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Performance Assessment of Transfer Lines with Unreliable Transfer Mechanism and Non-Negligible Transfer Times

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Abstract

This paper deals with automated production lines composed of multiple machines in series interconnected by a common and automatic transfer mechanism. The automated production line is dedicated to manufacturing a specific product type. The transfer mechanism and production machines are subject to random operation dependent failures. The automated transfer mechanism has a non-negligible transfer time. The purpose of this paper is to propose new analytical formulations to assess the steady-state availability and the throughput of such production lines. Based on several production line configurations, and compared to simulation results, the paper proves first the exactness and the robustness of the proposed models. The paper also shows the impact of the transfer mechanism operational, reliability, and maintainability parameters on the overall performance of automated production lines.

Keywords

Transfer lines, unreliable transfer mechanism, Throughput, Steady-state Availability, simulation modeling.

1. Introduction

Automated production lines consist of several machines or workstations which are linked together by work handling devices that transfer parts from one workstation to the next according to the part production process and to the system layout. The transfer of work parts occurs automatically and the workstations carry out their specialized operations automatically. These production lines are product oriented manufacturing systems employed in industry for mass production. Despite their poor flexibility, they were considered as the best solution to producing parts with the required high production rate at minimal cost. For many decades, several researches have been carried out to model and to analyze the performance of transfer lines. The throughput is often considered as the main performance measure of transfer lines, which is defined as the average long run production rate of these manufacturing systems. The transfer line throughput, which is dependent on the cycle time and the line efficiency or steady-state availability, is directly affected by station interferences: blocking and starvation (Yeralan and Muth 1987), and the failure mode of the manufacturing machines: time-dependent or operation-dependent failure modes (Papadopoulos and Heavey 1996, Sherwin 2000, Schneeweiss 2005, Dhouib et al. 2006). An important work has been done to evaluate the throughput and the steady-state availability of mono-product homogeneous transfer lines assuming a perfect work balancing through all the manufacturing workstations (Zimmern 1956, Buzacott 1968, Buzacott and Shanthikumar 1993, Gershwin 1994, Dhouib et al. 2006). Since it is very difficult, in practice, to get perfectly balanced transfer lines, few authors have proposed approximate approaches to analyze the performance of non-homogeneous transfer lines. Gershwin (1987), Dallery et al. (1989), and Liu and Buzacott (1990) propose aggregation and homogenization approaches to deal with non-homogeneous transfer lines where machine processing times are different. These approaches consist on replacing the original non-homogeneous transfer line by an equivalent homogeneous one, with all equivalent machines having the same production rate. The authors assign the fastest machine processing time of the original line to all equivalent machines. Chen and Yuan (2004) analyze non-homogeneous, mono-product transfer lines and propose to consider the line somewhat as one whose machines have the smallest production rate among the original machines (the bottleneck). However, no modifications were introduced to the failure and the repair rates of the original transfer line machines. Dhouib et al. (2009) have developed a simulation model to analyze the effectiveness of the four aforementioned proposals. They have shown that all proposed approaches underestimate the throughput of non-homogeneous, mono-product transfer lines subject to operation-dependent failures. In a recent paper, Dhouib et al. (2008) propose a homogenization approach and analytical models to assess the steady-state availability and the expected throughput of non-homogeneous, mono-product transfer lines subject to operation-dependent failures. Compared to simulation results generated for thousands of transfer line configurations, the authors prove the exactness and the robustness of the proposed analytical formulae.

Although transfer lines are composed of two fundamental elements: workstations and transfer mechanisms, most of the research carried out to date about these manufacturing systems often consider that transfer times are negligible and that transfer mechanisms are reliable. In this communication, we propose analytical models to assess the steady-state availability and the throughput of homogeneous, unbuffered transfer lines subject to operation-dependant failures and having unreliable transfer mechanisms. The reminder of the paper is organized as follows. The next section describes the studied manufacturing system and gives the assumptions employed. Section three proposes mathematical formulations for the availability and the throughput of these production lines in the case where transfer times are negligible or not. Section four presents first a simulation model mimicking the dynamic and stochastic behavior of automated transfer lines in order to demonstrate the exactness and the robustness of the proposed analytical models. It also gives numerical analysis to show the impact of transfer times and the reliability and maintainability characteristics of the transfer mechanism on the overall production line performance. Finally, section five gives the main conclusions and extensions for future research.

