A Simplified Analytical Approach for Efficiency Evaluation of the Weaving Machines with Automatic Filling Repair

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Abstract: – A machine interference problem regarding a group of weaving machines with automatic filling repair and filling break tolerance is treated in this paper. Two indicators have to be evaluated: the efficiency of the weaving machines and the work loading for the weaver. A simplified analytical method, based on the superposition principle and a reduced semi-Markov chain, for evaluating with accuracy the two indicators previously defined is proposed. A case study in which analytical and simulation results are compared demonstrates the effectiveness of this simplified analytical approach.

Key–Words: Weaving Process, Automatic Filling Repair, Break Tolerance, Interference Time, Markov Chains.

1 Introduction

The weaving process is a discrete event one because the warp yarns and the filling yarn break off at random instants. In case a weaving machine (loom) is down, because a yarn has broken, a weaver (loom operator) must remedy the broken yarn and than start up the loom again. In other words, a weaving machine is a system with repair. The problem of allocation of looms to the weavers is a very important one in a large weaving mill. Two conflicting aspects must be considered: the loom efficiency (losses caused by interference) and the work loading for the weaver. The prediction of the loom efficiency and the weaver work loading, when a group of weaving machines are allocated to one ore more weavers is a machine interference problem. The problem of allocation of looms in weaving is widely dealt with in textile literature, both from a theoretical and a practical point of view (for example, [1] and [5]). In this work we focus on the machine interference problem for the looms with automatic filling repair and filling break tolerance between packages and the prewinder.

The analytical approach of machine interference problem is based on the queueing theory. The standard model is a Markov chain for which the steady–state probabilities are required. If the Markov chain has s states, s linear equations must be solved. This method is simple in essence, but we must have in view the complexity of Markov models [1], [2], [3]. For any sizable practical problem s becomes very large and the solution time becomes very long, so that, the classical approach is difficult to apply. When the Markov chain is very large, the two approaches available to deal with this problem are to either tolerate the largeness or avoid it. In this work, a largeness avoidance technique for an approximate evaluating of the loom efficiency in a weaving process with automatic filling repair is proposed.

The simulation is a complementary approach for machine interference problem [1], [4]. A simulation program based on a stochastic coloured Petri net has been used in order to validate the analytical results.

The remainder of this paper is organized as follows. In Section 2 the interference problem concerning the weaving process is defined in details. In Section 3 two simple cases with one and two looms, respectively, are solved based on semi-Markov chains. In order to generalize the problem, in Section 4 a simplified analytical method for evaluating with accuracy the efficiency of the weaving machines is proposed. Section 5 presents a case study in which analytical and simulation results are compared. The paper is closed with final remarks.

2 Problem Formulation

Consider m identical looms, served by one weaver, carrying out a weaving process completely known from a statistical point of view. Usually, a loom works with many packages for the same filling yarn. Thus, in case the filling yarn between a package and the prewinder breaks off, an automatic switch selects a spare package and avoids the stop of the loom. We say that the spare packages ensure a filling break tolerance for the weaving process. On the other hand, when the filling yarn breaks off into the shed, the broken yarn is removed automatically without a weaver intervention. In this case the loom efficiency does not depend on the machine interference time.

For a stochastical modelling of a weaving process, six primary random variables are considered:

- Time to break off a warp yarn − let λ_W be the warp breakage rate;
- Time to break off the filling yarn into the shed − let λ_F be the breakage rate into the shed;
- Time to break off the filling yarn between a package and the prewinder − let λ_{PP} be the breakage rate between packages and prewinder;
- Time to remedy a warp breakage − let μ_W be the remedying rate of warp breakages;
- Time to remedy a breakage into the shed − let μ_F be the remedying rate of breakages into the shed;
- Time to remedy a breakage between a package and the prewinder − let μ_{PP} be the remedying rate of this type of breakages.

For the looms with automatic filling repair (Dornier AS, for example), the broken yarn is removed automatically from the shed in a constant interval of time, noted by RTS. In this case, $\mu_F = \dfrac{1}{RTS}$.

