RELIABILITY OF A CHEMICAL PROCESS SYSTEM: A SIMULATION APPROACH

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ABSTRACT

This paper presents a general approach to estimation of the reliability of a chemical production system using discrete system simulation. Three factors which are considered to be of major importance in the reliability of a chemical system are design (e.g. serial or parallel units), the failure patterns of the individual units, and the maintenance policies and staffing. A GPSS simulation model which takes into account all three factors has been developed and is illustrated by use of an example.

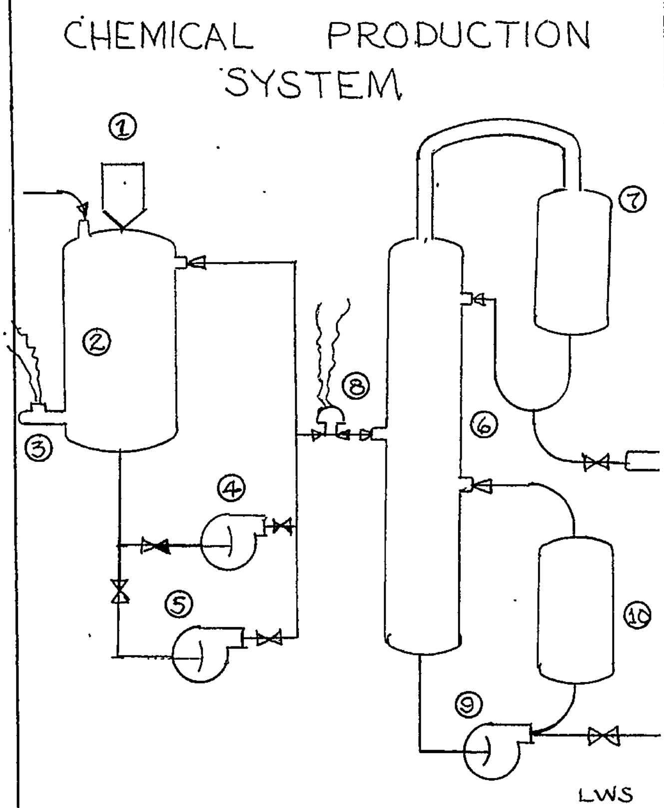
BACKGROUND

Reliability has been formally defined (1) as follows: "Reliability is the probability that an item will perform a defined task satisfactorily for a specified length of time when used for the purpose intended and under the conditions for which it was designed to operate". That probability is often referred to as the probability of survival. Three terms used frequently in reference to reliability are failure, hazard rate, and mean time to failure. The mathematical definitions of these terms and the relationships of each to reliability are given in Appendix A; a more complete treatment of the subject is given in (1) and (5).

Historically, the electronics and aerospace industries were foremost in applying the theory and principles of reliability. Current literature on the subject of reliability reflects the predominance of applications in those two industries. Although many parallels can be drawn between a system of electrical components performing some function and a continuous chemical production system there are some important differences when it comes to applying reliability concepts. In this paper an attempt is made to characterize the problem and to present one method for estimating the reliability of a chemical production system.

In the chemical industry bulk or high volume products are generally produced in large production systems which operate continuously rather than in batch mode. A typical system consists of a reactor and a series of distillation columns complete with heat exchangers, pumps, and instrumentation. The system components, or units, are assembled serially into a train as shown in Figure 1. Frequently two or more units are placed in parallel to improve the system reliability. Typically, the product flows in

FIGURE 1



Item No.	Item	Item No.	Item
1	Agitator Motor	6	Distillation Col.
2	Reaction Vessel	7	Vapor Condensor
3	Level Sensor	8	Flow Control Valve
4	Product Pump	9	Liquid Circulating Pump
5	Auxiliary Product Pump	10	Heat Exchanger

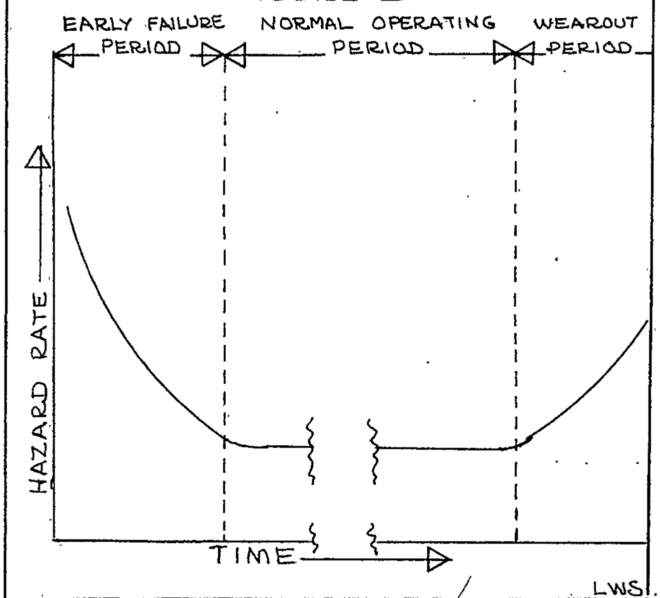
an interrupted stream from one unit to the next although some in-process storage may be provided to dampen the effects of minor process upsets.

