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Availability analysis for a Specific assembly System with intermediate buffers: A case study

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Abstract

In this paper, we explore the problem of availability analysis for a specific assembly system inspired from a real case. Contrary to regular assembly systems, we consider a three-working-station case where we have two intermediate buffers. The flow of materials is discrete. Since availability rate is one of the most important performance indicators for any company, we aim at providing tools to calculate the underlying measure for the assembly systems studied here. We tackle the problem by both simulation and analytical models. We use discrete event approach to simulate model, while in analytical model, we utilize Markov chain to assess the availability. Finally, we evaluate the performance of analytical model by comparing it against the simulation model proposed in this paper.

Keywords: Availability analysis, assembly system, Intermediate buffer, simulation model, Markov chain.

Introduction

Due to today's world competitive environment, companies are generally intending to have more reliable production systems with higher availability performance[1]. Reliability along with maintainability plays a crucial role in ensuring the success of companies as they determine system availability and thus significantly contribute to process economics and safety. Therefore, maintenance and maintenance policy arethe major keys in achieving systems' operational effectiveness at minimum cost. Reliability is a good indicator of the efficiency of a system[2].

This usually decreases when the operation time of a machine or its components increases. Reliability is the probability that a machine or a system perform a required operation for a given time period without any failure. A machine's reliability is often characterized by its mean-time-to-failure (MTTF). On the other hand, availability is a proportion of time that a machine or system is able to perform its required function[3].

A machine or a system is called repairable (maintainable) if once the failure has occurred, it can be restored to its as-good-as-new original state. The time elapsed between the failure and its return to the as-good-as-new conditions is called downtime or repair time. The average time to repair is called mean-time-to-repair (MTTR) by which machine's maintainability is characterized. If the machine is non-repairable, the reliability function is equal to availability function[1]. The consideration of systems with repairable machines is of interest in many engineering fields. In this case,the calculation of availability gains more attention among researchers because it is a measure of both reliability (MTTF) and maintainability (MTTR), and it is generally a more useful measure for repairable systems than reliability. The availability of a system with one single machine is calculated as such:

$$\text{Availibility}(\text{a system with single machine}) = \frac{\text{MTTF}}{\text{MTTF+MTTR}}$$

The more complex a system is, the harder the availability calculation becomes. For example, if the system consists of the *m* machines in series, the system fails to perform the operations when any of those *m*machines fails. Therefore, the system availability is obtained by the following formula:

$$\text{Availibility}\left(\begin{matrix}\text{a system with m}\\ \text{machines in series}\end{matrix}\right) = \prod_{i=1}^{m}\left(\frac{\text{MTTF}_i}{\text{MTTF}_i+\text{MTTR}_i}\right)$$

For another case, let us suppose we have a system with *m* machine in parallel. The system fails only if all of those *m* machine fail to operate. As a result, the system availability is computed as follows:

$$\text{Availibility}\left(\begin{matrix}\text{a system with}\\ \text{m machines}\\ \text{in parallel}\end{matrix}\right) = 1-\left\{\prod_{i=1}^{m}\left(\frac{\text{MTTR}_i}{\text{MTTF}_i+\text{MTTR}_i}\right)\right\}$$

In a nutshell, in systems with series machines,the whole system availability is a product of machines availability while in systems with parallel machines, the whole system availability is a product of machines unavailability. In a complex system with numerous combinations of simultaneous parallel and series machines, the calculation is even getting harder, yet achievable.

Two common ways in industries to improve the system availability are: Duplication of machines in parallel just in case one of the machines fails, the other ones operate as a replacement, Establishment of intermediate buffers between machines to keep the system in operation even if a machine fails.

With reference to this explanation, suppose systems in which besides having machines in parallel and series, we have intermediate buffers. In this later case, the system availability calculation required, by far, more effort than exploitation of some simple formulas[4].

To analyze the availability of such an intricate system, there exist two types of techniques, analytic andsimulation approaches. In both techniques, the system is characterized through random variables of the states of the corresponding machines in that system. In simulation, we draw a realization of each random variable and then determine which machines are down and for how long, from which the system availability over the interval of interest can be determined[5]. By repeating this procedure an estimate of the system availability is obtained. Analytical techniques, on the other hand, use structural results from applied probability theory and stochastic processes like Markov chain to make statements on various performance measures, such as the steady-state or the interval availability[6].

In this paper, we deal with a specific case of assembly systems with intermediate buffers. The objective is to calculate the availability of the underlying system. We first attack the problem by the development of a simulation model. We then tackle the problem through the analytical approaches, more specifically through Markov chain. Finally we compare the results obtained by the two approaches.