Assume that all parameters λ_W, λ_F, λ_{PP}, μ_W, μ_F, μ_{PP} and RTS are known. The problem of prediction the loom efficiency (*EF*) and the weaver work loading (*WL*), depending on the number of looms allocated to the weaver, is treated in this paper. A similar problem is presented in [1] and [2], where weaving machines with filling break tolerance are considered. In this work we focus especially on the weaving machine with automatic filling repair, but the filling break tolerance is also considered.

Assumtions:

- The weaving process is in a steady–state condition.
- All random variables are exponentially distributed.
- A weaving machine is either up or down, with no partial or intermediate states.
- All break events are stochastically independent.

3 Examples

Two examples regarding the weaving machines with automatic filling repair are presented in this section. In the weaving process, two identical packages are used to feed the shed with filling yarn.

3.1 The first example

Take the most simple case in which the weaver serves a single weaving machine (m=1). To estimate the loom efficiency, two different approaches based on Markov chains are presented: first, a classical approach and than, a simplified one.

a) *A classical approach*

The weaving process is modeled by a semi-Markov chain with the following states:

- S_1 – The loom is running on and no yarn breaks exist (the initial state);
- S_2 – While the loom is running on, the weaver works to remedy a broken yarn between a package and the prewinder;
- S_3 – The loom is down and the weaver works to remedy a warp breakage;
- S_4 – The loom is down because of a yarn breakage into the shed; the broken yarn is removed automatically from the shed;
- S_5 – The loom is down and the weaver works to remedy a warp breakage. A yarn between a package and the prewinder is also broken, but this remedying is temporary suspended.
- S_6 – The loom is down because both packages are unavailable. The weaver works to remedy a breakage between a package and the prewinder.
- S_7 – The loom is down because of a breakage into the shed; while the broken yarn is removed automatically from the shed, the weaver works to remedy a breakage between a package and the prewinder.

The state diagram of the semi-Markov chain describing this weaving process is given in Fig. 1.

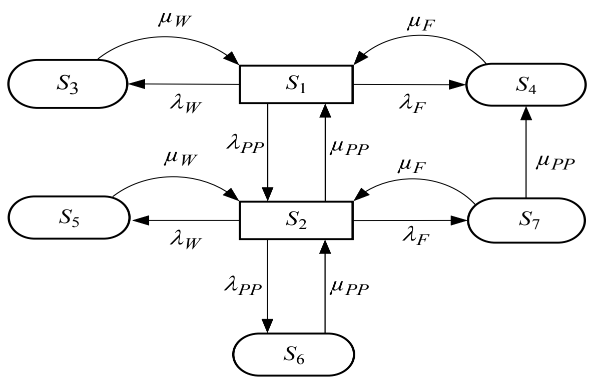

Fig. 1 – Markov chain for a weaving machine.

The matrix **M,** illustrated in Fig. 2, presents the transition rates between states. The location (i,j) in matrix **M**, $i \neq j$, comprises the transition rate from state j to state i. The value of location (i, i) is equal to the sum, taken with minus, of the transition rates in column i.

$$\begin{pmatrix}
-(\lambda_{PP}+\lambda_W+\lambda_F) & \mu_{PP} & \mu_W & \mu_F & 0 & 0 & 0 \\
\lambda_{PP} & -(\mu_{PP}+\lambda_{PP}+\lambda_W+\lambda_F) & 0 & 0 & \mu_W & \mu_{PP} & \mu_F \\
\lambda_W & 0 & -\mu_W & 0 & 0 & 0 & 0 \\
\lambda_F & 0 & 0 & -\mu_F & 0 & 0 & \mu_{PP} \\
0 & \lambda_W & 0 & 0 & -\mu_W & 0 & 0 \\
0 & \lambda_{PP} & 0 & 0 & 0 & -\mu_{PP} & 0 \\
0 & \lambda_F & 0 & 0 & 0 & 0 & -(\mu_F+\mu_{PP})
\end{pmatrix}$$

Fig. 2 – Transition matrix **M** of Markov chain presented in Fig. 1.