Type of Failure

Since reliability of a chemical production system refers to probability of survival of the total system not all of the units in a typical system need be included in an evaluation. In other words not all units in a typical system design are critical to the survival of the system. Chemical production systems probably have from ten to one hundred critical units.

Most of the failures which occur are due to wear out, however, some are due to early failure or "infant mortality". Figure 2 shows a plot of hazard rate versus time for a typical unit of equipment. Hazard is more often used by industry than the failure rate as the measure of the breakdown rate because the data is usually easier to gather in that form.

FIGURE 2



Failure of a critical unit can be described as partial, complete or catastrophic. Partial failures are quite common and generally are just one stage in the gradual deterioration of performance. Examples of partial failure are leaking of product through mechanical seals, reduced catalyst activity, reduced output from pumps and compressors due to wearout, and reduced separation of products in a distillation column due to minor damage from corrosion or abrasion. Complete failure occurs when there is a total stoppage of the unit or when performance has reached an intolerably low or hazardous stage. A catastrophic failure is a complete failure which occurs suddenly and may result in damage to other units.

When a critical item of equipment fails, the system must be shut down until that item is repaired or replaced. Downtime will depend upon the item, the severity of the failure, availability of men and materials, and the maintenance priority. If an auxiliary or spare item is installed in parallel the system downtime may be only the time required to divert the product flow and start the auxiliary unit. For that situation much depends on whether the failure of the first unit was partial, in which case there is usually ample time to smoothly switch to an auxiliary or parallel unit. But if the failure was catastrophic there may be insufficient time for recovery and even though a parallel unit is available a total system failure is likely.

Maintenance Practices and Policies

Since rotating mechanical equipment such as pumps, compressors and motors require special skills and tools to repair the usual practice is to establish a central shop for such repairs. The failed units are removed, transported to the shop, repaired, transported back and installed. While the central shop concept may allow for higher quality work it obviously imposes burdens on the organization when rapid turnaround is important. The availability of the required maintenance crafts and skills, transportation equipment, and expediting service is therefore a factor in system reliability in a chemical plant.

The policy of the plant toward the stocking of spare units is also a factor in system reliability. If the unit design is unique within the plant then a failed unit must be repaired and returned directly to the system from which it came. Where system outage cost is high relative to the cost of the equipment for a unique design then the spare can usually be justified and installed as a parallel unit. Pumps, compressors and other rotating equipment of unique design with relatively high mechanical failure rate often are installed in parallel.

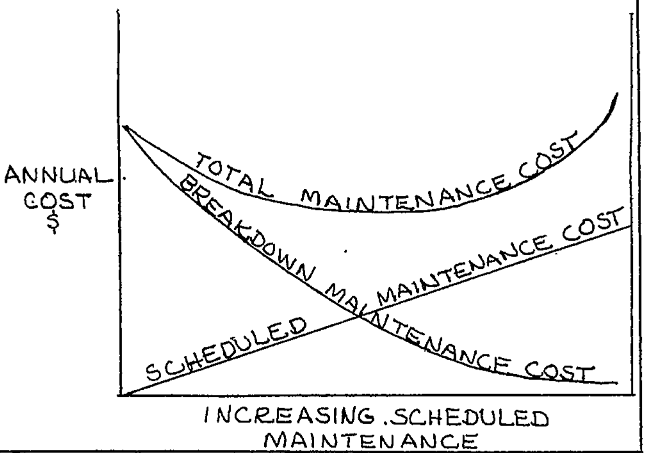
For other types of equipment, such as instrumentation or electric motors, design probably is not unique; e.g., there may be many such items within the plant. For such units the system downtime is only long enough to remove the failed unit and replace it with a similar unit from the plant inventory of spares. After repair the failed unit is returned to the plant spares inventory. System downtime in such a case is the length of time to replace the unit with a plant spare if available. Inventory policy, therefore, becomes an important factor in the system reliability.

Maintenance and Other Costs

Maintenance can be divided into two major categories the first of which are those repairs which are a direct result of a system breakdown. The costs attributable to the repairs include not only the labor and materials to repair the unit but also the cost of lost production. The other category of maintenance is that of repairs and adjustments done to extend the life of the unit and to prevent breakdown. Such maintenance is scheduled in advance. If a planned shutdown of the system is required in order to perform the scheduled maintenance then the usual practice is to take that opportunity to schedule several such repairs at the same time to reduce the total system downtime. Shutdowns can be planned when partial failures are known or when predictive techniques such as vibration analysis or statistical inference based on failure history are used to avoid catastrophic failure.

