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Availability Studies for Processing Systems with In-process Storage

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by

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Abstract

Availability studies for processing systems with in-process storage

Methods of availability planning determine with regard to existing data of process parameters whether

- the effectivity (availability) of the processing system is sufficient to guarantee production for a definite period or
- improvements of the system structure are possible to increase effectivity.

Exact approximative (both by Markov - modelling) and simulative solutions are shown and applied in the field of nuclear waste management.

Zusammenfassung

Verfügbarkeitsstudien für Prozeßsysteme mit Zwischenlagern

Methoden der Verfügbarkeitsplanung ermöglichen es bei vorgegebenen Daten zu Prozeßparametern festzustellen, ob

- die Effektivität (Verfügbarkeit) eines Prozeßsystems hinreichend ist, um die Produktion für einen vorgeschriebenen Zeitraum zu garantieren, bzw.
- Verbesserungsmöglichkeiten der Systemstruktur bestehen, um die Effektivität zu erhöhen.

Exakte, approximative (beides mit Hilfe von Markov-Modellen) und simulative Lösungen werden dargelegt und im Bereich der nuklearen Abfallbehandlung angewandt.

Contents

1. Subject of the study

The subject of our studies are production systems consisting of a given number of interrelated process parts (process units, machines). The material to be produced passes (flows) successively through all process parts. Normally, a process part operates at a given production rate (throughput). Then it fails and the production of the machine is interrupted until successful repair work has been done.

In nuclear engineering the reprocessing of spent nuclear fuels and the process systems for storage without canisters and solidification of MLW/LLW in caverns below ground (in-situ concept) are examples of the systems mentioned above. (MLW = Medium Level Waste, LLW = Low Level Waste)

2. The problem

The problem consists in determining the "effectivity" of the production system using methods of systems analysis.

The measure of effectivity of the production system is the availability which is defined by the quotient of mean productive time and total time available or, in other words, by the quotient of the actual throughput obtained and the theoretically possible throughput. The throughput is the production rate in units of mass per unit of time. With the help of systems analysis we try to find out whether

- the effectivity of the production system is sufficient to guarantee production for a definite period, or
- improvements of the system structure are possible to increase effectivity.

The studies concern the data of production rates, mean production and repair times, storage capacities etc.

3. Description of the situation

On the basis of flowcharts of production specified for the plant in question, structures of block diagrams must be developed which take into account the logical sequence of production. They resemble the schematic block diagrams used in reliability computations and can serve as models for mathematical and simulation treatment, respectively.

The individual steps of production are exposed to random influences (process parts fail unexpectedly, repairs take different times depending on the nature of failure. That may cause problems in the production process. Therefore, measures must be taken as early as possible in the planning phase to ensure a smooth sequence of production.

4. Improvement of the situation

It can be said that a strong interdependence by a serial arrangement of process parts will lead generally to the standstill of the whole system as soon as only one machine fails.

To reach the aim of production the following steps can be taken

- improvement of the reliability (and availability, respectively) of machines;
- redundant planning of machine parts;
- construction of storage buffers.

It depends on the constructional, process technological and economic conditions which measures seem to be suitable for the increase of the effectivity of the production system.

5. Possible solutions

Our aim is to indicate the effectivity, i.e. the availability of the underlying production system. Since failures or different duration of processes are not only of deterministic nature but also of a random (stochastic) nature, the random behavior of the production system must be considered, Therefore, the digital simulation or mathematical modeling based on the theory of the stochastic processes can be used for analysis.

5.1 Mathematical modeling

In this paragraph a survey of the mathematical instruments and the necessary postulations are presented.

Regarding the first two possibilities (improvement of reliability, redundancy), well-known methods and results of reliability computation can be applied. Methods and results for analyzing production system including intermediate storage buffers seem to be less well-known.

5.1.1 Production systems with and without intermediate storage buffers of infinite size

Serial systems are systems of elements in series. The failure of one element (component) causes the whole system to fail. Two modes of behavior can be distinguished:

a) If one component fails, the other components are forced down, i.e. always one component only can have failed at a time. Here a dependence exists: If one machine fails, the failure probabilities of the other machines are set zero. (Operation dependent failures)

b) If one component fails, the rest of components will continue to "operate" and therefore they may still fail.
The failure probabilities remain the same. (Time dependent failures)

The following can be shown:

For systems with k components ('k-stage line' without storage buffers) the system availability V_{sys}, i.e., the probability P that the system is intact, is given by

$$\text{(a)} \quad V_{sys}^{(a)} = P(\text{System intact}) = \left(1 + \sum_{i=1}^{k} \frac{MTTR_i}{MTBF_i}\right)^{-1}$$

$$\text{(b)} \quad V_{sys}^{(b)} = \prod_{i=1}^{k} \frac{MTBF_i}{MTTR_i + MTBF_i} ,$$

(MTBF = Mean Time Between Failure; MTTR = Mean Time To Repair)

However, these formulas can be applied for serial production systems with discrete production and material flow through the system only on condition that

- If one machine fails, all the other machines will stop.
- Unloading of a machine must coincide with loading of the machine which follows.
- A machine stops either at the beginning or at the end of a processing step since otherwise semi-finished workpieces are produced.
- Simultaneous failures of several machines are impossible.

We have the following inequalities:

$$V_{sys}^{(b)} \leq V_{sys}^{(a)} \leq V_{sys}^{\infty} = \min_{1 \leq i \leq k} \{V_i\} , \tag{5.1}$$

where V_{sys}^{∞} is the availability of a k-stage line with intermediate storage buffer of infinite size. Thus, the availability of a serial line is substantially restricted by its "weakest" component.