Let p_i be the steady–state probability of state S_i, $i \in \{1, 2, \ldots, 7\}$. To determine these probabilities, the set of linear equations (1) must be solved, in which $\mathbf{P}=[p_1, p_2, \ldots, p_7]^T$, and $\mathbf{Z}=[0, 0, \ldots, 0]^T$.

$$\begin{cases} \mathbf{M}\cdot\mathbf{P}=\mathbf{Z} \\ p_1+p_2+\cdots+p_7=1 \end{cases} \tag{1}$$

This set of equations leads to the probabilities,

$$p_1=\frac{1}{1+\rho_W+\rho_F+(1+\mu_{PP}\cdot RTS\cdot\rho_1+\rho_W+\rho_{PP}+\rho_1)\dfrac{\rho_{PP}}{1+\rho_1}}$$

$$p_2=\frac{\rho_{PP}}{1+\rho_1}p_1, \tag{2}$$

where

$$\rho_W=\frac{\lambda_W}{\mu_W},\ \rho_F=\lambda_F\cdot RTS,\ \rho_{PP}=\frac{\lambda_{PP}}{\mu_{PP}} \text{ and } \rho_1=\frac{\lambda_F}{\mu_F+\mu_{PP}}.$$

The loom efficiency EF and the work loading for the weaver WL are equal to

$$EF=p_1+p_2,\ \ WL=1-p_1. \tag{3}$$

b) *A simplified approach*

In order to reduce the Markov chain, the rule of superposition is applied, so that, the loom efficiency is determined in two steps: in the first step, the warp breakages and the breakages between packages and the prewinder are considered, whereas, in the second one, the attention is moved to the filling breakages into the shed.

Step 1. If the filling breakages into the shed are ignored, only the states S_1, S_2, S_3, S_5 and S_6 are possible. The Markov chain describing this weaving process is presented in Fig. 3. For this case, the steady–state probabilities p_1 and p_2 are

$$p_1=\frac{1}{1+\rho_W+\rho_{PP}+\rho_W\rho_{PP}+\rho_{PP}^2},\ \ p_2=\rho_W p_1. \tag{4}$$

The first estimation for the loom efficiency is

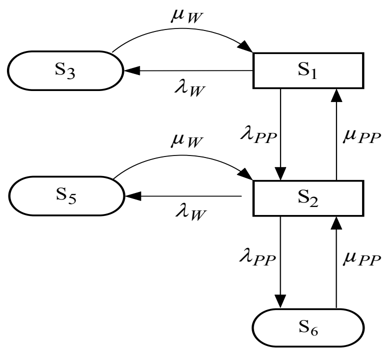

Fig. 3 – Markov chain for a weaving machine when the filling breaks into the shed are ignored.

$$EF^1=\frac{1+\rho_W}{1+\rho_W+\rho_{PP}+\rho_W\rho_{PP}+\rho_{PP}^2}. \tag{5}$$

Step 2. Now, let us consider only the filling breakages into the shed. Remember that the rate of filling breaks is λ_F, and the remedying time for a breakage is a constant noted by *RTS*. In this case, the loom efficiency (EF^2) is equal to

$$EF^2=\frac{1}{1+\lambda_F\cdot RTS}. \tag{6}$$

When all types of yarn breakages are considered, we can use the superposition rule to obtain the loom efficiency, so that $EF=EF^1\cdot EF^2$. (7)

To demonstrate the effectiveness of this simplified method, a numerical evaluation is presented. Take a weaving process with filling break tolerance and automatic filling repair, described by the following parameters:

- λ_W = 4.77 warp breakages/h;
- λ_F = 2.05 filling breakages into the shed/h;
- λ_{PP} = 1.37 yarn breakages between packages and prewinder/h;
- μ_W = 58.88 warp remedies/h;
- μ_F = 220.02 filling remedies/h (*RTS*=0.004545 h);
- μ_{PP} = 43.20 yarn remedies between packages and prewinder/h.

Based on the result of classical approach (Eqs. (3) and (4)), the loom efficiency is EF=0.9161, and by using the method in two steps, EF=0.9159.