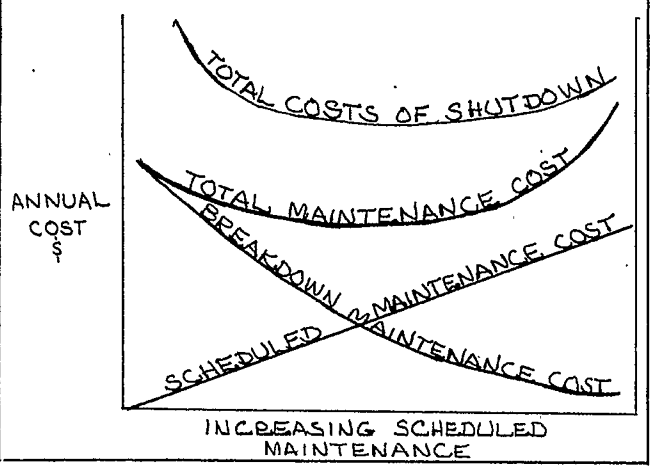
There is an economic trade-off between breakdown maintenance and the scheduled maintenance. The more frequent the scheduled maintenance is performed then the less frequent will breakdowns occur. If only maintenance costs are considered the cost

FIGURE 3.



curves will resemble Figure 3 . If shutdown costs are added then the total costs will resemble Figure 4.

FIGURE 4.



Ways to Improve Reliability

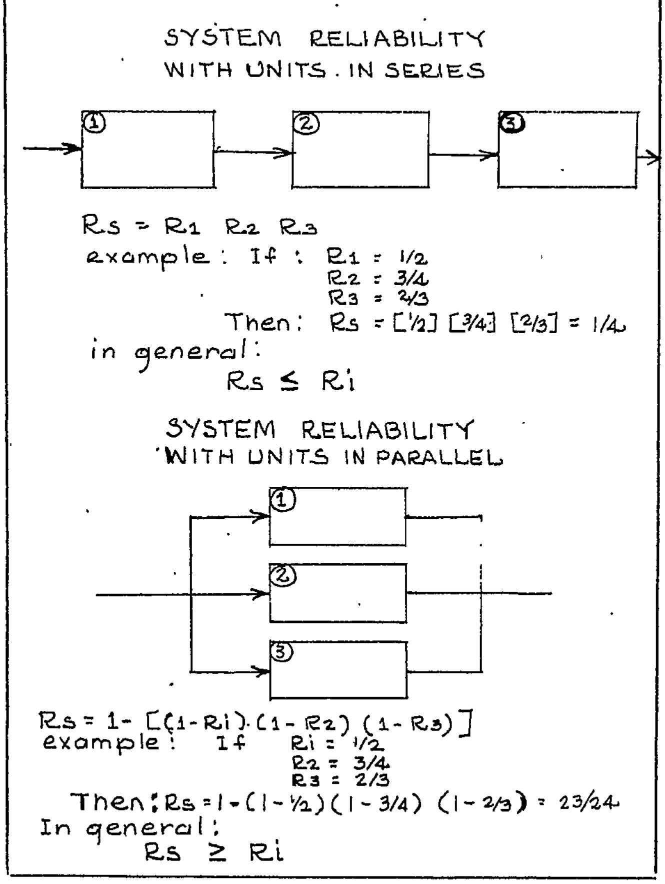
To improve the reliability of a production system there are seven distinguishable (2) courses of action. The seven listed below with comments on their application to a chemical production system.

1. Use more reliable components. Although it is immediately obvious that such a course of action is beneficial the information which is required as a basis for selection is usually not avilable. Three reasons account for the void:

   a) whereas in the electronics industry use of a specific component may easily number in the millions a specific model (e.g. pump of a specific type) for use in the process industry may at most number in the thousands and more likely in the tens or hundreds,
   b) process conditions to which a component is subjected have such an important bearing that data on identical components in different services often cannot be grouped for comparison purposes,
   c) mean time to failure is generally so long that several years may be required to gather sufficient data on a specific component in order to predict reliability.

2. Install parallel units (see Figure 5). Again the benefits for such a course of action are

FIGURE 5.



obvious but there are many considerations, such as providing adequate instrumentation, which must go into the system design to make such a solution practical. As indicated in the discussion above there has been a failure in primary unit and before total system shutdown is necessary. Good predictive maintenance techniques such as vibration analysis and statistical inference based on historical data can help in making parallel design more effective.

3. Design the system so that the units are easy to get to for inspection and repair. The effect of such a course of action on the reliability of the system can be tested by the model described in this paper.

4. Utilize a preventive maintenance policy. The question to be resolved with this course of action is how much preventive maintenance should be done. Figure 3 shows hypothetical cost curves which intuitively represent the true relationships of cost to increasing amounts of preventive maintenance. In actual practice it is practically impossible to capture the supporting data for such relationships because:
   a) there is an unknown time lag between the performance of a given level of preventive maintenance and the arrival at equilibrium of the corresponding breakdown costs and
   b) total time span to collect representative data may be several years and therefore the effects of a specific preventive maintenance policy may be obscured by other factors such as process changes.
5. Increase the size of the repair crew so that mean time to repair a failed unit can be reduced. As with a preventive maintenance policy there is no question about the benefits to be derived but rather the real question is what is the optimal size to make the pool of available maintenance crafts. The question has many aspects such as the profitability of the system, the cost of labor, the availability of contract services, the failure patterns of all production systems being serviced by the maintenance pool, etc.. The model described in this paper can be used to evaluate a given set of conditions but not to direct search for the optimum pool size.
6. Maintain spare parts inventory. As with the two previous items on this list it is obviously good to maintain an inventory of spare parts but an optimization problem is at the heart of the issue. A good assessment of the contribution of spare parts to the reliability of a specific system requires historical data which identifies parts used by that system.
7. Maintain interstage inventories in order to decouple successive stages of the production system.