5.1.2 Production systems with finite intermediate storage buffers

Suitably chosen intermediate storage buffers permit to reduce the influence of machine failures on the production. To describe such systems in a formal mathematical model one needs detailed knowledge about the theory of the Markov processes. The indication of closed formulas for calculation of the system availability offers the advantage that the dependence of availability can be described formally for any values of system parameters. To study weak points and to make detailed analyses, respectively, the mathematical description of the system behavior may be useful.

With $p_i = 1/MTBF_i$; $r_i = 1/MTTR_i$; M_i = stage i ... i = 1, ..., k .

Zl_j = Buffer j ; N_j = Capacity of Zl_j j = 1, ..., k-1

and D = Throughput (normalized D=1)

we have:

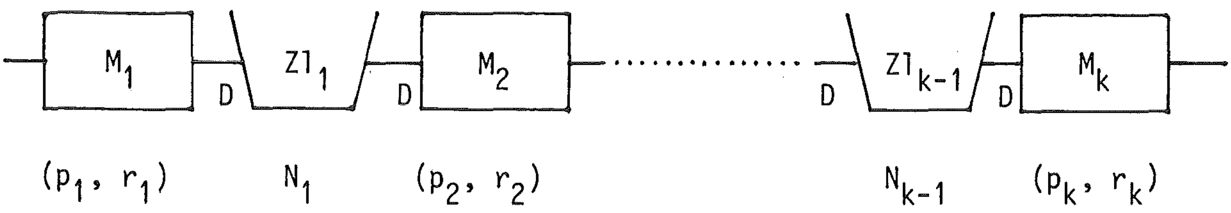


Fig. 1: k-stage line with storage buffers

Specific assumptions are made concerning the state space and the distributions of system parameters:

- The system has reached a steady (stationary) state.
- The operating and repair times are distributed geometrically for a discrete parameter space with the probabilities p_i and r_i ($i = 1, \ldots, k$), and for a continuous parameter space, respectively, they are distributed exponentially with the parameter $\lambda_i = 1/MTBF_i$, $\mu_i = MTTR_i$ ($i=1,\ldots,k$).
- Successive operation and repair times are mutually independent.
- The time of transport of workpieces is negligible.
- The supply for the first machine is reliable. The last machine can always deliver its products. For the i-th machine of a k-stage line a variable α_i is defined:

$$\alpha_i = \begin{cases} 0 & \text{in case machine i is intact} \\ 1 & \text{in case machine i is defective} \end{cases}$$

The state of the j-th storage buffer ($j = 1,\ldots,k-1$) is described by the variable n_j ($0 \leq n_j \leq N_j$). The system state can be described by the vector

$$(\alpha_1,\ldots,\alpha_k \, ; \, n_1,\ldots,n_{k-1})$$

The number of system states is:

$$2^k \prod_{j=1}^{k-1} (N_j + 1) \qquad (5.2)$$

Then the system availability, V^N_{sys}, is defined as the sum of all probabilities of system states on condition that:
The last machine delivers a finished product to the storage buffer.

5.1.2.1 Two-stage line with one storage buffer

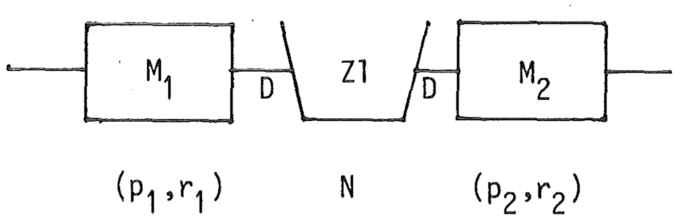


Fig. 2: Two-stage line with one storage buffer

We use a well-known result of Buzacott /1/ for a two-stage line with a storage buffer.

$$s := \frac{p_2}{r_2} \cdot \frac{r_1}{p_1} = \frac{1-V_2}{V_2} \cdot \frac{V_1}{1-V_1} = \frac{s_2}{s_1} \qquad (5.3)$$

$$s_1 := \frac{p_1}{r_1} \qquad s_2 := \frac{p_2}{r_2} \qquad r = \frac{p_2}{p_1} \qquad (5.4)$$

$$C = \frac{(p_1+p_2)\ (r_1+r_2) - p_1 r_2 (p_1+p_2+r_1+r_2)}{(p_1+p_2)\ (r_1+r_2) - p_2 r_1 (p_1+p_2+r_1+r_2)} \qquad (5.5)$$

For a long period, T, both stages must have equal efficiencies.
The total line efficiency for the two-stage system can be expressed as follows

$$\begin{aligned} V^N_{sys} &= V^o + B_1\ h_{12}(s,N) \\ &= V^o + B_2\ h_{21}(s,N) \qquad V^o := V^{(a)}_{sys} \end{aligned} \qquad (5.6)$$

where

$$B_i := \frac{p_1}{r_i} V^o \qquad i=1,2$$

are the proportion of the period T that the first and second stages respectively are under repair.

h_{12} is the proportion of the time in T when the first stage is under repair that the line is up,

h_{21} is the proportion of the time in T when the second stage is under repair that the first stage is operating.

$$\begin{aligned} d_{12} &:= 1-h_{12} \\ d_{21} &:= 1-h_{21} \end{aligned} \qquad (5.7)$$

Buzacott /1/ presents the formula:

$$h_{12}(s,N) = \begin{cases} s(1-C^N)/(1-sC^N) & s \neq 1 \\ N r_1 r_2/(r_1+r_2+(N-1)r_1 r_2) & s = 1 \end{cases} \qquad (5.8)$$

and

$$h_{21}(s,N) = h_{12}(s,N)/s$$

We have the inequalities:

$$V_{sys}^{(b)} \leq V_{sys}^{(a)} \leq V_{sys}^{N} \leq V_{sys}^{\infty} \quad (5.9)$$

Buzacott's formula tends to overestimate line efficiency. This is because of the assumption that both stages will not be broken at the same time.