2. Transfer line description, notations and working assumptions

The automated production line being studied is a set of m automatic machines interconnected by a common and synchronous transfer mechanism. No intermediate buffers were included between workstations. The automated production line is dedicated to manufacturing a single product type to respond to a continuous demand. Parts are transferred through machines simultaneously and flow in sequence from the first machine until they reach the last one after which they leave the production line as finished products. We assume that no product is scrapped during manufacturing or transfer operations. Figure 1 shows an m-machine automated production line with synchronous transfer mechanism.

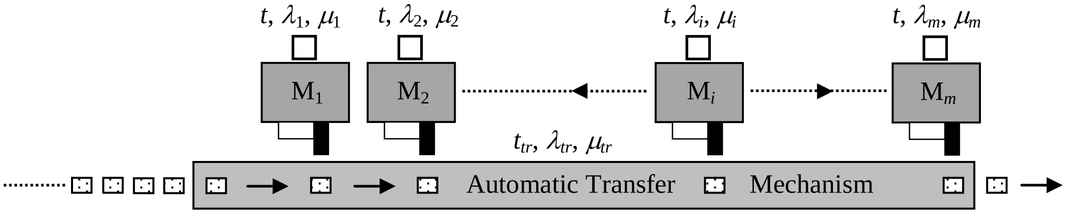


Figure 1: Automated production line with transfer mechanism

Manufacturing machines and the transfer mechanism are subject to random operation-dependent failures. Hence, a failure does not occur when a workstation or the transfer mechanism is in an idle state (Dhouib et al. 2006). At the occurrence of a failure, the production line upstream machines are blocked and the downstream ones are starved until the failed machine is repaired. The times to failure and the times to repair of a specific machine M_i (of the transfer mechanism) are exponentially distributed with respective parameters λ_i and μ_i (λ_{tr} and μ_{tr}). We assume that on failure, parts remain on their respective workstations (or on the transfer mechanism) and processing (transfer) resumes after repair completion at the point it was stopped when the failure occurs. To be processed on any workstation, a part required a deterministic amount of time denoted t. therefore, the production line is said to be homogeneous. Ounce processed, all manufactured parts are simultaneously transferred to their respective subsequent workstation during a deterministic amount of time denoted t_{tr}. We assume that the production line operates under saturation such that the first one is never starved due to lack of raw material and the last one is never blocked due to lack of space.

3. Availability and Throughput of transfer line

The automated production line being studied is a set of m automatic machines interconnected by a common and synchronous transfer mechanism. No intermediate buffers were included between workstations. The automated production line is dedicated to manufacturing a single product type to respond to a continuous demand.

3.1 Production line with negligible transfer time

Throughput is widely used as the primary performance measure for transfer lines, and is affected mainly by the line's steady state availability, often designated up time ratio (*UTR*). In fact, and in homogeneous cases, the throughput of unbuffered, mono-product transfer lines is obtained by multiplying the transfer line steady state availability by its production rate (Eq. (1)) (Buzacott 1968), where $1/t$ is the processing rate of the production line:

$$Th = UTR \cdot \frac{1}{t} \tag{1}$$

When workstations are subject to operation-dependent failures, the steady state availability of an m-machine transfer line is given by equation (2) (Papadopoulos and Heavey 1996, Sherwin 2000, Schneeweiss 2005):

$$UTR = \frac{1}{1+\sum_{i=1}^{m} \lambda_i / \mu_i} = \frac{1}{1+\sum_{i=1}^{m} MTTR_i / MTTF_i} \tag{2}$$

3.2 Production line with non-negligible transfer time

When transfer times are negligible, the production line cycle time is equal to the part processing time t. However and in real context, product transfer times are non-negligible. In this context, the production line cycle time is given by equation (3).

$$t_{cyc} = t + t_{tr} \tag{3}$$

For homogeneous lines with negligible transfer times, working machines are perfectly balanced and each machine operates continuously (Fig. 2).