In the illustrative example given in this paper only factors 1, 2, 3 and 5 from the above list were included in the sample model although similar models in actual use have incorporated changes in the other factors too.

THE MODEL

It should be evident at this point that determination of the operating time of a chemical production system may be too complex for an analytical model. One technique available for such a situation is simulation. In the remainder of this paper use of GPSS to build a general model of such a processing system is described. The assumption is made that the reader is familiar with simulation in general.

Data Collection

To model the chemical production system one first needs the general system layout such as shown in Figure 1. It is important to note which of the units are in parallel for reliability purposes. In the example shown, unit numbers 4 and 5 serve the same purpose and only one must be in operation for the system to operate. All of the other units in the system must operate or else the system fails.

The next step is to convert historical data on the failure of individual units into a distribution function and compute the mean time to failure. Two bases can be used for collecting the data and for modeling reliability and it is important to distinguish the two and keep the usage consistent. In the first and most frequently used basis the time between failures for any specific unit is elapsed time; the implied assumption is that when that specific unit is not in failure state, the entire system is operating. While there is an obvious error in such an assumption it is by far and away the easier way to collect data and to develop the model. The model used in this paper is developed using the basis just described, because such data was already available. The second basis counts time between failures as only the time which the unit is actually operating.

There are cases where the elapsed time basis for gathering data will lead to significant error in the results. These might include: (1) when the system downtime, for any reason, is a significantly high percentage the total time (perhaps even as low as 5 percent, depending primarily on cost of downtime), (2) when it is desirable to develop distribution functions from failure data collected on similar units from several different types of systems, (3) when the downtime for any one unit is a high percentage of the total system downtime. Where such restrictions or conditions exist (which was not the case in the present problem) it is important to collect the data and build the model on actual system operating time between failures.

In the model presented here, time between failures has been represented as exponential with the mean a function of the unit type. Historically exponential functions have been used more than any other type to represent time between failures. In more recent work, however, Weibull models have been found to give a more accurate representation of the actual failure patterns in the early portion of the operating life when infant mortality is a factor and in the latter portion of operating life when wearout becomes much more prevalent.

The final step before modeling is to collect information on the plant maintenance procedures and policies. In the model presented in this paper, the typical situation is represented. There is one central shop in the plant and the large failed units are removed and transported to that shop for repair. Maintenance crews are available locally to the system for removing and replacing the failed units. Transportation between the system and the shop requires a significant amount of time and must be included in the model. There are queues on all three services, local repair crews, transportation, and shop crews and facilities.

Program Logic

The primary treatment of the system for simulation is as follows: a) the system is considered to be a storage which has capacity for the exact number of units in the system, b) the elements flowing through the system are the units. A new or repaired unit enters the system storage as soon as there is space, c) the unit number in storage becomes synomous with the type of unit represented. The unit number, therefore, provides the linkages to the failure patterns, etc., for that type of unit, d) when a unit fails it does not leave the storage until either a replacement has been found or the original unit has been repaired and is ready to be returned to service. At that point in the simulation logic the unit which was in failure state but which is now repaired leaves the storage and simultaneously a similar unit in good repair enters the storage.

The treatment of the production system as a storage for individual units and the supporting logic allows for easy tabulation in the model of the vital reliability data. A flow chart of central logic within the model is shown in Figure 8 and the corresponding GPSS program is listed in Appendix B.

Model Objective

The objective of the simulation is to develop an estimate of the system reliability. Since reliability is synomous with the probability of successful operation the study objective can be restated as being the development of an estimate of the fraction of time which the system will operate satisfactorily for an assumed set of conditions and policies.

Because the ultimate objective of a study in an industrial environment is to make economic comparisons, it is desirable to translate the system reliability and the underlying parameters into costs and profits. Some study parameters, such as maintenance policies, are easily translated into dollars since the changes in service rates are directly related to changes in manpower. Other changes are much more difficult to translate into direct costs. Investment for example must be depreciated over the life of the item of equipment. Cost of downtime is much more complicated because it implies both lost profits in the short range and lost customers in the long range. Methods of treatment of the costs and profits are well documented but outside the scope of this study and therefore will not be considered further. The emphasis in this paper is on determination of the system reliability as a function of several parameters with the underlying assumption that the economics can be developed.

AN EXAMPLE

A model was constructed for the typical system design shown in Figure 1. The system is assumed to be part of a plant containing many such systems. There is a crew of repair men in the local vicinity of the system to make repairs and to remove the equipment when it must be sent to a central shop for extensive repairs. Transportation to and from the shop must be shared with other systems in the plant.