The problem description

Generally in assembly systems, given materials need to visit a set of working stations. Each working station is devoted to perform a specific operation on materials. So long as materials pass through all required stations, the jobs are done. The material could be either continuous or district. Our assembly systems use the district material; therefore, it follows the Markov models[5].

The problem under consideration, we have three unreliable working stations. Two of them are parallel, but they operate different functions. Each of the first two stations has its own buffer to put its output. That is, the products of stations 1and 2 are separately collected in an unshared buffer with a maximum of M_1 and M_2 products, respectively.Station 3 carries out another function on the work-in-process materials collected in the buffers. After visiting station 3, the process on materials completes. As a result, the system is down when station 3 fails to operate. This could be the consequence of either the emptiness of any of the two buffers or station 3 failures. Figure 1 shows the graphical outline of the assembly system studied here.
Stations 1, 2 and 3 process materials with rates r_1, r_2 and r_3, respectively; where r_3 is greater than both r_1 and r_2. We need to indicate that system composes of three randomly failing repairable machines where machines fail independently of each other and with constant mean failure rates. After the failure takes place, the repair can start immediately. The repair time has a random duration, independent of the states of the other machines, with an exponential distribution. Moreover, stationary conditions are assumed so that the probabilistic characteristics of the machines and the system do not vary over time.

Theoretically, the problem considered in this paper could be tackled by both a simulation model and Markov model. In the analytical approach developed in this paper, we use the homogeneous Poisson model for the initiation of the failure and repair events and directly obtain the stationary solution without considering the initial state of the system.

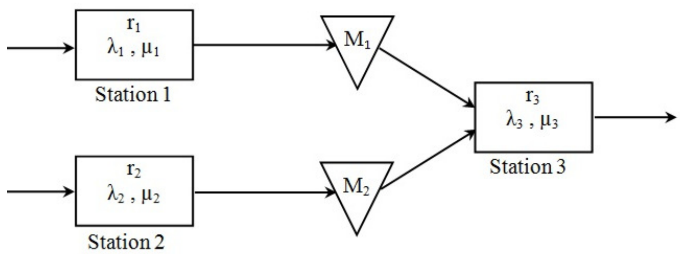

Figure-1
Three-working-station assembly system with discrete material flow

Simulation model

In the recent decades, simulation has been introduced as the most common and valuable tools in the operation research in the area of manufacturing and other research areas[10,11]. With the continuing developments in computer technology, simulation is receiving increasing attention as a decision making tool. Most real-world systems are so complex that computing values of performance measures and finding optimal decision variables analytically is very hard and sometimes impossible[7]. Therefore, computer simulation is frequently used in evaluating complex systems and optimizing responses.

In this paper, a simulation model has been proposed for evaluating the availability of the considered system as depicted in figure-1. The solution of the simulation model can be used as a control strategy for the solution of analytical approach. We make the following assumptions about introduced assembly system: Uptime and downtime of all stations in the given manufacturing system have exponential distributions with different parameter. Production rate of each station is based on Poisson distribution. After failing, a station is immediately brought up (without any loss time). Buffers cannot fail and therefore buffers do not have to be repaired. The overall system production rate cannot exceed production rate of station 3. If a buffer hits the buffer capacity, the preceding station of this buffer stops. If any of two buffers hit empty, the station 3 stops (even if it be in operational status). To initialize the simulation, a warm-up period is used to eliminate unstable situation of system. If multiple stations fail at a time, they are simultaneously repaired.

Because of the complexity of the presented system, the usual definition of time dependent availability is difficult to apply. We define availability as the ratio of the actual number of products produced in a sufficiently long period of time to the total number of products that would have been produced. We refer to this alternative definition as product-based availability.

To estimate product-based availability we simply observe and accumulate the total number of products actually produced during a sufficiently long simulated time period (such as 1 or 2 years). Such a simulated time period ensures a reasonably stable estimate of availability. While the total number of products actually produced represents the numerator of the availability ratio, the denominator is simply the length of the time period multiplied by the production rate. The availability ratio is determined by the following formula[8]:

We develop and use a discrete-event simulation model to estimate the product-based availability for introduced system depicted in figure-1. We used the most well-known commercial simulation software, namely Arena 7.01 for modeling the considered assembly system. The figure-2 illustrates the simulation model of the system in working condition.

Analytical Model

This section has been devoted for developing an analytical approach to consider the availability of the three-station assembly system with unreliable stations, illustrated in Figure 1. We assume that there is no limit for the buffer in front of stations 1 and 2. Consumption factor of the parts produced in stations 1 and 2 in assembly station (station 3) is one. The production times of each part produced in stations 1, 2 and 3 follows an independent Poisson process with parameter r_i. The two work centers and the assembly station follow first-come first-service (FCFS) discipline. There is one type of finished product after assembly.

