ANALYSIS OF A BUFFERLESS, PACED, AUTOMATIC TRANSFER LINE WITH MASSIVE SCRAPPING OF MATERIAL DURING LONG FAILURES

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Abstract: *We develop a model of a failure-prone, bufferless, paced, automatic transfer line, with continuous processing of material throughout the length of its workstations. When a workstation fails, it stops operating and so do all the workstations upstream of it. The quality of the material trapped in the stopped workstations deteriorates with time. If it remains still in the same place for a long enough time, its quality becomes unacceptable and so it must be scrapped. We develop analytical expressions for key system performance measures, for two variants of the model, under the assumption that the workstation uptimes and downtimes follow memoryless distributions. We then present a brief summary of two numerical experiments, one on the effect of system parameters on system performance and the other on the performance comparison between the original model and a modified model, in which the workstation downtimes do not follow memoryless distributions.*

Keywords*: automatic transfer line, scrapping, performance evaluation*

1 Introduction

A traditional, wide-spread form of organizing high-volume, low-variety production is the *transfer line*. Transfer lines require all material to visit workstations in the same sequence, thus simplifying material handling. Transfer lines are common in both discrete-parts and continuous processing manufacturing. With increasing production volume, it becomes economically attractive to automate individual workstations, integrate them into one system by a common automated transfer mechanism and a common control system, and link them so that they can begin their tasks simultaneously. Transfer lines with these characteristics are often referred to as *paced, automatic transfer lines*. Much of the work that was done on transfer lines until the mid 90's can be found in [1] [2] [4] [5] [7]. Most of this work and the work that followed it dealt with the influence of buffer stock between the workstations. Inserting buffers in a low- to medium-speed transfer line can be very effective in increasing the actual production capacity of the line, because the buffers absorb some of the downtime of failed workstations. Placing buffers in a high-speed line, however, is impractical, because buffers can hold only a relatively small amount of material. Hence, they get full quickly, causing the entire line upstream of the failed workstation to stop within a short period of time, as if there were no buffers between the workstations. Moreover, in many high-speed lines, especially in the process industries, it may not be possible to store in-process material because of technological limitations. For these reasons, high-speed lines, generally, do not have buffers between workstations [6]. When an unexpected failure occurs in a bufferless line, the failed workstation stops and forces the part of the line upstream of the failure to go on standby mode, i.e., operate at a minimum level without transferring material. This causes a gap in production downstream of the failure. Since a workstation on standby mode is for the most part operating, except that material movement has stopped, it may fail itself. It is, therefore, reasonable to assume that the failure times of workstations are *time dependent* instead of *operation dependent*. Moreover, in many industries, if the failure is sufficiently long, some or all of the material that is trapped in the stopped section of the line may have deteriorated in quality to such a point that it will have to be scrapped because it is unacceptable. Besides the havoc that this may bring about, it will also create a significant additional gap in production upstream of the failure. As a result, the actual output rate of the line can be substantially lower than its nominal production rate. The costs associated with the drop in output and the scrapping of material can be significant, especially if the scrapped material is not reusable.

We first encountered the problem of massively scrapping material during long failures in automatic transfer lines in the bread & bakery products industry, where the most important type of quality deterioration is the rise of dough [13] [14]. In particular, in [14], we found that approximately half of the drop in efficiency of such a line was due to the gap in production caused by failures and the other half was due to the gap in production caused by scrapping during long failures. We subsequently became aware that the problem of scraping during long failures is encountered in the production of many other food products, where processes such as pasteurization, fermentation, proofing, carbonation, etc. must be performed in a timely and carefully controlled manner, and disruptions in the production process may cause quality deterioration. In fact, there is a plethora of manufacturing processes where material is scrapped because its physical and/or chemical characteristics fall out of specifications during a stoppage. A plant manager in a large metallurgical products industry told us of a severe scrapping problem in the rolling process of his plant. We were also told of a similar problem that occurs in the thermosetting plastics industry, where in case of a failure in the molding phase, the process upstream of the failure freezes, and the material in the die starts solidifying. There is a plethora of other examples of manufacturing processes, where material may have to be massively scrapped because of long stoppages, so the problem is very important from a manufacturing systems practitioner's point of view. Yet, to the best of our knowledge, the problem has not been studied from a manufacturing systems engineering perspective, perhaps because most of the research effort in this area has been directed towards discrete parts manufacturing, where the problem of massive scrapping material during long failures is less severe than in automated continuous and semi-continuous processes. There are a few works that explicitly consider scrapping of parts when a workstation of a transfer line fails [1] [4] [6] [12] [15] [17]. Apart from these works, some work has been also reported on the related area of rework/scrap and productivity [8] [10] [16] [18]. In all of the above works, it is assumed that when a failure occurs at a workstation, a single part – that which is on the workstation – is either definitely scrapped or scrapped with a static probability, independently of the failure time.