Groover /6/ mentions that it seems more accurate to express the total line efficiency of a two-stage line as follows

$$V_{sys}^{N} = V^{o} + B_1 \; V_2 \; h_{12}(s,N) \quad (5.10)$$

Remark

Parameter studies have shown:

- The decisive parameter for the dimensioning of intermediate storage buffers is the mean repair time of the system components.
- With the intermediate storage capacity increasing, the gain in system availability declines.
- For a predetermined storage buffer capacity well-balanced systems (i.e., the availability of the components is nearly identical) provide the maximum system availability achievable.

Variants of such 'two-stage models' and comparative studies on 'three-stage models' have been described in detail in /3/, /5/, /7/ - /9/.

Multistage lines with storage buffers can no longer be treated in an exact mathematical way. This would be too complicated because of the number of system states (see (5.2)).

Nevertheless, the mathematical tools developed for two-stage and three-stage lines can be used for k-stage lines. For this purpose, larger serial systems with intermediate storage buffers are decomposed into a number of two-stage and three-stage lines with storage buffers respectively and treated by known methods of computation (for details see /4/).

The quality of such approximation techniques is not known since exact formulas of computation for system availability are not available.

It seems that the convergence of approximation procedures has been neglected up to now. For this reason I intend to describe an approximation procedure and try to prove its monotony and convergence properties.

5.1.2.2 Three-stage line with two storage buffers
(Approximation procedure)

We now have a closer look at an extended line with corresponding parameters.

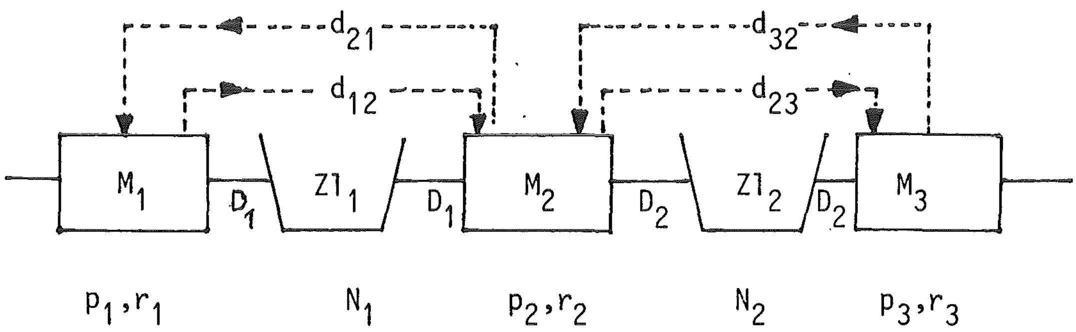


Fig. 3: Three-stage line two storage buffers

Parameters:

p_i := Breakdown rates

r_i := Repair rates ; $r_1 = r_2 = r_3 =: r_c$

D := Throughput ; $D := D_1 = D_2$ (D = 1)

d_{ij} := Coefficient of disturbance from M_i to M_j $(i \neq j)$

(i = 1,2,3 ; j = 1,2,3)

We try to trace back the calculation for extended lines to two-stage or three-stage lines by putting machines and storage buffers together.

According to Buzacott the well-known calculation method for the treatment of two-stage lines can be applied. For the present I confine myself to systems which components have identical repair rates.

5.1.2.2.1 CASE A: Equal repair rates

Algorithm

Step 1:

- Calculate availability, $V_{A(1)}$, of the two-stage line

$$A(1):\quad M_1 - Zl_1 - M_2$$

with parameters:

$$(p_1,r_c) - N_1 - (p_2,r_c)\ ,\qquad d_{12}(1)$$

- Compute variable $u_2(1)$ from:

$$V_{A(1)} = (1 + (u_2(1)/r_c))^{-1} \tag{5.11}$$

- Define:

$$u_2(1) := p_2 + p_1\ d_{12}(1) \tag{5.12}$$

and

$$n = 1$$

Step 2:

- Calculate the total availability, $V_{SL(n)}$, of the 'two-stage line':

$$\begin{array}{llllll} SL(n): & A(n) & \text{——} & Zl_2 & \text{——} & M_3 \\ & (u_2(n),r_c) & \text{——} & N_2 & \text{——} & (p_3,r_c)\ ,\quad d_{32}(n) \end{array}$$

with

$$\begin{array}{llllll} A(n): & M_1 & \text{——} & Zl_1 & \text{——} & M_2 \\ & (p_1,r_c) & \text{——} & N_1 & \text{——} & (p_2,r_c)\ ,\quad d_{12}(n) \end{array}$$

- Compute variable $u_3(n)$ from :

$$V_{SL(n)} = (1 + (u_3(n)/r_c))^{-1} \tag{5.13}$$

- Define:

$$u_3(n) := u_2(n) + p_3\, d_{32}(n) \qquad (5.14)$$

$$v_2(n) := p_2 + p_3\, d_{32}(n) \qquad (5.15)$$

Step 3:

- Calculate the total availability, $V_{SR(n)}$, of the 'two-stage line':

$$SR(n): \quad M_1 \text{ —— } Zl_1 \text{ —— } B(n)$$
$$(p_1, r_c) \text{ —— } N_1 \text{ —— } (v_2(n), r_c), \quad d_{12}(n+1)$$

with

$$B(n): \quad M_2 \text{ —— } Zl_2 \text{ —— } M_3$$
$$(p_2, r_c) \text{ —— } N_2 \text{ —— } (p_3, r_c), \quad d_{32}(n)$$

- Calculate variable $v_1(n)$ from:

$$V_{SR(n)} = (1 + (v_1(n)/r_c))^{-1} \qquad (5.16)$$

- Define:

$$v_1(n) := v_2(n) + p_1\, d_{12}(n+1) \qquad (5.17)$$

$$u_2(n+1) := p_2 + p_1\, d_{12}(n+1) \qquad (5.18)$$

Step 4:

Compare $V_{SR(n)}$ and $V_{SL(n)}$, that is $v_1(n)$ and $u_3(n)$

- If $| V_{SR(n)} - V_{SL(n)} | \leq \varepsilon$, then

  for prescribed $\varepsilon > 0$, we approximatively have:

  $$V^N_{sys} = V_{SR(n)} \approx V_{SL(n)}$$

- If $| V_{SR(n)} - V_{SL(n)} | > \varepsilon$, then
  . increase n by one and
  . go back to step 2.

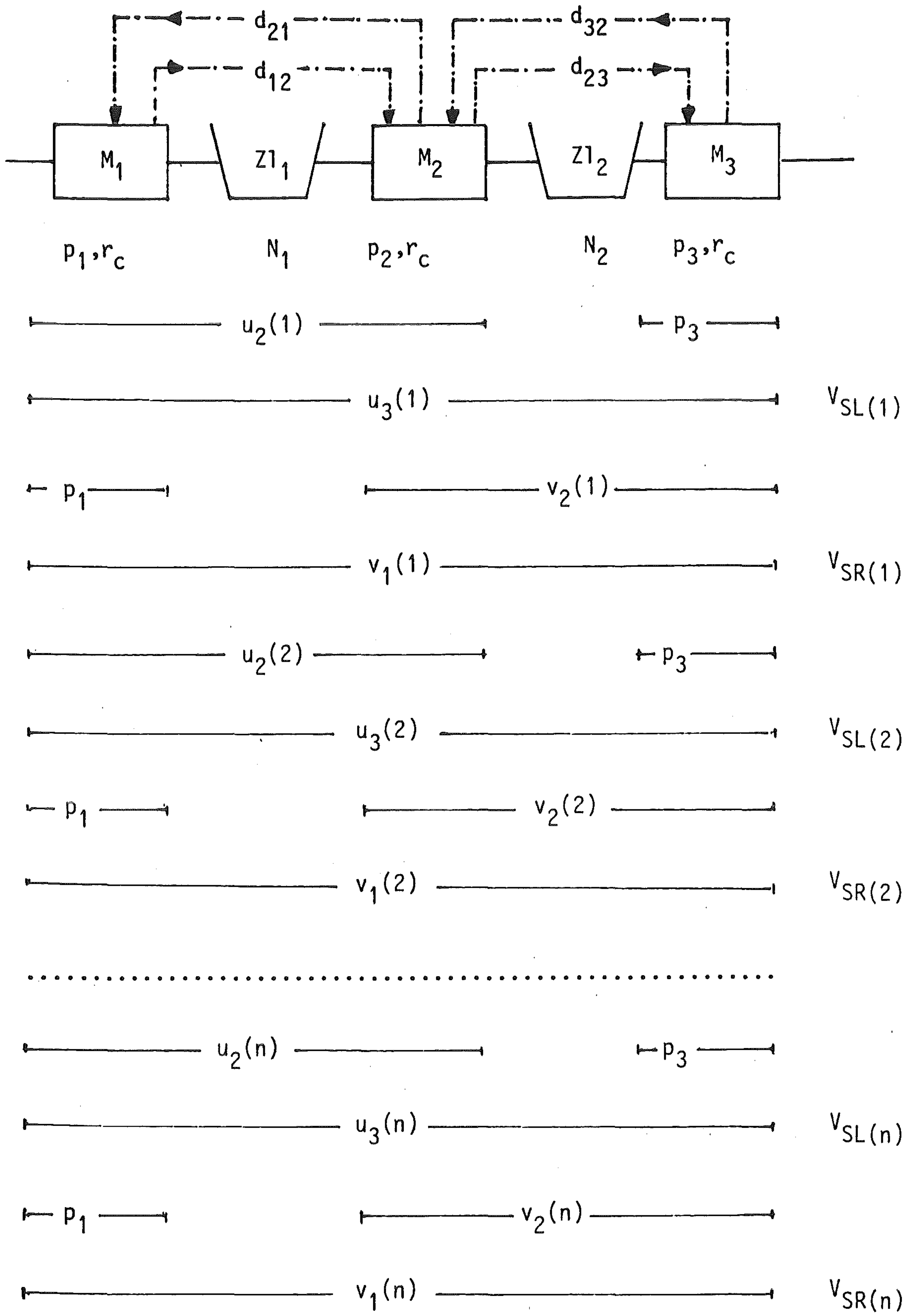


Table 1: Scheme of procedure

$n = 1$	$p_1, p_2 \rightarrow$	$d_{12}(n)$ $u_2(n)$
	$u_2(n), p_3 \rightarrow$	$d_{32}(n)$ $u_3(n)$
	$p_2, p_3, d_{32}(n) \rightarrow$	$v_2(n)$
	$p_1, v_2(n) \rightarrow$	$d_{12}(n+1)$ $v_1(n)$
$n > 1$	$p_1, p_2, d_{12}(n) \rightarrow$	$u_2(n)$
	$u_2(n), p_3 \rightarrow$	$d_{32}(n)$ $u_3(n)$
	$p_2, p_3, d_{32}(n) \rightarrow$	$v_2(n)$
	$p_1, v_2(n) \rightarrow$	$d_{12}(n+1)$ $v_1(n)$

Table 2: Sequence of parameter - calculation.

