$P_{10A,2} = \mu'_{RB}\,\Delta t$

$P_{10A,4A} = \mu_{SC}\,\Delta t$

$P_{11,11} = 1 - (P_{11,3} + P_{11,4})$

$P_{11,13} = \mu_{RB}\Delta t$

$P_{11,4} = \mu_{FB}\Delta t$

$P_{14,14} = 1 - (P_{14,5} + P_{14,7} + P_{14,10})$

$P_{14,5} = \mu_{RB}\Delta t$

$P_{14,7} = \mu_{SC}\Delta t$

$P_{14,10} = \mu_{CM}\Delta t$

$P_{17,17} = 1 - (1 - P_{17,8} + P_{17,10})$

$P_{17,8} = \mu_{RB}\Delta t$

$P_{17,10} = 2\mu_{SC}\Delta t$

$P_{18,18} = 1 - (P_{18,9} + P_{18,10} + P_{18,11})$

$P_{18,9} = \mu_{RB}\Delta t$

$P_{18,10} = \mu_{FB}\Delta t$

$P_{18,11} = \mu_{SC}\Delta t$

Table 4—Definition of transition probabilities for Model A and Independent Repair Policy (constant failure and repair rates).

$P_{00} = 1 - (P_{01} + P_{02} + P_{03} + P_{04} + P_{0,4A})$

$P_{01} = \lambda_{CH}\Delta t$

$P_{02} = 2\lambda_{SC}\Delta t$

$P_{03} = \lambda_{FB}\Delta t$

$P_{04} = \lambda_{RB}\Delta t$

$P_{0,4A} = \lambda'_{RB}\Delta t$

$P_{11} = 1 - P_{10}$

$P_{10} = \mu_{CH}\Delta t$

$P_{22} = 1 - (P_{20} + P_{25} + P_{28} + P_{29} + P_{2,10} + P_{2,10A})$

$P_{20} = \mu_{SC}\Delta t$

$P_{25} = \lambda_{CH}\Delta t$

$P_{28} = \lambda_{SC}\Delta t$

$P_{29} = \lambda_{FB}\Delta t$

$P_{2,10} = \lambda_{RB}\Delta t$

$P_{2,10A} = \lambda'_{RB}\Delta t$

$P_{33} = 1 - P_{30}$

$P_{30} = \mu_{FB}\Delta t$

$P_{44} = 1 - (P_{40} + P_{47} + P_{4,10B} + P_{4,11})$

$P_{40} = \mu_{RB}\Delta t$

$P_{47} = \lambda_{CH}\Delta t$

$P_{4,10B} = 2\lambda_{SC}\Delta t$

$P_{4,11} = \lambda_{FB}\Delta t$

$P_{4A,4A} = 1 - P_{4A,0}$

$P_{4A,0} = \mu'_{RB}\Delta t$

$P_{55} = 1 - P_{51}$

$P_{51} = \mu_{SC}\Delta t$

$P_{77} = 1 - P_{71}$

$P_{71} = \mu_{RB}\Delta t$

$P_{88} = 1 - P_{82}$

$P_{82} = \mu_{SC}\Delta t$

$P_{99} = 1 - P_{93}$

$P_{93} = \mu_{SC}\Delta t$

$P_{10,10} = 1 - (P_{10,4} + P_{10,14} + P_{10,17B} + P_{10,18})$

$P_{10,4} = \mu_{SC}\Delta t$

$P_{10,14} = \lambda_{CH}\Delta t$

$P_{10,17B} = \lambda_{SC}\Delta t$

$P_{10,18} = \lambda_{FB}\Delta t$

$P_{10B,10B} = 1 - (P_{10B,2} + P_{10B,14B} + P_{10B,17} + P_{10B,18B})$

$P_{10B,2} = \mu_{RB}\Delta t$

$P_{10B,14B} = \lambda_{CH}\Delta t$

$P_{10B,17} = \lambda_{SC}\Delta t$

$P_{10B,18B} = \lambda_{FB}\Delta t$

$P_{10A,10A} = 1 - P_{10A,4A}$

$P_{10A,4A} = \mu_{SC}\Delta t$

$P_{11,11} = 1 - P_{11,3}$

$P_{11,3} = \mu_{RB}\Delta t$

$P_{14,14} = 1 - P_{14,7}$

$P_{14,7} = \mu_{SC}\Delta t$

$P_{14B,14B} = 1 - P_{14B,5}$

$P_{14B,5} = \mu_{RB}\Delta t$

$P_{17,17} = 1 - P_{17,8}$

$P_{17,8} = \mu_{RB}\Delta t$

$P_{17B,17B} = 1 - P_{17B,10B}$

$P_{17B,10B} = \mu_{SC}\Delta t$

$P_{18,18} = 1 - P_{18,11}$

$P_{18,11} = \mu_{SC}\Delta t$

$P_{18B,18B} = 1 - P_{18B,9}$

$P_{18B,9} = \mu_{RB}\Delta t$

Table 5—Definition of transition probabilities for Model A and First-Come-First-Served Repair Policy (constant failure and repair rates).