In this paper, we address the issue of massively scrapping material during long failures in bufferless, paced, automatic transfer lines. We consider a model of a transfer line in which material flows through different workstations in series, where it receives continuous processing. No storage buffers are allowed in between the workstations. When a workstation fails, it stops operating and so do all its upstream workstations. The quality of the material that is trapped in the stopped workstations deteriorates as time passes. If it remains still in the same place for a long enough time, its quality becomes unacceptable and so it must be scrapped. The maximum allowable standstill time of material in any workstation depends on the workstation. If this time is zero, then the material must be immediately scrapped. If it is infinite, then no material is ever scrapped from the workstation. For the maximum allowable standstill time of the material we consider two cases. In the first case, the quality deterioration during a failure is fully recoverable, so that when the workstation starts operating again, the material in it – assuming that it has not been scrapped – is as good as new. In the second case, the deterioration is cumulative, so that when the workstation starts operating again, the remaining maximum allowable standstill time of the material in it – assuming that it has not been scrapped – is less than before the stoppage. In section 2, we develop analytical expressions for key performance measures of the system for the two cases described above, under the assumption that the uptimes and downtimes of the workstations are geometrically distributed. In section 3, we give a brief summary of two numerical experiments that we performed, one on the effect of system parameters on system performance and the other on the performance comparison between the original model and a modified model, in which the workstation downtimes do not follow memoryless distributions.

2 Analysis of Transfer Line

Consider an automatic transfer line with M workstations in series and no buffers between the workstations. Material flows from outside the system to workstation 1, to workstation 2 … to workstation M, and then out of the system. Once material enters a workstation, it flows at a constant speed through the workstation, where it receives continuous processing. Time and space are discrete. Specifically, the length of each workstation is broken into a number of discrete positions. Let N_i denote the number of discrete positions of workstation i. Material is also broken into discrete parts so that each position in each workstation can accommodate one part. Thus, at each workstation i, a part moves from outside the workstation to position 1, to position 2 … to position N_i, and then out of the workstation. The transfer line is paced so that all the workstation positions have equal and constant processing times. Time is scaled so that the processing time of every part in every position of every workstation is one time period. An inexhaustible supply of parts is available upstream of the first workstation and an unlimited storage area is present downstream of the last workstation. A schematic representation of the line is shown in Figure 1.

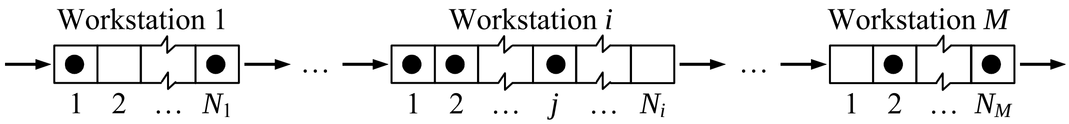

Figure 1: Schematic representation of a transfer line with *M* workstations.

Workstations are subject to random failures, so at any time, a workstation is either *up* or *down*. Moreover, a workstation is *blocked* if one or more of its downstream workstations are failed. This means that a workstation is *stopped* when it is either failed or blocked, and it is *operating* when it is up and not blocked. Failures are time dependent. At each workstation, the times between failures and the times to repair are i.i.d. random variables with geometric distributions. Let p_i denote the probability that workstation *i* is down in period *t*, given that it was up in period $t – 1$. Let r_i denote the probability that workstation *i* is up in period *t*, given that it was down in period $t – 1$. Let e_i denote the *efficiency in isolation* of workstation *i*, i.e. the percentage of time that the workstation is up. It is easy to see that

$$e_i = r_i \big/ \left(r_i + p_i\right), \quad \text{for } i = 1,\ldots,M. \tag{1}$$