Remark

The problem is how to determine (calculate) the breakdown rates $u_2(n)$ resp. $v_2(n)$ of a fictitious 'machine' A(n) (two-stage line) resp. of a fictitious 'machine' B(n) (two-stage line). We know the breakdown rates $u_3(n)$ and $v_1(n)$ from the calculations of the availability $V_{SL(n)}$ and $V_{SR(n)}$. We solve formulas containing $u_3(n)$ resp. $v_1(n)$ for $d_{32}(n)$ resp. $d_{12}(n+1)$. These terms are put in the formulas for $u_2(n)$ and $v_2(n)$.

We get recursively:

For n = 1,2,3,....

$$u_2(n+1) = v_1(n) - v_2(n) + p_2 \tag{5.19}$$

$$v_2(n) = u_3(n) - u_2(n) + p_2 \tag{5.20}$$

The assumption of a two-stage line with one storage buffer as a fictitious exponential machine is nothing but an approximation as in general there is no (geometric) exponential operation or failure behaviour. In certain cases the difference of the exponential (geometric) behaviour is slight (compare Buzacott /1/).

Lemma 5.1

Because of formulas (5.6) - (5.8) the avaibility, V^N_{sys}, is increasing in the variables V_1, V_2 that is V^N_{sys} is decreasing in p_1, p_2 (if r_1, r_2 are constant).

Proof: clear

Lemma 5.2

Sequences $\{d_{12}(n)\}$ resp. $\{d_{32}(n)\}$ are decreasing resp. increasing in n.

Proof:

Because of Buzacott /2/

$$d_{12}(S,N) = 1 - h_{12}\,(S,N)$$

is decreasing in p_2 (increasing in p_1) and

$$d_{32}(s,N) = 1 - h_{32}(s,N)$$

is increasing in p_3 (decreasing in p_2).

We have:

$$d_{32}(n) = d_{32}\left(\frac{p_3}{u_2(n)}, N\right)$$

$$d_{12}(1) = d_{12}\left(\frac{p_2}{p_1}, N\right)$$

$$d_{12}(n) = d_{12}\left(\frac{v_2(n-1)}{p_1}, N\right) \qquad n \geq 2$$

□

<u>Chain of consequences:</u>

<u>Step 1</u>:

$$v_2(1) > p_2 \quad \rightarrow \quad (L.2) \quad d_{12}(2) < d_{12}(1)$$

set n = 1

<u>Step 2</u>:

$$d_{12}(n+1) < d_{12}(n) \quad \rightarrow \quad (p.d.) \quad u_2(n+1) < u_2(n)$$

$$(L.2) \downarrow (L.1)$$

$$v_2(n) < v_2(n+1) \; (p.d.) \quad \leftarrow \quad d_{32}(n) < d_{32}(n+1)$$

$$u_3(n+1) < u_3(n)$$

$$\downarrow (L.2)$$

$$d_{12}(n+2) < d_{12}(n+1)$$

<u>Step 3</u>:

If $|v_1(n) - u_3(n)| \leq \varepsilon$ then stop

If $|v_1(n) - u_3(n)| > \varepsilon$, then

increase n by one and go back to Step 2.

Summary of consequences

1.) $\{v_2(n)\}$ is increasing in n and has an upper bound.

2.) $\{u_2(n)\}$ is decreasing in n and has a lower bound.

3.) $\{v_1(n)\}$ is increasing in n and has an upper bound.

4.) $\{u_3(n)\}$ is decreasing in n and has a lower bound.

Lemma 5.3 :

$$u_3(n) \geq v_1(n) \qquad \text{for all } n$$

Proof:

By (5.19) and (5.20) we have:

$$\begin{array}{l} v_2(n) = u_3(n) - u_2(n) + p_2 \\ v_2(n) = v_1(n) - u_2(n+1) + p_2 \\ \hline u_3(n) - v_1(n) = u_2(n) - u_2(n+1) \end{array} \quad \Big| \; -$$

By consequence 2 the lemma is proved.

Especially:

$$\max u_3(n) \geq \min v_1(n) \quad \text{or äq.}$$

$$\min V_{SL(n)} \geq \max V_{SR(n)}$$

□

Theorem 5.1

We suppose the increasing sequence $\{v_1(n)\}$ and the decreasing sequence $\{u_3(n)\}$ under the condition

$$v_1(n) \leq u_3(n) \quad \text{for all } n .$$

If $\{z(n)\}$ has the limit $\lim_{n\to\infty} z(n) = 0$, where $z(n) := u_3(n) - v_1(n)$,

there is a unique limit g

$$g = \lim_{n\to\infty} u_3(n) = \lim_{n\to\infty} v_1(n)$$

Proof:

By Lemma (5.1) - (5.3) and consequences 3 and 4 we only have to demonstrate:

$$\lim_{n\to\infty} z(n) = 0$$

By the convergence of the sequence $\{u_2(n)\}$ we have

$$\lim_{n\to\infty} y(n) = 0$$

where $y(n) = u_2(n) - u_2(n+1)$

and $z(n) = y(n)$. □

5.1.2.2.2 CASE B: Unequal repair rates

Now we are able to extend the results of Case A to three-stage lines with unequal repair rates.