Figure 2: Work load of a production machine when transfer time is negligible

If transfer times are non-negligible, each workstation and the transfer mechanism operate intermittently. In fact, at each manufactured part, a workstation operates during t time units and remains idle during transfer time t_{tr} (Fig. 3). Inversely, the transfer mechanism operates during t_{tr} time units and remains idle during manufacturing time t (Fig. 4).

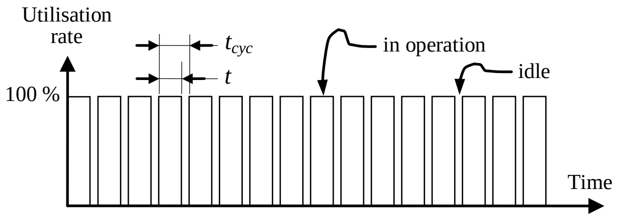


Figure 3: Work load of a production machine when transfer time is non-negligible

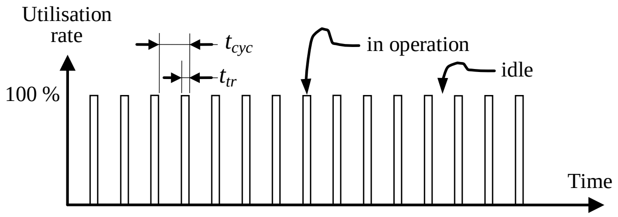


Figure 4: Work load of the transfer mechanism

Based on operation-dependent failure mode, neither workstations nor the transfer mechanism can go down; consequently, they do not age during idle periods t_{tr} and t, respectively. Whereas production lines are discrete event systems (Figs. 3 and 4), availability is a continuous time random function. To evaluate the steady-state availability and the throughput of these discrete automated production lines, we propose a two-step homogenization approach. The first step consists in converting the transfer mechanism into an additional workstation so that the original homogeneous m-machine production line is assimilated to a non-homogeneous one having (m+1) workstations where the first m machines operate under the workload of figure 3 and the last one operates under the workload given in Figure 4.

The second step consists in converting the non-homogeneous production line into an equivalent homogeneous one where the (m+1) machines operate continuously with the same manufacturing time. Therefore, the original discrete operating machine M_i, which intermittently operates at full capacity during a period with length t and remains idle during a period with length t_{tr}, will be represented by an equivalent and continuous operating one with a processing time equal to the cycle time (t_{cyc}), a reduced failure rate (λ_i^e), and a repair rate equal to that of the original machine (μ_i). Also, the original transfer mechanism, which intermittently operates at full capacity during a period with length t_{tr} and remains idle during a period with length t, will be represented by an equivalent and continuous operating machine with a processing time equal to the cycle time (t_{cyc}), a reduced failure rate (λ_{tr}^e), and a repair rate equal to that of the original machine (μ_{tr}). The reduced failure rate (λ_i^e) of an equivalent machine (i) is given by equation (4); where CF_i is the failure rate correction factor (i = 1, 2, …, m, tr).

$$\lambda_i^e = \lambda_i \cdot CF_i \tag{4}$$

The correction factor is estimated by the utilization rate of the non-homogeneous machine when operating without failures. Thus, the failure rate correction factor of a specific machine M_i is given by equation (5).

$$CF_i = t_i / t_{cyc} \tag{5}$$

Consequently, the steady state availability and the throughput of an m-machine automated transfer line with an unreliable transfer mechanism having a transfer time t_{tr} are given by equations (6) and (7), respectively.