3.2 The second example

Consider two weaving machines with automatic filling repair and filling break tolerance, served by one weaver. In this case, the classical approach for evaluating the loom efficiency is difficult to apply because the Markov chain is composed of 46 states. For this reason, the method in two steps based on the rule of superposition is more appropriate.

Step 1. If the filling breaks into the shed are ignored, the Markov chain that models the weaving process is composed of 26 states, as illustrated in Table 1. The following notations are used to denote the states of a weaving machine: WPP – the weaving machine is running on, no break exists; $\underline{W}PP$ – the weaving machine is down because of a warp breakage; $WP\underline{P}$ – the weaving machine is running on but a yarn breakage between a package and prewinder has occurred; $W\underline{PP}$ – the weaving machine is down because both packages are unavailable. Regarding the weaver, the notation R_W denotes a warp break remedying, whereas, R_{PP} reflects a filling break remedying between a package and the prewinder. The transition matrix is $\mathbf{M}=[a_{i,j}]$, $i, j \in \{1, 2, \ldots, 26\}$, where $a_{i,j}$, $i \neq j$, denotes the rate transition from state j to state i, and $a_{i,i}$ is the sum of transitions in column i, taken with minus.

To obtain the steady-state probabilities, MATLAB program can be used, and then, the loom efficiency EF^1 can be calculated by applying Eq. (8).

$$EF^1 = p_1 + p_3 + p_9 + 0.5(p_2 + p_5 + p_6 + p_7 + p_8 + p_{11} + p_{14} + p_{16} + p_{17} + p_{18} + p_{20}). \quad (8)$$

Step 2. If only the filling breakages into the shed are considered, the loom efficiency does not depend on the machine interference time. Consequently, the loom efficiency (EF^2) is given by Eq. (6).

Table 1 – The states and the transition rates of Markov chain (the second example).