The algorithm of approximation operates in the same way as before.

We define for the system (p_1,r_1) — N — (p_2,r_2)

$$V_i := (1+s_i)^{-1} \qquad i = 1,2$$

where $s_i = p_i/r_i \qquad s = s_2/s_1$ (see (5.4))

and

$$s_{sys} = s_1 + s_2\, d_{12} \text{ bzw. } s_{sys} = s_2 + s_1\, d_{21} \quad . \tag{5.21}$$

The probability, P_{out}, of a system breakdown is the inverse of cycle time

$$\begin{aligned} P_{out} &= 1/\text{cycle time} \\ &= 1/(MTBF_{sys} + MTTR_{sys}) \end{aligned} \tag{5.22}$$

$$\begin{aligned} V_{sys} &= MTBF_{sys}/(MTBF_{sys} + MTTR_{sys}) \\ &= r_{sys}/(p_{sys} + r_{sys}) \end{aligned} \tag{5.23}$$

The formulas for the two-stage system

$$(p_2,r_2) — N_2 — (p_3,r_3)$$

are analogue to (5.21) - (5.23).

Remark

We choose the following notations vs_1, vs_2, us_2, us_3 resp. (5.12) - (5.18).

We get the variable r_{sys} of the corresponding two-stage lines from the parameters s_{sys} and $MTBF_{sys}$ of the two-stage lines using (5.24).

Another approximation method is the so-called

Simple method:

Step 1: Calculate V_{12}, availability of stage 1 and 2 in isolation.

Step 2: Find x by $V_{12} = 1/(1+x)$
and calculate the parameters p_x and r_x $(x = p_x/r_x)$

Step 3: Calculate V_{23}, availability of the two-stage system where parameters of first stage are x, p_x, r_x and of second stage are p_3, r_3.

Step 4: Take the total line availability as V_{23} .

(You can use this method for multistage lines, too)

In the three-stage case a good agreement was found of the results obtained under the exact (E), the approximation (A), the simple (ASM) and the simulation (S) methods (see the examples in Table 3). The simulation will be treated in more detail in the following section.

case	p_1	p_2	p_3	r_1	r_2	r_3	N	E	S	ASM	A
1	.2	.3	.4	.4	.3	.5	2	.4136	.3844	.4070	.3935
2	.2	.3	.4	.4	.3	.5	3	.435	.4028	.430	.4153
3	.2	.3	.4	.4	.3	.5	4	.4495	.4188	.445	.4308
4	.2	.3	.4	.4	.3	.5	5	.4598	.4369	.456	.4424
5	.2	.3	.4	.4	.3	.5	6	.4675	.4467	.465	.4514
6	.2	.3	.4	.4	.5	.5	7	.4734	.4547	.471	.4586

Table 3: Example of three-stage lines

Note: Always S < A < ASM < E on this data.

In case of line systems containing up to eight intermediate storage buffers parameter studies were made to compare approximation with simulation.

Case	Number of machines	p_1	p_2	p_3	p_4	r_1	r_2	r_3	r_4	N	S	ASM	A
1	4	.05	.025	.01	.05	.02	.015	.01	.015	8	.6735	.6347	.6950
2	5	M_1 - M_4 as in case 1 $M_5 = M_1$								8	.6456	.6223	.6848
3	6	M_1 - M_5 as in case 2 $M_6 = M_2$								8	.6327	.6056	.6829
4	7	M_1 - M_6 as in case 3 $M_7 = M_3$								8	.6269	.5933	.6694
5	8	M_1 - M_7 as in case 4 $M_8 = M_4$								8	. 6202	.5739	.6554
6	9	M_1 - M_8 as in case 5 $M_9 = M_1$								8	.6046	.5618	.6481

Table 4: Multi-stage line with storage buffers of size N

Note: Always ASM < S < A on this data.

Remark

It's advantageous to describe processing systems by formulas in order to indicate precisely the influence of parameters on the effectivity. That's why the studies of nuclear plants use as far as possible formal descriptive methods (theory of reliability, Markov processes, etc.). However it's difficult to adapt mathematical models to technical particularities.

Therefore simulation seems to be a more flexible means.

6. Simulation of production systems
(Application in nuclear technology)

For systems more complex than line systems without or with intermediate storage buffers, e.g. branched flow charts of reprocessing plants and the flow charts of waste treatment (Figs. 4-7) simulation techniques are suitable to simulate processes. Such techniques offer some advantages:

- Simulations are flexible concerning the process structure and thus permit to consider technological particularities.
- The operations and repairs are randomly distributed. Random generators can generate data.
- Several parameters may be subjected to variations. It is possible to compare various measures to improve the total availability.

For availability studies of the structures above a simulation program was developed and applied at the IDT institute which is called APSIS (Availability for Processing Systems with Interstage Storage). The programming language is SIMULA.

Example (in-situ concept)

LLW/MLW concentrates pellets from a reprocessing plant are mixed above ground at the final repository site with a cement suspension and flow into a cavern through a feed pipe. The product consisting of pellets and suspension hardens on the cavern. Before the LLW/MLW concentrate is finally stored, the following steps must be performed: granule production, production of the granule cement suspension, conveyance of the product below ground.

The effectivity of the production system must be sufficient to feed the cavern over a period of five years (corresponding to 15,000 m^3/a of conditioned MLW/LLW).

On the basis of flow charts of production (process) technology specified for the plant in question, structures of block diagrams must be developed which take into account the logical sequence of production. They resemble the block diagrams used in reliability computations and can serve as models for simulative treatment.