Three reliability indices that stem from the average of the penalized availability function are defined. These indices measure the effect of the component's reliability in the system against any standard. They are:

1. *Forced Production Downtime Index* (FPDI) is defined as the expected or average duration of non-productive shifts per section for a specified time period due to equipment failure in the production line. It is given in shifts/year.
2. *Productivity Curtailment Index* (PCI) is defined as the expected or average amount of tons of coal per man-year which is not mined due to equipment failure. It is given in tons/man-year.
3. *Reliability Cost Index* (RCI) is defined as the cost of downtime due to equipment failure. It is given in dollars/year.

Face Equipment Subsystem Data[6]

In order to calculate the steady-state penalized availability, a meaningful data for hazard and repair rates for the fire pieces of equipment included in Figure 1 has to be used. Table 6 summarizes these data.

Results and Conclusions

The availability models for the face equipment subsystem are analyzed with the aid of a computer. The computer results are summarized and presented in a manner deemed useful for this study. Table 7 compares the steady-state availability and penalized availability values for the three models and two repair policies. They are calculated at the quiescent values of hazard and repair

Table 6.—Quiescent values of failure rate and mean time-to-repair used to analyze the availability models of the Face Equipment Subsystem.

EQUIPMENT	FAILURE RATE (failures/machine-shift)	MEAS TIME-TO-REPAIR (minutes)
Continuous Miner	$\lambda_{CM} = 0.40$	$r_{CM} = 75$
Shuttle Car	$\lambda_{SC} = 0.37$	$r_{SC} = 60$
Feeder-Breaker	$\lambda_{FB} = 0.14$	$r_{FB} = 80$
Roof Bolter—Model A	$\lambda_{RB} = 0.10$; $\lambda'_{RB} = 0.14$	$r_{RB} = 50$; $r'_{RB} = 80$
Roof Bolter—Model B	$\lambda'_{RB} = 0.24$	$r'_{RB} = 70$
Roof Bolter—Model C	$\lambda_{RB} = 0.24$	$r_{RB} = 70$

rates. The derating factor for the penalized availability is 50%. These values can be compared with the availability of a series reliability model which is found to be 0.824.

Numerically, the values are not widely apart but if the FPDI is calculated, the difference can become appreciable. Table 8 summarizes the FPDI values and is based on the availability and penalized availability given in Table 7. Between repair policies, there is a difference of 3-4.5 shifts/year of downtime.

The FPDI is appreciably different among the three availability models and between repair policies. The difference can go from 3 to 10 shifts/year. If a completely series reliability model is used for the subsystem, there is a difference of 17 to 20 shifts/year. If a classical availability function is used as opposed to the penalized availability, discrepancy of 17 to 19 shifts/year exists.

The sensitivity analysis gives rise to the following equation; that is,

$$A_p = A_{p0} + c_1\Delta\lambda_{CM} + c_2\Delta\lambda_{SC} + c_3\Delta\lambda_{FB} + c_4\Delta\lambda_{RB} + c_5\Delta\lambda'_{RB}$$

$$+ d_1\Delta\mu_{CM} + d_2\Delta\mu_{SC} + d_3\Delta\mu_{FB} + d_4\Delta\mu_{RB} + d_5\Delta\mu'_{RB} \qquad (4)$$

Table 9 summarizes the constants of equation (4) for each of the three models and an independent repair policy. Table 10 does the same for an FCFS repair policy. Two values for the c_i's are given. The one enclosed in parenthesis is used if the failure rate is in failures/machine-shift, while the other one is used if failure rate is in failures/machine-hour. Meanwhile, the repair rate should be expressed in repairs/hour.

Table 7. — Comparison of availability and penalized availability of the Face Equipment Subsystem for different roof bolter models and repair policies. Quiescent values of failure rate and repair rate are used.*

REPAIR POLICY	AVAILABILITY			PENALIZED AVAILABILITY		
	MODEL A	MODEL B	MODEL C	MODEL A	MODEL B	MODEL C
INDEPENDENT	0.900	0.891	0.919	0.864	0.855	0.882
FIRST-COME-FIRST-SERVED	0.893	0.883	0.911	0.858	0.849	0.873

* For a completes series reliability model, availability is the same as penalized availability and is equal to 0.824.