The *efficiency in the system* of a workstation is the percentage of time that the workstation is operating (up and not blocked). Let E_i^d denote the efficiency in the system of workstation *i*. It is easy to see that

$$E_i^d = \prod\nolimits_{j=i}^{M} e_j, \quad \text{for } i = 1,\ldots,M. \tag{2}$$

Let p_i^d be the probability that workstation *i* is stopped in period *t*, given that it was operating in period $t – 1$. It is easy to see that

$$p_i^d = 1 - \prod\nolimits_{j=i}^{M} \left(1 - p_j\right), \quad \text{for } i = 1,\ldots,M. \tag{3}$$

Let r_i^d be the probability that workstation *i* is operating in period *t*, given that it was stopped in period $t – 1$. Then, $E_i^d = r_i^d \big/ \left(r_i^d + p_i^d\right)$, for i = 1, …, *M*, from which it follows that

$$r_i^d = p_i^d\, E_i^d \big/ \left(1 - E_i^d\right), \quad \text{for } i = 1,\ldots,M. \tag{4}$$

When a workstation is stopped, the quality of the parts trapped in it deteriorates with time. We consider two cases of quality deterioration. In the first case, we assume that parts have no memory of the damage done to them during past stoppages. In the second case, we assume that parts have memory of the damage done to them during previous stoppages of the workstation that they are in. Next, we analyze these two cases separately.

2.1 Case 1: Material with No Memory of Damage during Previous Stoppages

In case 1, we assume that if a part remains still in the same position of a workstation for more than a maximum allowable standstill time associated with this workstation, it must be scrapped. If a part "survives" a stoppage at a particular position of a workstation, however, its quality condition after the stoppage is "as good as new." This means that it can remain still in the next position for up to the same maximum allowable standstill time without having to be scrapped. In other words, the material has no memory of the damage done to it during previous stoppages. Let n_i denote the maximum allowable standstill time of a part in any position of workstation *i*. Let R_i denote the conditional time it takes for workstation *i* to start operating once it is stopped. It is easy to see that R_i is geometrically distributed with mean $1\big/r_i^d$; therefore, the probability that any part in any position of workstation *i* will not be scrapped, given that the workstation is stopped, is given by

$$P\left\{R_i \le n_i\right\} = 1 - \left(1 - r_i^d\right)^{n_i}, \quad \text{for } i = 1,\ldots,M. \tag{5}$$

Let us follow a part from the moment that it moves to a particular position of a workstation, say workstation i, at the beginning of period t, which implies that workstation i is operating at the beginning of period t. The time that the part spends in this position is one time period of processing plus an extra waiting time. This extra time is zero, if the workstation keeps operating after one time period, i.e. at the beginning of period $t + 1$. If the workstation is stopped at the beginning of period $t + 1$, however, then the extra waiting time of the part depends on whether the stoppage time of workstation is greater than or equal to n_i or not. More specifically, if the stoppage time of workstation i is smaller than or equal to n_i, then the part waits on average for $E[R_i|R_i \leq n_i]$ time periods and then moves on to the next position, where

$$E\left[R_i \middle| R_i \leq n_i\right] = 1/r_i^d - n_i\left(1-r_i^d\right)^{n_i} \Big/ \left(1-\left(1-r_i^d\right)^{n_i}\right), \quad \text{for } i = 1,\dots,M. \tag{6}$$

On the other hand, if the time that workstation i is stopped is greater than n_i, the part waits for n_i time periods and then is scrapped because its quality has become unacceptable. From the above discussion, it can be shown that the conditional expected time that a part spends in any position of workstation i, given that it has moved into this position, denoted by l_i, is given by

$$l_i = 1 + \left(p_i^d / r_i^d\right)\left(1-\left(1-r_i^d\right)^{n_i}\right), \quad \text{for } i = 1,\dots,M. \tag{7}$$

Let q_i denote the conditional probability that a part will not be scrapped from a particular position of workstation i, given that it has entered this position. It can be shown that

$$q_i = 1 - p_i^d\left(1-r_i^d\right)^{n_i}, \quad \text{for } i = 1,\dots,M. \tag{8}$$

Let $q_{i,j}$ denote the conditional probability that a part will enter position j of workstation i, given that it has entered workstation i. This probability is given by

$$q_{i,j} = q_i^{\,j-1}, \quad \text{for } i = 1,\dots,M, \quad j = 1,\dots,N_i. \tag{9}$$