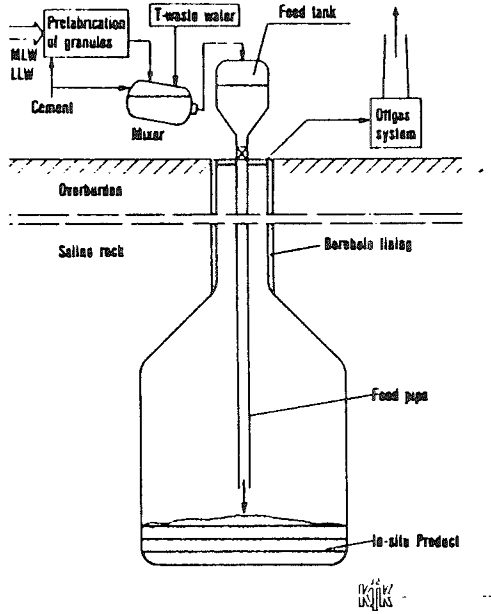


Fig. 4 Scheme of the In-situ Concept.

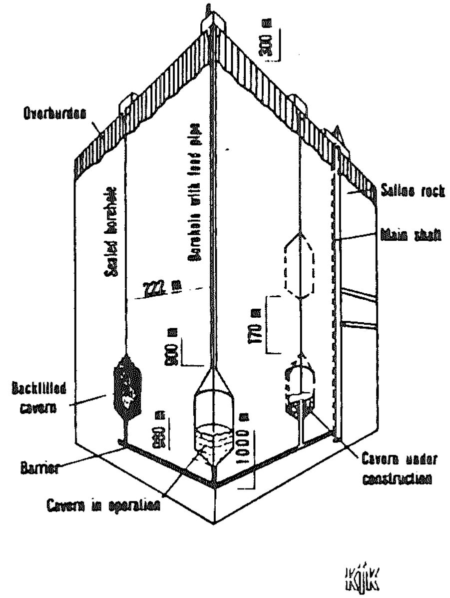
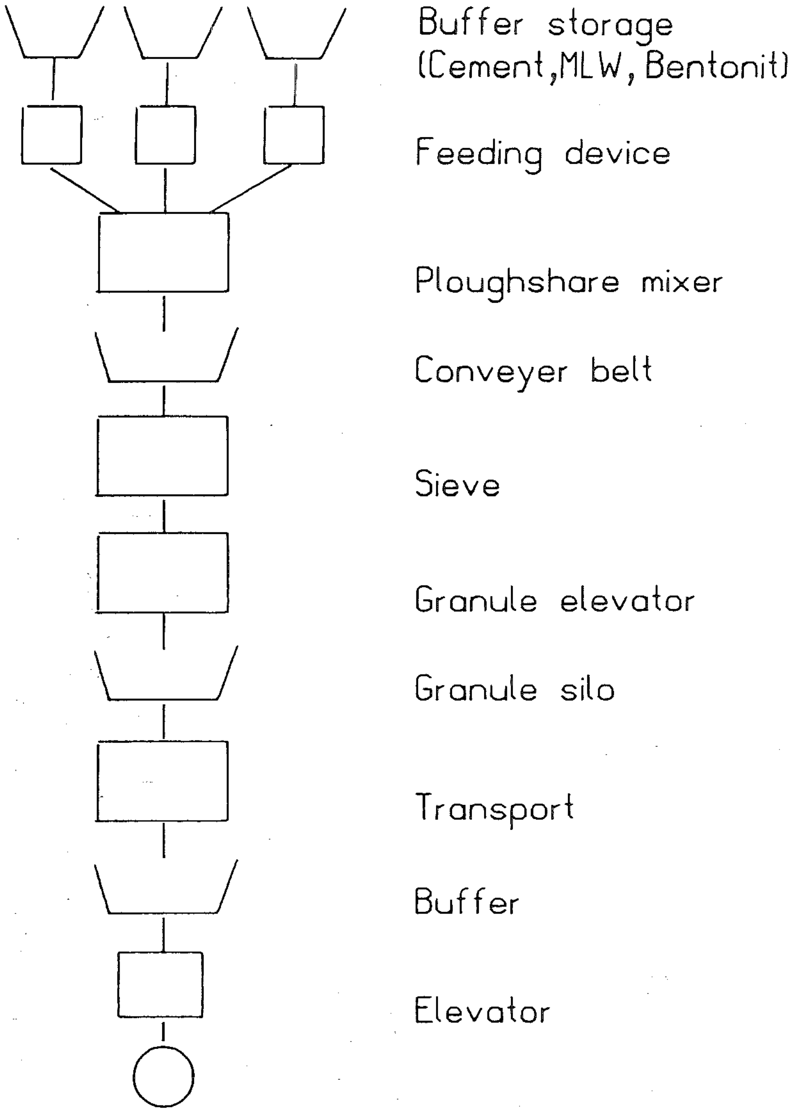


Fig.5 In-situ Cavern System.