The time to failure, repair and transport times are assumed to have an exponential distribution. Figure 6 shows the data on mean times used in this example.

```
MATRIX HALFWORD NUMBER 2
    ROWS  = UNIT INDEX
    COL1  = MEAN TIME TO FAILURE
    COL2  = MEAN TIME TO REPAIR
    COL3  = MEAN TIME TO REMOVE/INSALL
    COL4  = MEAN TRANSPORT TIME
```

MATRIX HALFWORD SAVEVALUE 2

	COL. 1	2	3	4
ROW 1	400	11	4	2
2	1900	10	3	3
3	200	9	5	2
4	500	11	9	3
5	500	12	7	2
6	2800	10	4	3
7	2500	9	3	2
8	800	8	6	3
9	300	7	5	2
10	1800	6	2	3
11	300	7	5	2

FIGURE 6

Unit numbers 4 and 5 are in parallel and only one need be in operation for the system to operate. For all of the other units whole system is down if any if any unit is down due to a severe failure. Special accounting must be used for the parallel units since the system is down only if all units in parallel are down. Severity of failure is the measure of the need for repairs extending from only minor repairs by a local crew to major repairs in the shop. Two different functions in the model produce random severity of failure from a prespecified index for each unit. Figure 7 shows the severity of failure index and the linkages for parallel units. Note that only data changes and not program changes are required when configuration of the system changes.

The output from the model included a table of queue times for each item of equipment and for the local repair crew, transportation, and the shop, and the distribution of system failure times as well as the total system downtime for one year of simulated operation (8760 hours).

The following four cases were considered in the example problem in order to test proposed changes to improve system reliability:

1. Base case: initial design
2. Case I: similar to the base case but replacing the critical unit 9 with a more

reliable one (MTF 300 hours instead of 600 hours).

3. Case II: similar to the base case but increasing the size of the local repair crew so that the repair time for all work is reduced to 2 $\pm$ 1 hours.
4. Case III: similar to the base case but with a second unit 9 installed in parallel.

The results of the four cases are summarized in Figure 7. It appears that the last case is the best among the four considered alternatives. The system was down only 2.2% of the time, and never longer than 40 hours. Of course, the small size of the simulation illustrated in this example does not permit general conclusions. However, it is obvious that longer simulations and examination of more alternatives could aid management in adopting the engineering design and maintenance policy which are more to their advantage.

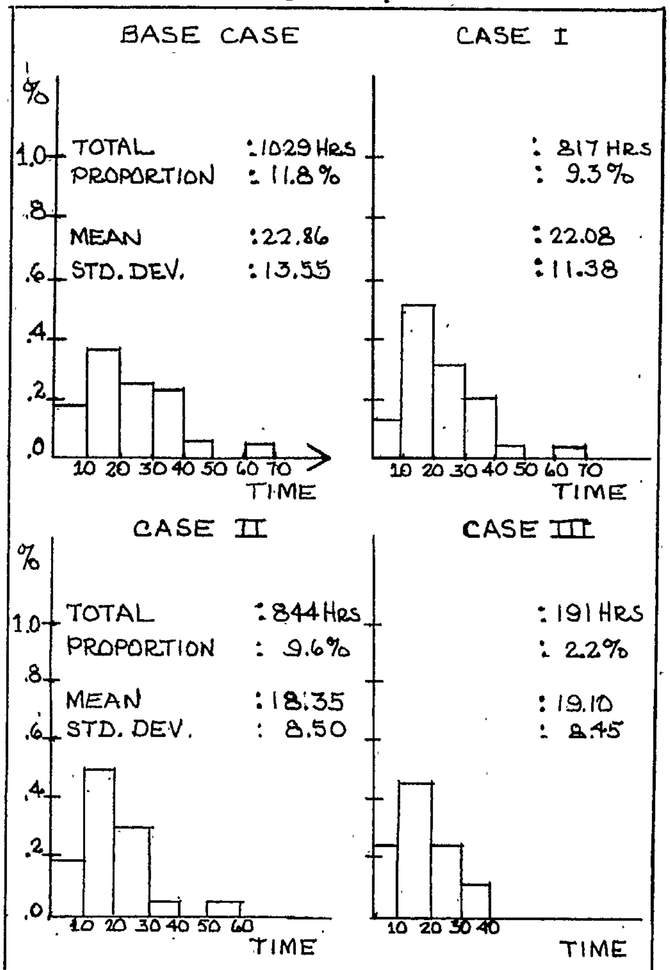


FIGURE 7. SYSTEM DOWNTIME DISTRIBUTION.

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APPENDIX A

Definitions of Terms

RELIABILITY

$R(t) = Pr(X > t) = 1 - F(t)$ Reliability R is the probability of successful performance or more specifically the probability that an item will not fail before time t (where the random variable X represents the life length of the item).

FAILURE

$f(t) = \frac{dF(t)}{dt}$ Failure rate f(t) is the instantaneous speed of failure, i.e. the probability density function

or

$f(t) = \lim_{\Delta t \to 0} \frac{n(t) - n(t+\Delta t)}{N \Delta t}$ Failure rate at a specified time is the change in the number of surviving units n(+) over some time interval Δt normalized with respect to the original population N.