Let $l_{i,j}$ denote the conditional expected time that a part spends in position j of workstation i, given that it has entered workstation i. Then, $l_{i,j}$ is given by

$$l_{i,j} = l_i q_{i,j} = l_i q_i^{\,j-1}, \quad \text{for } i = 1,\dots,M, \quad j = 1,\dots,N_i. \tag{10}$$

Let L_i denote the conditional expected flow time of a part at workstation i, given that it has entered this workstation. It can shown that

$$L_i = \sum\nolimits_{j=1}^{N_i} l_{i,j} = l_i\left(1-q_i^{N_i}\right)\Big/\left(1-q_i\right), \quad \text{for } i = 1,\dots,M. \tag{11}$$

Let Q_i denote the conditional probability that a part will move from workstation i (or from outside the system, if $i = 0$) to workstation $i + 1$ (or out of the system, if $i = M$), given that it has entered workstation i. It is easy to see that

$$Q_0 = 1 \text{ and } Q_i = q_i^{N_i}, \quad \text{for } i = 1,\dots,M.$$

Let $\hat{Q}_i$ denote the unconditional probability that a part will move from workstation i (or from outside the system, if $i = 0$) to workstation $i + 1$ (or out of the system, if $i = M$). It is easy to see that

$$\hat{Q}_i = \prod\nolimits_{j=0}^{i} Q_j, \quad \text{for } i = 0,\dots,M. \tag{12}$$

Let $\hat{L}_i$ denote the unconditional expected flow time of a part at workstation i. It is easy to see that

$$\hat{L}_i = L_i \hat{Q}_{i-1}, \quad \text{for } i = 1,\dots,M. \tag{13}$$

Finally, let $\hat{L}_{TOT}$ denote the total unconditional expected flow time of a part in the line. Then,

$$\hat{L}_{TOT} = \sum\nolimits_{i=1}^{M} \hat{L}_i. \tag{14}$$

The *input rate* of a workstation is the average number of parts that enter the workstation per time period. The *output rate* of a workstation is the average number of good parts that exit the workstation per time period. Let I_i denote the input rate, and let O_i denote the output rate of workstation i. It is easy to see that the input rate of the first workstation is equal to the percentage of time that the workstation is operating (up and not blocked), i.e.

$$I_1 = E_1^d. \tag{15}$$

It is also easy to see that

$$I_i = O_{i-1}, \quad \text{for } i = 2,\dots,M, \tag{16}$$

$$O_i = I_i Q_i, \quad \text{for } i = 1,\dots,M, \tag{17}$$

From (12) and (15)-(17), it follows that

$$I_i = E_1^d \hat{Q}_{i-1}, \quad \text{for } i = 1,\dots,M, \tag{18}$$

$$O_i = E_1^d \hat{Q}_i, \quad \text{for } i = 1,\dots,M, \tag{19}$$

Note that the output or *throughput* rate of the line is the output rate of the last workstation, i.e.

$$O_M = E_1^d \hat{Q}_M. \tag{20}$$

Let B_i denote the average number of parts in workstation i. Then, from Little's law, B_i is given by

$$B_i = E_1^d \hat{L}_i, \quad \text{for } i = 1,\dots,M. \tag{21}$$

Finally, let B_{TOT} denote the average number of parts in the entire line. Then,

$$B_{TOT} = \sum_{i=1}^{M} B_i . \tag{22}$$

2.2 Case 2: Material with Memory of Damage during Previous Stoppages at a Workstation

In case 2, we assume a part has memory of the damage done to it during all the previous stoppages of a workstation while it remains in this workstation. In particular, the maximum allowable standstill time of any part in any position of a workstation is equal to the maximum allowable standstill time associated with this workstation minus the cumulative standstill time of this part in all the preceding positions of the workstation. If the part "survives" all the stoppages at a workstation, however, its quality condition after exiting this workstation is "as good as new." This means that it can remain still in the next workstation for up to the maximum allowable standstill time associated with that workstation without having to be scrapped. As in case 1, let n_i denote the maximum allowable standstill time of a part in workstation i, when its quality condition is as good as new, and let R_i denote the conditional time it takes for workstation i to start operating given that it is stopped. Then, R_i is geometrically distributed with mean $1/r_i^d$. Let us assume for a moment that there is no issue of quality deterioration during a stoppage; therefore, a part may never be scrapped from workstation i. Let $W_{i,j}$ denote the time that workstation i is stopped from the moment that a part enters position j of workstation i until it exits this position. Clearly,

$$W_{i,j} = \begin{cases} 0, & \text{with probability } (1 - p_i^d), \\ R_i, & \text{with probability } p_i^d. \end{cases} \tag{23}$$