$$UTR = \frac{1}{1 + \sum_{i=1}^{m} \frac{MTTR_i}{MTTF_i} \cdot \frac{t}{t_{cyc}} + \frac{MTTR_{tr}}{MTTF_{tr}} \cdot \frac{t_{tr}}{t_{cyc}}} \tag{6}$$

$$Th = \frac{1}{t_{cyc} + t \cdot \sum_{i=1}^{m} \frac{MTTR_i}{MTTF_i} + t_{tr} \cdot \frac{MTTR_{tr}}{MTTF_{tr}}} \tag{7}$$

In the case where the transfer mechanism is reliable and the transfer time is non-negligible and equal to t_{tr}, the steady state availability and the throughput of the *m*-machine automated transfer line are given by equations (8) and (9), respectively.

$$UTR = \frac{1}{1 + \frac{t}{t_{cyc}} \cdot \sum_{i=1}^{m} \frac{MTTR_i}{MTTF_i}} \tag{8}$$

$$Th = \frac{1}{t + t_{tr} + t \cdot \sum_{i=1}^{m} \frac{MTTR_i}{MTTF_i}} \tag{9}$$

The next section proposes first a general simulation model to show the exactness and the robustness of the proposed mathematical models. We then analyze the impact of the transfer mechanism parameters on the steady-state availability and the throughput of automated production lines.

4. Simulation model and result analysis

4.1 Transfer line Simulation model

A general discrete event simulation model was developed with the AweSim/VisualSlam system (Pritsker and O’Reilly 1999) to determine the steady-state availability and the throughput of unbuffered automated production lines with transfer mechanism subject to operation-dependent failures. It mimics the real dynamic and stochastic behavior of such lines. Figure (5) gives the flow chart of the simulation model with the following description of the principal modules:

- INITIALIZATION module: sets for each experiment the number of line machines, the part processing time, the part transfer time, the mean time to failure, and the mean time to repair for each machine and for the transfer mechanism. The simulation horizon and the warm up period after which statistics are cleared are also assigned at this step.
- PRODUCTION module: controls the flow of parts through each machine in the transfer line and manages interference situations.
- FAILURE and REPAIR module: samples times to failure and repair durations for each machine and for the transfer mechanism from their respective probability distributions.
- PERFORMANCE module: saves the number of produced parts during simulation horizon. This allows the evaluation of the transfer line steady-state availability and its throughput.

For each line configuration, simulation program was run for 10 replications in order to obtain 10 incurred steady-state availability and throughput observations, which will be next compared to analytical results generated by the proposed models (Eqs. 6 and 7). The simulation model has also been run for long time and a warm-up period has been considered to guarantee the stability of performance measures. For each generated configuration, we have also compared simulation results with those obtained analytically with the proposed approach through the Student’s t test.

4.2 Mathematical models validation

In order to analyze and to confirm the performance of the different formulations considered in this study, thousands of experiments on several production line configurations were carried out. This study has considered lines with 2, 3, …, 10 workstations. For each configuration of the automated production line, product, workstations and transfer mechanism parameters have been randomly generated.