After being processed by the work centers, respectively, the two types of work pieces are transferred to stage-II for being assembled. The maximal buffer sizes for type-1 and type-2 work pieces are M_1 and M_2, respectively. Such finiteness of the intermediate buffers may cause *blocking* at stations 1 and 2 and *starvation* in station 3. Blocking occurs when a work piece finished by work stations 1 and 2 cannot enter the intermediate buffer because it is full. This work piece will occupy the stations and prevent the stations from processing the next work piece until a space becomes available in the intermediate buffer. Starvation occurs when there is no work piece of type 1 and 2 because the buffers 1 and 2 are empty. We assume that breakdowns of the stations may happen only during its busy period. We further assume that the lifetimes of the stations are exponentially distributed with parameter λ_i. When the stations break down, it will be repaired immediately. The repair time is exponential with parameter μ_i.

In this section, we utilize a Markov process to characterize and analyze the availability of the three station assembly system[9]. At each given time, there are two possible states for a station; i.e., a station is either up or down. Up or down status of each station is either due to its failure or due to docking or starvation. Thus, there are eight possible combinations of three stations. Each combination is assigned an index from the index set I = {UUU, UUD, UDU, DUU, UDD, DUD, DDU, DDD}. The first component from the index set show that at a given time the three stations are up.

$$\text{Availability ratio} = \frac{\text{Total number of products actually produced in determined length of time}}{\text{Determined length of time} \times \text{production rate}}$$

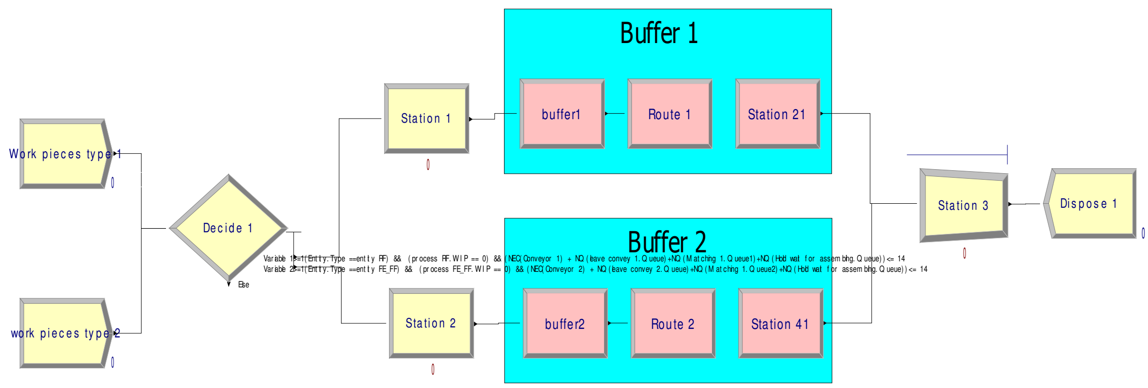

Figure-2
The general outline of the simulation model

It can be inferred that the state probability of system at time t can be written by the following equation:

$$P_{ij}^t = p_r(H(t) = j, j \in I \mid H(0) = i, i \in I)$$

For example: $p_r(H(t) = (UUU, x, y) \mid H(0) = (DDU, s, z))$

Now, the state transition matrix can be calculated. The component of this matrix indicate the probability in which the system for example goes from state {DDU, s, z} at time zero to state {UUU, x, y} at time t. matrix A represent the state probability matrix.

$$A^t = \begin{bmatrix} a_{11}^t & a_{12}^t & \cdots & a_{18}^t \\ a_{21}^t & a_{22}^t & \ldots & a_{28}^t \\ \vdots & \vdots & \vdots & \vdots \\ a_{81}^t & a_{82}^t & \ldots & a_{88}^t \end{bmatrix}$$

Here, as an example, we show how P_{11}^t is calculated. The remaining probability can be derived by simple modification of P_{11}^t.

$$P_{11}^t = p_r(H(t) = (UUU, x, y) \mid H(0) = (UUU, s, z))$$
$$= \left[\prod_{i=1}^{3} p_r(\text{station } i \text{ don't fail during time period } t)\right]$$
$$\times \left[p_r(\text{buffers 1 and 2 are not empty at time } t)\right]$$
$$= \prod_{i=1}^{3} p_r(TTF_i > t) \times p_r(X > 0) \times p_r(Y > 0)$$

Where, $p_r(TTF_i > t) = \int_t^\infty \lambda_i e^{-\lambda_i x} dx = e^{-\lambda_i t}$