IDT 4.3.83 Fisch 8

Fig. 6

Block diagram of granule production

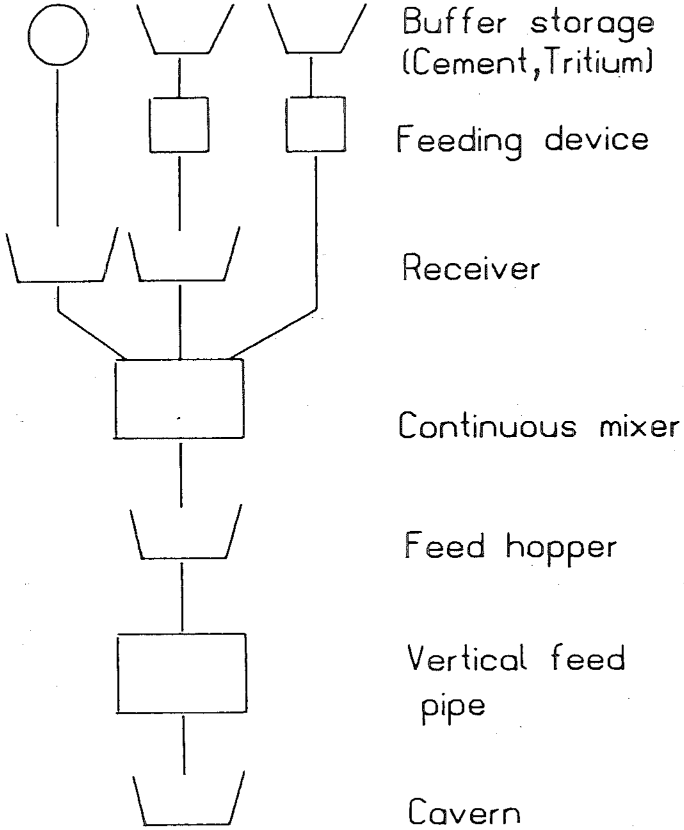


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Fig. 7

Block diagram of mixing and feeding plant

To avoid unnecessary simulation times the best thing was to an obvious solution to divide the flow chart of the in-situ concept into "granule production" and the "mixing and feeding" system (cf. Figs. 4-7). The parameters of the facility can be seen from Tables 5 and 6.

Units	Capacity (m^3)	Throughput (m^3/h)	Availability *
Buffer (Cement)	100	-	-
Buffer (Bentonit)	10	-	-
Buffer (MLW/LLW)	10	-	-
Feeding device	-	19 Cem/2 Bent/ 5,5 MLW/LLW	0.97
Ploughshare mixer	-	3	0.97
Conveyer belt	2.5	-	0.97
Sieve	-	6	0.97
Granule elevator	-	6	0.97
* chosen for all components: MTBF = 90 days, MTTR = 3 days → V = 0.97			

Table 5: Characteristics of granule production

Units	Capacity (m^3)	Throughput (m^3/h)	Availability *
Transport	-	5	0.97
Granule silo	40	-	0.97
Elevator	-	5	0.97
Buffer (Granule)	5	-	0.96
Buffer (Tritium)	20	-	0.96
Feeding device (Tritium)	-	1	0.97
Cement silo	30	-	0.96
Feeding device (Cement)	-	20	0.97
Buffer (Cement)	3	-	0.96
Continuous mixer	-	5	0.97
Feed hopper	7	-	0.96
Vertical feed pipe	-	4.4	0.97
* chosen for all components: MTBF = 90 days, MTTR = 3(4) days → V = 0.97 (0.96)			

Table 6: Characteristics of mixing and feeding plant

a) Granule production

The facility shall be capable of processing 830 tons of salt with a daily operating time of 24 hours and 150 working days per year. With a salt content in the granules of 7 wt. % this corresponds to 11,868 tons of granules per year and a mean hourly throughput of 3.3 t/h, respectively.

Since, however, failures must be expected, the process must have a higher throughput. The proposed ploughshare mixer has a volume of 4 m^3. With a filling level of 45% a bulk density of 1.5 t/m^3 and a batch duration of 1 hour such a mixer attains an hourly throughput of 2.7 t/h. Thus the mixer must be redundant (active reserve) to guarantee the required throughput of 3.3 t/h is not attained.

In case the mixers operate at active reserve a total throughput of 2 x 2.7 = 5.4 t/h is obtained unless there are failures. From this is follows that the mixers should have a minimum availability of $\frac{3.3}{5.4}$ = 61%. The requested throughput is only attained in case all components operate reliably. Since they do not operate reliably, the mixer must an availability higher than 61%.

The mean times between failures (MTBF) and the mean times to repair (MTTR) can be taken from Table 5. During the simulation run the assumption was made of exponentially distributed operation and failure periods.

Results of the simulation computations:

The throughput of the granulating system lies within the range of 3.4 - 4.3 t/h with an assumed availability of the mixer of 66%-97%. The availability of the sub-system of granule production is determined by the bottleneck throughput of the mixer and attains between 63% and 80%.

Conclusion:

With the technical data specified the sub-system has been sufficiently dimensioned to granulate the MLW/LLW stream provided that this sub-system is redundant (active reserve).

b) Mixing and feeding sub-system

It is assumed that sufficient transport safety and capacity are provided.

By simulation computation we had to demonstrate that the sub-system of mixing and feeding facility achieves the requested throughput of 15,000 m^3 per year (see Table 6).

Conclusion:

For this sub-system a mean throughput of 3.34 m^3/h was calculated. Related to the mean pipe throughput of 4.4 m^3/h at 65 nominal width, derived from the measured values, this corresponds to an availability of 76%. But with 3,600 working hours per year the sub-system produces only 12,000 m^3/a waste.

To attain the aim of production the availabilities of components or the throughputs can be increased. Since the availabilities of components are already very high (see Table 6) a change of the number of operating days to 187 days per annum was proposed or an increase in the throughput of the sub-system of mixing and feeding facility to 5.5 m^3/h.

7. Summary

The availability analysis is a means of systems analysis for evaluating the applicability of technical systems; it can be used already at the planning stage and can be used during operation as well. I depends on the requirements which suitable mathematical tools (reliability theory, stochastic processes, simulation) are selected in order to get an idea for the design of nuclear facilities for reprocessing and waste treatment.

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