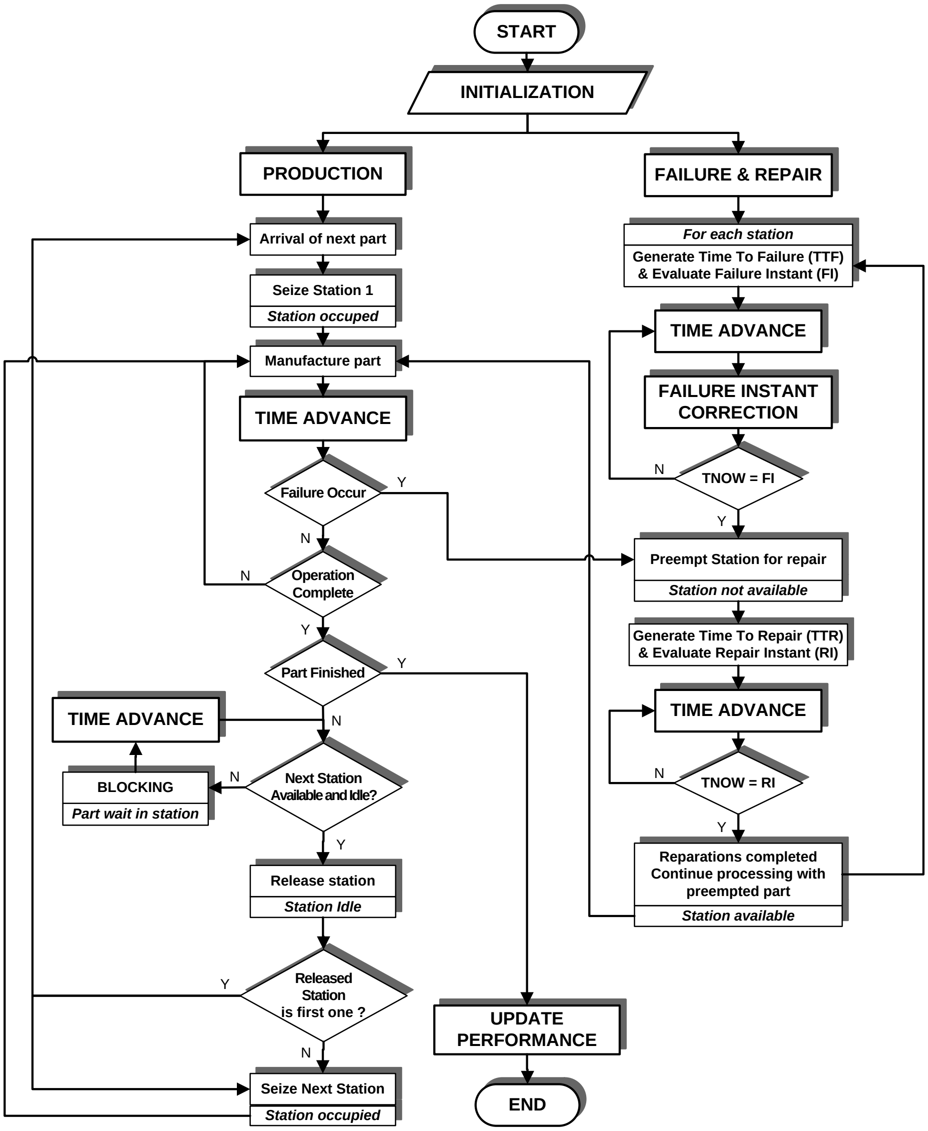


Figure 5: Simulation model flow chart

A program has been developed with Visual Basic programming language in order to randomly generate all parameters characterizing a specific automated production line. First, the program randomly generates the product processing time ($t \in [10, 25]$ time units). Transfer time is then evaluated by considering that it is equal to 5% of the processing time. Finally, and for each equipment composing the production line, the program randomly generates the individual equipment availability ($UTR_i \in [70,75\%]$). It also randomly generates the mean time to repair for each equipment ($MTTR_i \in [60,360]$ time units) and evaluates its mean time to failure using equation (10).

$$MTTF_i = MTTR_i \cdot (UTR_i / (1 - UTR_i)) \tag{10}$$

In order to demonstrate the exactness and the robustness of the proposed models, table 1 shows, for each *m*-machine transfer line, the absolute values of the availability and the throughput mean relative errors for 100 randomly generated configurations by comparing simulation results to analytical ones (Eqs. 11-12).

$$\varepsilon_{UTR}(\%) = \frac{\sum_{c=1}^{100} \frac{\left|\overline{UTR}_{s\_c} - UTR\right|}{\overline{UTR}_{s\_c}}}{100} \cdot 100\% \tag{11}$$

$$\varepsilon_{Th}(\%) = \frac{\sum_{c=1}^{100} \frac{\left|\overline{Th}_{s\_c} - Th\right|}{\overline{Th}_{s\_c}}}{100} \cdot 100\% \tag{12}$$

were c is the c^{th} randomly generated configuration of an m-machine transfer line. For a specific configuration c, $\overline{UTR}_{s\_c}$ and $\overline{Th}_{s\_c}$ are the respective mean steady-state availability and throughput values generated from 10 executed replications.