Let $S_{i,j}$ denote the cumulative time that workstation i is stopped from the moment that a part enters position 1 of workstation i until it exits position j of workstation i, i.e.

$$S_{i,j} = \sum_{k=1}^{j} W_{i,k}, \quad i = 1,\dots,M, \quad j = 1,\dots,N_i.. \tag{24}$$

We want to find the probability distribution of $S_{i,j}$, $P\{S_{i,j} = k\}$. Firstly, it is easy to see that

$$P\{S_{i,j} = 0\} = \left(1 - p_i^d\right)^j, \quad i = 1,\dots,M, \quad j = 1,\dots,N_i. \tag{25}$$

To find $P\{S_{i,j} = k\}$, for $k > 0$, let us follow a part from the moment that it enters position 1 of workstation i until it exits position j of the same workstation. Consider the event that in its trajectory from position 1 into position j, the part does not stop at all in m out of the j positions and stops in the remaining $j - m$ positions, and that the total time that the part is stopped is k, where $k > 0$. It can be shown that the probability of this event is given by

$$\binom{j}{m}\left(1 - p_i^d\right)^m \left(p_i^d\right)^{j-m} \binom{k-1}{j-m-1}\left(1 - r_i^d\right)^{k-(j-m)} \left(r_i^d\right)^{j-m}. \tag{26}$$

It can also be shown that m can take any value from $\max(0, j - k)$ to $j - 1$. Then, the desired probability $P\{S_{i,j} = k\}$ is the sum of the probabilities given by (26) over all possible values of m, i.e.

$$P\{S_{i,j} = k\} = \sum_{m=\max(0,j-k)}^{j-1} \binom{j}{m}\left(1 - p_i^d\right)^m \left(p_i^d\right)^{j-m} \binom{k-1}{j-m-1}\left(1 - r_i^d\right)^{k-(j-m)} \left(r_i^d\right)^{j-m}, \quad \text{for } i = 1,\dots,M, \; j = 1,\dots,N_i, \; k = 1,2,\dots. \tag{27}$$

Now, let us return to our original assumption that a part is scrapped from workstation i if its cumulative standstill time in this workstation is greater that n_i. The analysis to compute the conditional expected flow time of a part at workstation i, L_i, is similar to the analysis carried out in the no memory case in section 2.1. The only difference is that each time a part enters a new position j of workstation i, where j = 2, …, N_i, its remaining maximum allowable standstill time is $n_i - S_{i,j\text{-}1}$ instead of n_i, as was the situation in the no memory case. For j = 1, the remaining maximum allowable standstill time of the part is n_i, as in the no memory case. With this in mind, let $l_{i,1}$ denote the conditional expected time that a part spends in position 1 of workstation i, given that it has entered workstation i. Then, $l_{i,1}$ is given by the same expression as that derived for l_i in the no memory case, i.e. expression (7). Hence,

$$l_{i,1} = 1 + \left(p_i^d / r_i^d \right)\left(1 - \left(1 - r_i^d\right)^{n_i}\right), \quad \text{for } i = 1,\ldots,M. \tag{28}$$

For j = 2, …, N_i, let $l_{i,j,k}$ denote the conditional expected time that a part spends in position j of workstation i, given that it has entered workstation i and given that the cumulative stoppage time up until it enters position j is k, i.e. $S_{i,j\text{-}1} = k$. Then, $l_{i,j,k}$ is given by

$$l_{i,j,k} = \begin{cases} 1 + \left(p_i^d / r_i^d \right)\left(1 - \left(1 - r_i^d\right)^{n_i - k}\right), & \text{for } i = 1,\ldots,M, \quad j = 2,\ldots,N_i, \quad k \le n_i, \\ 0, & \text{for } k > n_i, \end{cases} \tag{29}$$

where, the above expression is the same as (7) except that we have replaced n_i by $n_i - k$. Moreover, for j = 2, …, N_i, let $l_{i,j}$ denote the conditional expected time that a part spends in position j of workstation i, given that it has entered workstation i. Then, it can be shown that

$$l_{i,j} = \sum_{k=0}^{n_i} \left(1 + \left(p_i^d / r_i^d \right)\left(1 - \left(1 - r_i^d\right)^{n_i - k}\right)\right) P\left\{S_{i,j-1} = k\right\}, \quad \text{for } i = 1,\ldots,M, \quad j = 2,\ldots,N_i. \tag{30}$$