HAZARD

$Z(t) = \frac{f(t)}{R(t)}$ Hazard rate at a specified time is the change in the number of surviving units n over some time interval Δt normalized with respect to the number of surviving units n(t)

or

$Z(t) = \lim_{\Delta t \to 0} \frac{n(t) - n(t+\Delta t)}{n(t) \Delta t}$ Hazard rate is the failure rate relative to the reliability at a specified time, i.e. the conditional probaility that an item will fail given that it survived up to time t.

MEAN TIME TO FAILURE

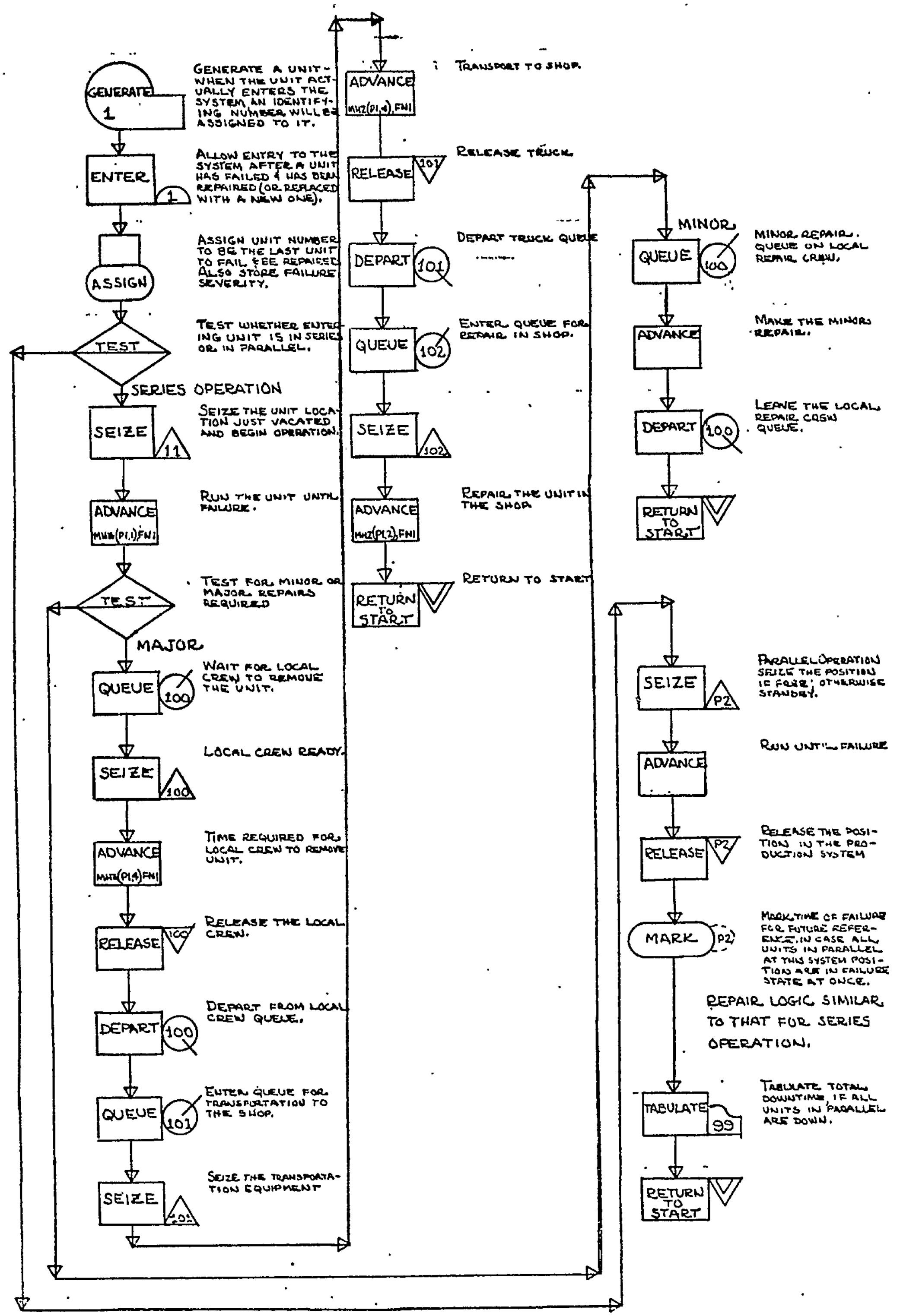
$$MTTF = \int t f(t)dt = \int R(t)dt$$

Mean time to failure is the expected life length.

$$MTTF = E(t) = \frac{1}{n}\sum_{i=1}^{n} t_i$$

Mean time to failure is the average failure time of n units failing at times $t_i (i=1,2,...,n)$