The probability in which the buffer 1 is not empty can be rewritten by the Following equation:

$$p_r(X > 0)$$

Therefore,

$$p_r(X > 0) = p_r(R_3 - R_1 + s > 0)$$
$$= \sum_{e_3=0}^{\infty} p_r(R_3 - R_1 + s > 0 \mid R_3 = e_3) p_r(R_3 = e_3)$$
$$= \sum_{e_3}^{\infty} \sum_{j=0}^{s+e_3} e^{-r_1 t} \frac{(r_1 t)^j}{j!} . e^{-r_3 t} \frac{(r_3 t)^{e_3}}{e_3!}$$

Similarly,

$$p_r(Y > 0) = p_r(R_3 - R_2 + z > 0)$$
$$= \sum_{e_3=0}^{\infty} p_r(R_3 - R_2 + z > 0 \mid R_3 = e_3) p_r(R_3 = e_3)$$
$$= \sum_{e_3}^{\infty} \sum_{j=0}^{z+e_3} e^{-r_2 t} \frac{(r_2 t)^j}{j!} . e^{-r_3 t} \frac{(r_3 t)^{e_3}}{e_3!}$$

Ultimately,

$$P_{11}^t = \sum_{s=0}^{M_1} \sum_{z=0}^{M_2} \left\{ \begin{array}{l} \prod_{i=1}^{3} e^{-\lambda_i t} \left[\sum_{e_3}^{\infty} \sum_{j=0}^{s+e_3} e^{-r_1 t} \frac{(r_1 t)^j}{j!} . e^{-r_3 t} \frac{(r_3 t)^{e_3}}{e_3!} \right] \\ \left[\sum_{e_3}^{\infty} \sum_{j=0}^{z+e_3} e^{-r_2 t} \frac{(r_2 t)^j}{j!} . e^{-r_3 t} \frac{(r_3 t)^{e_3}}{e_3!} \right] \end{array} \right\}$$

The instantaneous availability is obtained by the following equation:

$$Ava(t) = \sum_{i=1}^{8} a_{i1} + \sum_{i=1}^{8} a_{i3} + \sum_{i=1}^{8} a_{i4} + \sum_{i=1}^{8} a_{i7}$$

Then the steady state availability can be derived by the following equation:

$$\lim_{t \to \infty} Ava(t) = \lim_{t \to \infty} \left[\sum_{i=1}^{8} a_{i1}^t + \sum_{i=1}^{8} a_{i3}^t + \sum_{i=1}^{8} a_{i4}^t + \sum_{i=1}^{8} a_{i7}^t \right]$$

Now, to validate the proposed analytical model, we apply it to an example, and then compare its results with those obtained by simulation model. Let us suppose we have a three-working-station assembly system with the specifications shown in Table 1. We implement the simulation model in Arena 7.01 and run on a PC with 2.0 GHz Intel Core 2 Duo and 2 GB of RAM memory. After 2000 hours simulation of the systems, the availability becomes 91.5%. We also calculate the measure of interest through Markov model. The availability again becomes 92.08%. Since these two values are very close two each other, we can conclude that the analytical model is a good estimation for the system availability.

Table 1
The assembly system's specification

Station	Parameter		
	r	μ	λ
1	250	1/2	1/2000
2	200	1/4	1/2000
3	200	1/3	1/1500

Conclusion

We considered the availability assessment of a variant of assembly system with three-working-station and intermediate buffers between the stations where the flow of materials was discrete. We introduced tools to calculate the availability rate for the assembly systems. We first modeled the problem by Simulation using discrete event approach. Then, we analytically calculated the availability through Markov chain. Finally, we evaluated the performance of analytical model by comparing it against the simulation model.

As a future research, it could be interesting to extend the considered problem to a system with continuous material flow. Another interesting clue is to assess the availability of a more complex, yet realistic variant of the problem such as a whole production line with several working stations.

Notations: In this paper the following notations are used:

x, y	Number of work pieces in buffers 1 and 2 at time t
X	Random variable of number of work pieces in buffer 1 at time t
Y	Random variable of number of work pieces in buffer 2 at time t
$H(t)$	The state of the system at time t that is characterized by three component, i.e. the stations status, number of parts in buffer 1 and 2, e.g. $H(t) = \{UUU, x, y\}$.
TTF_i	Exponentially distributed random variable to model time to failure of station i.
λ_i	Failure rate at station i
TTR_i	Exponentially distributed random variable to model time to repair of station i.
μ_i	Repair rate at station i
R_i	Poisson random variable of number of part produced in station i
r_i	Production rate of station i

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