Let L_i denote the conditional expected flow time of a part at workstation i, given that it has entered this workstation. It is easy to see that

$$L_i = \sum\nolimits_{j=1}^{N_i} l_{i,j}, \quad \text{for } i = 1,\ldots,M. \tag{31}$$

Finally, let Q_i denote the conditional probability that a part will move from workstation i (or from outside the system, if i = 0) to workstation i + 1 (or out of the system, if i = M), given that it has entered workstation i. It is easy to see that

$$Q_0 = 1 \text{ and } Q_i = P\left\{S_{i,N_i} \le n_i\right\}, \quad \text{for } i = 1,\ldots,M.$$

The rest of the analysis is identical to the analysis of the no memory case. In other words, equations (12) - (21) that were derived for the no memory case, also hold for the memory case.

3 Summary of Numerical Experiments

We used the analytical expressions derived in the previous section to study the effect of system parameters on system performance. More specifically, we numerically investigated how the system parameters p_i, r_i, and n_i, i = 1,…, M, affect the input rate capacity of the system, E_1^d, given by (2) for i = 1, the probability that a part will exit from the line without being scrapped, $\hat{Q}_M$, given by (12) for i = M, the average number of parts in the line, B_{TOT}, given by (22), and finally the total unconditional expected flow time, $\hat{L}_{TOT}$, given by (14). Recall, that the throughput rate of the line is given by (20). We found that as p_i increases, or r_i decreases, for some workstation i, E_1^d, $\hat{Q}_M$, and B_{TOT} decrease. The effect of p_i and r_i on $\hat{L}_{TOT}$ is less straight forward. Namely, an increase in p_i, or a decrease in r_i, raises the frequency of stoppages. This raise causes the parts that are trapped in the stopped section of the line to spend more time in the line, which increases $\hat{L}_{TOT}$. At the same time, an increase in p_i, or a decrease in r_i, reduces the probability that a part will exit from the stopped section of the line, which decreases $\hat{L}_{TOT}$. In other words, as p_i increases, $\hat{L}_{TOT}$ tends to both increase and decrease at the same time. Which of the two tendencies predominates depends on whether the increase-of-stoppage-time effect or the increase-of-scrapping effect is stronger. We found that all the above effects are linear in the probability of failure of a workstation, but concave in the probability of repair. This implies constant throughput gains as p_i decreases, but diminishing gains as r_i increases. We also found that all the effects are stronger for downstream workstations than for upstream workstations. This means that efforts to improve the uptime and downtime distribution parameters should start first at the last workstation and then move upstream towards the first workstation. Finally, we found that there is more scrapping in the memory case than in the no memory case, as was expected. As far as the effect of n_i on system performance is concerned, we found that as n_i increases uniformly for all workstations, $\hat{Q}_M$, B_{TOT}, and $\hat{L}_{TOT}$ increase, converging to some limiting values as n_i goes to infinity. These increases are sharper in the memory case than in the no memory case.

To evaluate the memoryless assumption of workstation uptimes and downtimes, we compared the performance of the original model with that of a modified model, in which the workstation downtimes do not follow memoryless distributions. The performance of the modified model was obtained via simulation. We found that when the maximum allowable standstill time is greater than the mean repair time, more parts are scrapped in the modified model than in the original model, whereas when the maximum allowable standstill time is smaller than the mean repair time, the opposite is true. At first, this was surprising, because we had expected that there should always be less scrapping in the modified model than in the original model, given that the workstation downtimes in the modified model have less than half the variance of the downtimes in the original model. However, looking at the analytical expressions more carefully, we realized that when the maximum allowable standstill time is smaller than the mean repair time, the probability that a part will not be scrapped in any particular position is higher in the original model than in the modified model. Perhaps the most important observation of our comparison was that the differences in the performance measures between the original and the modified models were fairly small. This means that the original model, which is analytically-tractable, can provide fairly accurate performance estimates for transfer lines with downtimes that do not follow memoryless distributions.

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