The analysis of table 1 shows that the proposed models assessing the steady-state availability and the throughput of automated unbuffered production lines with unreliable transfer mechanism generate a negligible error compared with simulation results for all transfer line configurations irrespective of the number of workstations and the availability range of individual equipments. Student's t-tests also show that the analytical proposed models reflect the real stochastic behavior of the automated production lines, which confirms the exactness and the robustness of the proposed analytical models.

Table 1: *UTR* and *Th* mean relative errors and accepted Student's t-tests ($UTR_i \in$ [70, 75%])

m	***UTR***		***Th***	
	$\varepsilon_{UTR}(\%)$	**Accep. Stud. tests (%)**	$\varepsilon_{Th}(\%)$	**Accep. Stud. tests (%)**
2	0.0523	100	0.1134	100
3	0.0575	100	0.1164	100
4	0.0656	100	0.1185	100
5	0.0606	100	0.1276	100
6	0.0621	100	0.1296	100
7	0.0769	100	0.1234	100
8	0.0788	100	0.1287	100
9	0.0834	100	0.1291	100
10	0.0858	100	0.1312	100

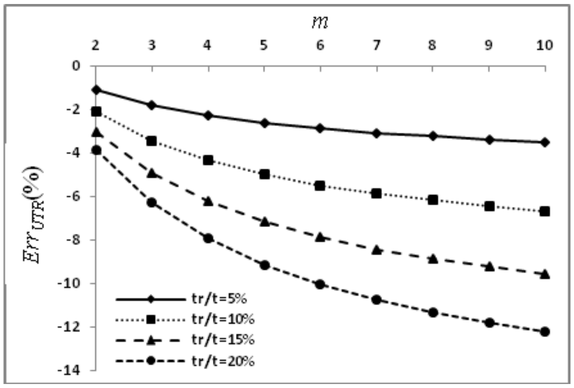
4.3 Impact of transfer mechanism parameters

In order to analyze the impact of the transfer mechanism parameters on the steady-state availability and the throughput of automated production lines, we consider homogeneous production lines composed of manufacturing machines and transfer mechanisms having the same lifetime and repair duration distributions. Equations (13) and (14), respectively, give the up-time ratio and the throughput relative errors evaluated by comparing the performance of these transfer lines when they integrate a reliable transfer mechanism with negligible transfer times (Eqs. 1 and 2) to that of transfer lines composed of unreliable transfer mechanisms having non-negligible transfer times (Eqs. 6 and 7).

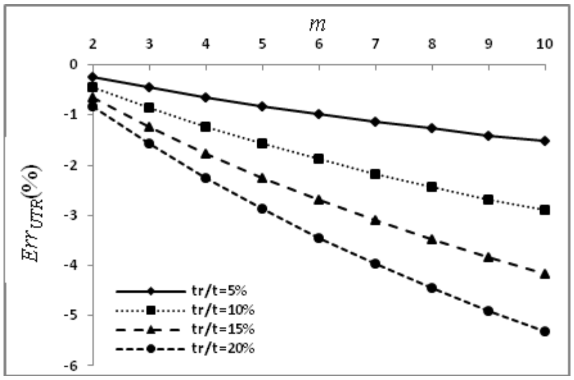
$$Err_{UTR}(\%) = \left(\frac{\mu + \frac{m \cdot \lambda \cdot t}{t + t_{tr}} + \frac{\lambda \cdot t_{tr}}{t + t_{tr}}}{\mu + m \cdot \lambda} - 1 \right) \cdot 100\% \tag{13}$$

$$Err_{Th}(\%) = \frac{t_{tr} \cdot (\mu + \lambda)}{t \cdot (\mu + m \cdot \lambda)} \cdot 100\% \tag{14}$$

Figures 6 and 7 give, for automated production lines having 2, 3, …, and 10 machines, with equipment availability equals to 70 and 95%, a processing time equals to 10 time units, and a transfer time equal to 5, 10, 15, and 20% of the processing time, the relative errors Err_{UTR}(%) and Err_{Th}(%), respectively.