FIGURE 8. SKELETON LOGIC FOR GPSS PROGRAM



```
*       SIMULATION TO DETERMINE THE RELIABILITY OF A CHEMICAL PRODTN SYS
*
*
*   ASSIGNMENT OF INFORMATION STORAGE UNITS
*
*      TRANSACTION PARAMETERS
*         1    NUMBER  OF THE UNIT WHICH THIS TRANSACTION REPRESENTS
*         2    FACILITY NO. IF DIFFERENT THAN UNIT NO. (PARALLEL UNITS)
*         3    FAILURE SEVERITY FOR NEXT FAILURE OF THIS UNIT
*         4    FAILURE SEVERITY FUNCTION INDEX
*      QUEUES
*         1    DOWNTIME FOR THE FIRST UNIT
*         2    DOWNTIME FOR THE SECOND UNIT
*         3    DOWNTIME FOR THE THIRD UNIT
*         .
*         .
*         .
*         N    DOWNTIME FOR THE NTH UNIT
*         100 UNIT MAINTENANCE CREW
*         101 VEHICLE FOR TRANSPORTATION TO SHOP
*         102 REPAIR SHOP
*
*      HALFWORD SAVEVALUES
*         1    TOTAL NUMBER OF UNITS IN THE SYSTEM
*         2    COUNTER USED DURING SYSTEM START-UP
*         3    NUMBER OF THE LAST UNIT TO FAIL
*         4    SYSTEM DOWNTIME FOR THEIS TRANSACTION
*         5    TOTAL SYSTEM DOWNTIME
*
*      FULLWORD SAVEVALUES
*         1    TOTAL SYSTEM DOWNTIME
*
*      MATRIX HALFWORD NUMBER 1
*         ROWS = UNIT INDEX
*         COL1 = NUMBER OF UNITS IN PARALLEL
*         COL2 = COMMON FACILITY NUMBER FOR PARALLEL UNITS
*         COL3 = INDEX FOR FAILURE SEVERITY FUNCTION FOR THIS UNIT
*         COL4 = 1 IF UNIT CAN BE GIVEN PREVENTATIVE MAINTENANCE
*      MATRIX HALFWORD NUMBER 2
*         ROWS  = UNIT INDEX
*         COL1  = MEAN TIME TO FAILURE - HOURS
*         COL2  = MEAN TIME TO REPAIR IN THE SHOP - HOURS
*         COL3  = MEAN TIME TO REMOVE/INSALL OR REPAIR BY LOCAL CREW
*         COL4  = MEAN TRANSPORT TIME TO/FROM SHOP - HOURS
*
       SIMULATE
*
*    POISSON FUNCTION
 1        FUNCTION    RN1    C24
0         0          .1       .104      .2        .222
.3        .355       .4       .509      .5        .69
.6        .915       .7       1.20      .75       1.38
.8        1.6        .84      1.83      .88       2.12
.9        2.3        .92      2.52      .94       2.81
.95       2.99       .96      3.2       .97       3.5
.98       3.9        .99      4.6       .995      5.3
.998      6.2        .999     7         .9998     8
*      FAILURE SEVERITY FUNCTIONS FOR UNITS AS SPECIFIED IN MH1
 2        FUNCTION    RN2    D11
0         0          .1       1         .2        2
```

```
.3        3         .4        4         .5        5
.6        6         .7        7         .8        8
.9        9         1.0       10
3         FUNCTION  RN3       D11
0         0         0.5       1         0.6       2
0.8       3         0.9       4         0.95      5
0.97      6         .98       7         .99       8
.999      9         1.0       10
*     THE FOLLOWING FUNCTIONS MODEL THE CHARACTERISTICS OF THE UNIT
*             CLEAN-UP FOR REPAIR AND START-UP AFTER REPAIR
*
8         FUNCTION  RN3       C7
0         0         .5        3         .6        3.5
.7        3.8       .8        4.0       .9        4.5
1.0       5.0
9         FUNCTION  RN3       C11
0         0         .1        2         .2        3
.3        5         .4        7         .5        7.5
.6        8.3       .7        9.5       .8        11
.9        12        1.0       14
 1        STORAGE   10
 1        MATRIX    H         11        4
          INITIAL   MH1(4,1),2/MH1(4,2),4
          INITIAL   MH1(5,1),2/MH1(5,2),4
          INITIAL   MH1(9,1),2/MH1(9,2),9
          INITIAL   MH1(11,1),2/MH1(11,2),9
          INITIAL   MH1(1,3),2
          INITIAL   MH1(2,3),2
          INITIAL   MH1(3,3),3
          INITIAL   MH1(4,3),2
          INITIAL   MH1(5,3),2
          INITIAL   MH1(6,3),2
          INITIAL   MH1(7,3),2
          INITIAL   MH1(8,3),3
          INITIAL   MH1(9,3),2
          INITIAL   MH1(10,3),2
          INITIAL   MH1(11,3),2
 2        MATRIX    H         15        4
          INITIAL   XH1,11
          INITIAL   MH2(1,1),0400/MH2(1,2),11/MH2(1,3),4/MH2(1,4),2
          INITIAL   MH2(2,1),1900/MH2(2,2),10/MH2(2,3),3/MH2(2,4),3
          INITIAL   MH2(3,1),0200/MH2(3,2),09/MH2(3,3),5/MH2(3,4),2
          INITIAL   MH2(4,1),0500/MH2(4,2),11/MH2(4,3),9/MH2(4,4),3
          INITIAL   MH2(5,1),0500/MH2(5,2),12/MH2(5,3),7/MH2(5,4),2