Table 8. — Comparison of the Forced Production Downtime Index in shifts/year for different roof bolter models and repair policies. The index is calculated based on the availability and penalized availability values given in Table 7.*

REPAIR POLICY	BASED ON AVAILABILITY			BASED ON PENALIZED AVAILABILITY		
	MODEL A	MODEL B	MODEL C	MODEL A	MODEL B	MODEL C
INDEPENDENT	50	54.5	40.5	68	72.5	59
FIRST-COME-FIRST-SERVED	53.5	58.5	44.5	71	75.5	63.5

* For a complete series reliability model, the FPDI is 88 shifts/year.

The equation allows a lot of flexibility in analyzing reliability trade offs and cost of reliability improvement among the pieces of equipment in the subsystem. The constants of equation (4) suggest that if the failure rate of any equipment can be reduced by any amount, then one should concentrate on the feeder-breaker because it creates the greatest improvement in the penalized availability. If it is the repair rate which can be improved by any amount, then it must be done for the continuous miner. On the other hand, if the least percentage change in failure rate is the easiest and most economical way to improve the FPDI, then one should work on the continuous miner.

The output derating factor k affects considerably the value of FPDI. For k between 0.5 and 0.1, the FPDI for the data of Table 6 can have values that differ by as many as 15 shifts/year. Moreover, when the derating factor is reduced to a value less than 30%, the shuttle car has the greatest influence on the penalized availability (or FPDI) both from the standpoint of least percentage criterion and smallest numerical increment criterion if the failure rates are changed.

Table 9.—Summary of the values of A_{po} and the constants c and d of equation (4) for an Independent Repair Policy and derating factor k = 0.5.

ASSOCIATED VARIABLE	COEFFICIENTS	VALUES OF COEFFICIENTS Model A	Model B	Model C
—	A_{po}	0.864	0.855	0.882
$\Delta\lambda_{CM}$	c_1	-0.954 (-0.1193)	-0.934 (-0.1168)	-0.994 (-0.1243)

$\Delta\lambda_{SC}$	c_2	-0.786 (-0.0983)	-0.773 (-0.0966)	-0.810 (-0.1013)
$\Delta\lambda_{FB}$	c_3	-1.020 (-0.1275)	-0.997 (-0.1246)	-1.060 (-0.1325)
$\Delta\lambda_{RB}$	c_4	0.014 (0.0018)	—) (—)	0.000 (0.000)
Δ'_{RB}	c_5	-1.010 (-0.1263)	-0.871 -0.1089	— (—)
$\Delta\mu_{CM}$	d^1	0.060	0.059	0.063
$\Delta\mu_{SC}$	d_2	0.035	0.035	0.037
$\Delta\mu_{FB}$	d_3	0.024	0.024	0.025
$\Delta\mu_{RB}$	d_4	-0.000	—	-0.000
$\Delta\mu'_{RB}$	d_5	0.024	0.031	—

Table 10.—Summary of the values of A_{po} and the constants c and d of equation (4) for an FCFS Repair Policy and derating factor $k = 0.5$.

ASSOCIATED VARIABLE	COEFFICIENTS	VALUES OF COEFFICIENTS Model A	Model B	Model C
—	A_{po}	0.858	0.850	0.873
$\Delta\lambda_{CM}$	c_1	-0.987 (-0.1234)	-0.960 (-0.1200)	-1.050 (-0.1313)
$\Delta\lambda_{SC}$	c_2	-0.923 (-0.1154)	-0.910 (-0.1138)	-0.952 (-0.1190)
$\Delta\lambda_{FB}$	c_3	-1.050 (-0.1313)	-1.020 (-0.1275)	-1.110 (-0.1388)
$\Delta\lambda_{RB}$	c_4	-0.046 (-0.0058)	— (—)	-0.113 (-0.0141)

$\Delta\lambda'_{RB}$	c_5	-1.030 (-0.1288)	-0.897 (-0.1121)	— (—)
$\Delta\mu_{CM}$	d_1	0.060	0.059	0.062
$\Delta\mu_{SC}$	d_2	0.044	0.049	0.045
$\Delta\mu_{FB}$	d_3	0.024	0.023	0.025
$\Delta\mu_{RB}$	d_4	0.001	—	0.007
$\Delta\mu'_{RB}$	d_5	0.024	0.031	—

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