(a) $UTR_i = 70\%$



(b) $UTR_i = 95\%$

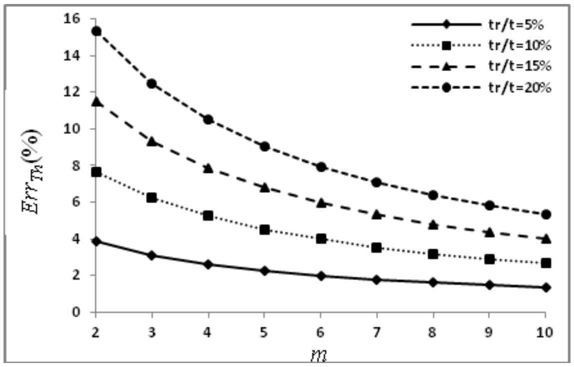
Figure 6: Production line *UTR* relative error evolution

The analysis of figure 5 (Fig.6) show that equation (2) (Eq. 1) assuming a reliable transfer mechanism with negligible transfer times underestimates (overestimates) the steady-state availability (throughput) of automated production lines. The results also show that Err_{UTR}(%) and Err_{Th}(%) increase with transfer times. Furthermore, the results show that Err_{UTR}(%) (Err_{Th}(%)) increases when UTR_i decreases (increases). Finally, Err_{UTR}(%) increases with *m* and tends to the asymptotic value of $t_{tr} / (t + t_{tr})$ when *m* goes to infinite. However, Err_{Th}(%) decreases when *m* increases and tends to the asymptotic value of 0 when *m* goes to infinite.

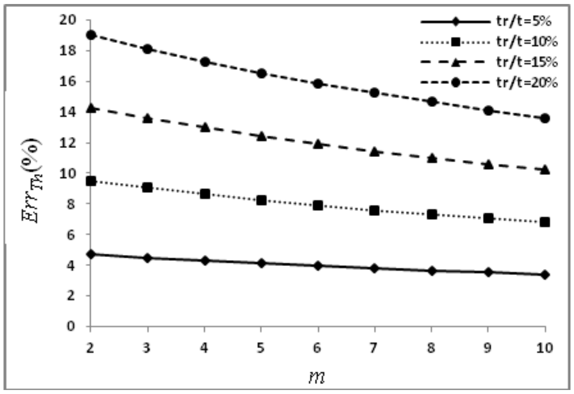
5. Conclusions

In this paper, the steady-state availability and the throughput of unbuffered automated production lines subject to operation-dependent failures with unreliable transfer mechanism and non-negligible transfer times were studied. A bi-phase homogenization approach was proposed based on transforming the discrete intermittent operating behavior of the *m*-machine production line into an equivalent homogeneous transfer line having (m+1) workstations. A general discrete event simulation model mimicking the behavior of such lines was also developed. It allows evaluation of the steady-state availability and the throughput of these automated production lines.

Several production line configurations including 2, 3, …, or 10 workstations with randomly generated parameters were analyzed in order to compare the exact performances given by the simulator to those evaluated using the proposed analytical models.



(a) UTR_i = 70%



(b) UTR_i = 95%

Figure 7: Production line *Th* relative error evolution

The results show that the proposed models produce a negligible relative error for all randomly generated configurations, no matter the transfer line length is, the values of processing and transfer times, and the availability range of individual equipments. This confirms that the proposed analytical models are exact and robust to assess the steady-state availability and the throughput of automated production lines subject to operation-dependent failures including unreliable transfer mechanisms with non-negligible transfer times. The paper also show the error generated by several models assuming that transfer mechanisms are reliable and that transfer times are negligible. This research can eventually be extended to develop analytical models for the analysis of the performance of more complex systems such as non-homogeneous transfer lines and mixed-model flexible transfer lines.

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