          INITIAL   MH2(6,1),2800/MH2(6,2),10/MH2(6,3),4/MH2(6,4),3
          INITIAL   MH2(7,1),2500/MH2(7,2),09/MH2(7,3),3/MH2(7,4),2
          INITIAL   MH2(8,1),0800/MH2(8,2),08/MH2(8,3),6/MH2(8,4),3
          INITIAL   MH2(9,1),0300/MH2(9,2),07/MH2(9,3),5/MH2(9,4),2
          INITIAL   MH2(10,1),1800/MH2(10,2),06/MH2(10,3),2/MH2(10,4),3
          INITIAL   MH2(11,1),300/MH2(11,2),7/MH2(11,3),5/MH2(11,4),2
 1        QTABLE    1         10        10        10
 2        QTABLE    2         10        10        10
 3        QTABLE    3         10        10        10
 4        QTABLE    4         200       200       10
 6        QTABLE    6         10        10        10
 7        QTABLE    7         10        10        10
 8        QTABLE    8         10        10        10
 9        QTABLE    9         10        10        10
10        QTABLE    10        10        10        10
96        QTABLE    100       10        10        10
97        QTABLE    101       10        10        10
```

```
 98     QTABLE      102    10      10      10
 99     TABLE       MP9    10      10      10
*
  1     GENERATE    1
  2     ENTER       1
  3     TEST E      XH2    XH1     5
  4     TRANSFER           7
  5     SAVEVALUE   2      S1      H
  6     SAVEVALUE   3      S1      H
  7     ASSIGN      1      XH3
  8     ASSIGN      4,MH1(P1,3)
  9     ASSIGN      3      FN*4
 10     TEST E      MH1(P1,1),K0,46
*
*   LOGIC BELOW IS FOR UNITS WITH NO PARALLEL REPLACEMENT.
*
*
 11     SEIZE       P1
 12     ADVANCE     MH2(P1,1),FN1
 13     RELEASE     P1
 14     TEST GE     P3     K5      83
 15     QUEUE       P1
 16     MARK        9
 17     ADVANCE     FN8
 18     QUEUE       100
 19     SEIZE       100
 20     ADVANCE     MH2(P1,3),FN1
 21     RELEASE     100
 22     DEPART      100
 23     QUEUE       101
 24     SEIZE       101
 25     ADVANCE     MH2(P1,4),FN1
 26     RELEASE     101
 27     DEPART      101
 28     QUEUE       102
 29     ADVANCE     MH2(P1,2),FN1
 30     DEPART      102
 31     QUEUE       101
 32     SEIZE       101
 33     ADVANCE     MH2(P1,4),FN1
 34     RELEASE     101
 35     DEPART      101
 36     QUEUE       100
 37     SEIZE       100
 38     ADVANCE     MH2(P1,3),FN1
 39     RELEASE     100
 40     DEPART      100
 41     TABULATE    99
*                                    CALCULATE THE UNIT DOWNTIME AND
 42     SAVEVALUE   5+     MP9     H
 43     ADVANCE     FN9
 44     DEPART      P1
 45     TRANSFER           88
*
*   PARALLEL UNITS OPERATION
*   NOTE THAT THE ACCOUNTING FOR THE SYSTEM DOWNTIME IS DIFFERENT FOR
*         PARALLEL UNITS
*
 46     ASSIGN      2,MH1(P1,2)
*                                    THERE ARE OTHER UNITS IN PARALLEL WITH
 47     SEIZE       P2
```

```
 48     ADVANCE       MH2(P1,1),FN1
 49     RELEASE       P2
*
 50     QUEUE         P2
 51     MARK          9
 52     SAVEVALUE     4        P9      H
*
 53     SEIZE         100
 54     QUEUE         100
 55     ADVANCE       MH2(P1,3),FN1
 56     RELEASE       100
 57     DEPART        100
 58     QUEUE         101
 59     SEIZE         101
 60     ADVANCE       MH2(P1,4),FN1
 61     RELEASE       101
 62     DEPART        101
 63     QUEUE         102
 64     ADVANCE       MH2(P1,2),FN1
 65     DEPART        102
 66     QUEUE         101
 67     SEIZE         101
 68     ADVANCE       MH2(P1,4),FN1
 69     RELEASE       101
 70     DEPART        101
 71     SEIZE         100
 72     QUEUE         100
 73     ADVANCE       MH2(P1,3),FN1
 74     RELEASE       100
 75     DEPART        100
 76     TEST E        F*2      K0      88
 77     ASSIGN        9        XH4
 78     SAVEVALUE     4        MP9     H
 79     SAVEVALUE     5+       XH4     H
 80     TABULATE      99
 81     DEPART        P2
 82     TRANSFER      .        88
*
*   LOGIC BELOW IS FOR MINOR FAILURES HANDLED BY THE LOCAL REPAIR CREW
*        NO SYSTEM DOWNTIME
*
 83     QUEUE         100
 84     SEIZE         100
 85     ADVANCE       MH2(P1,3),FN1
 86     RELEASE       100
 87     DEPART        100
*
*
*
 88     SAVEVALUE     3        P1      H
 89     LEAVE         1
 90     TERMINATE
*
 91     GENERATE      8760
 92     TERMINATE     1
        START         1
```