S_i	The states specification	The transition rates $a_{i,j}$, $i \neq j$.
S_1	$\{WPP\},\{WPP\}$	$a_{1,2}=\mu_W$; $a_{1,3}=\mu_{PP}$
S_2	$\{\underline{W}PP\}-R_W,\{WPP\}$	$a_{2,1}=2\lambda_W$; $a_{2,4}=\mu_W$; $a_{2,6}=\mu_{PP}$; $a_{2,7}=\mu_{PP}$
S_3	$\{W\underline{P}P\}-R_{PP},\{WPP\}$	$a_{3,1}= 2\lambda_{PP}$; $a_{3,5}=\mu_W$; $a_{3,8}=\mu_{PP}$; $a_{3,9}=\mu_{PP}$; $a_{3,11}=\mu_W$
S_4	$\{\underline{W}PP\}-R_W,\{\underline{W}PP\}$	$a_{4,2}= \lambda_W$; $a_{4,13}=\mu_{PP}$
S_5	$\{\underline{W}PP\}-R_W,\{W\underline{P}P\}$	$a_{5,2}=\lambda_{PP}$; $a_{5,14}=\mu_{PP}$; $a_{5,15}=\mu_{PP}$; $a_{5,19}=\mu_W$
S_6	$\{\underline{WP}P\}-R_{PP},\{WPP\}$	$a_{6,3}=\lambda_W$
S_7	$\{W\underline{P}P\}-R_{PP},\{\underline{W}PP\}$	$a_{7,3}=\lambda_W$
S_8	$\{W\underline{PP}\}-R_{PP},\{WPP\}$	$a_{8,3}=\lambda_{PP}$; $a_{8,12}=\mu_W$; $a_{8,18}=\mu_{PP}$
S_9	$\{W\underline{P}P\}-R_{PP},\{W\underline{P}P\}$	$a_{9,3}=\lambda_{PP}$; $a_{9,16}=\mu_{PP}$; $a_{9,20}=\mu_W$
S_{10}	$\{\underline{W}PP\}-R_W,\{\underline{WP}P\}$	$a_{10,5}=\lambda_W$; $a_{10,21}=\mu_{PP}$
S_{11}	$\{WPP\},\{\underline{WP}P\}-R_W$	$a_{11,10}=\mu_W$; $a_{11,17}=\mu_{PP}$
S_{12}	$\{\underline{W}PP\}-R_W,\{W\underline{PP}\}$	$a_{12,5}=\lambda_{PP}$; $a_{12,22}=\mu_{PP}$
S_{13}	$\{\underline{WP}P\}-R_{PP},\{\underline{W}PP\}$	$a_{13,6}=\lambda_W$; $a_{13,7}=\lambda_W$
S_{14}	$\{\underline{WP}P\}-R_{PP},\{W\underline{P}P\}$	$a_{14,6}=\lambda_{PP}$; $a_{14,9}=\lambda_W$
S_{15}	$\{W\underline{PP}\}-R_{PP},\{\underline{W}PP\}$	$a_{15,7}=\lambda_{PP}$; $a_{15,8}=\lambda_W$
S_{16}	$\{W\underline{PP}\}-R_{PP},\{W\underline{P}P\}$	$a_{16,8}=\lambda_{PP}$; $a_{16,9}=\lambda_{PP}$; $a_{16,24}=\mu_{PP}$; $a_{16,26}=\mu_W$
S_{17}	$\{W\underline{P}P\}-R_{PP},\{\underline{WP}P\}$	$a_{17,9}=\lambda_W$
S_{18}	$\{W\underline{P}P\}-R_{PP},\{W\underline{PP}\}$	$a_{18,9}=\lambda_{PP}$
S_{19}	$\{\underline{W}PP\},\{\underline{WP}P\}-R_W$	$a_{19,11}=\lambda_W$
S_{20}	$\{W\underline{P}P\},\{\underline{WP}P\}-R_W$	$a_{20,11}=\lambda_{PP}$; $a_{20,23}=\mu_{PP}$; $a_{20,25}=\mu_W$
S_{21}	$\{\underline{WP}P\}-R_{PP},\{\underline{WP}P\}$	$a_{21,14}=\lambda_W$; $a_{21,17}=\lambda_W$;
S_{22}	$\{\underline{WP}P\}-R_{PP},\{W\underline{PP}\}$	$a_{22,14}=\lambda_{PP}$; $a_{22,18}=\lambda_W$;
S_{23}	$\{W\underline{PP}\}-R_{PP},\{\underline{WP}P\}$	$a_{23,16}=\lambda_W$; $a_{23,17}=\lambda_{PP}$;
S_{24}	$\{W\underline{PP}\}-R_{PP},\{W\underline{PP}\}$	$a_{24,16}=\lambda_{PP}$; $a_{24,18}=\lambda_{PP}$;
S_{25}	$\{\underline{WP}P\},\{\underline{WP}P\}-R_W$	$a_{25,20}=\lambda_W$;

S_{26}	{W<u>PP</u>},{<u>WP</u>P}–R_W	$a_{26,20}=\lambda_{PP}$;

Finally, Eq. (7) is used to obtain the loom efficiency. With the parameters presented in section 3.1, the loom efficiency is equal to EF=0.9051. A closed result has been obtained by simulation, namely, EF=0.9053. As a conclusion, the number of states of Markov chain increases dramatically when the weaver serves more weaving machines. Usually, one weaver serves up to ten weaving machines, when the Markov chain has hundreds of states. Taking into account the complexity of Markov chains, the classical approach for exact evaluation of loom efficiency is difficult to apply. For this reason, an approximate analytical method is proposed in the following section.

4 Simplified analytical approach for machine interference problem

For the general case in which one weaver serves m weaving machines, the Markov chain is too large if all random variables presented in section 2 are considered. For this reason, we focus on an approximate method and propose a reduced Markov chain able to predict with accuracy the efficiency of the weaving machines. To simplify the analytical model, two points were having in view, as follows.

1) *Regarding the automatic filling repair* – The down time for remedying a breakage into the shed does not depend on the interference time, so that the loom efficiency can be evaluated in two steps, as presented in Section 3.

2) *Regarding the filling break tolerance* – To reduce the Markov chain when many packages are used for the same filling yarn, some serial and parallel transformations can be applied [1]. In this way, an approximite model with only two random variables describing the weaving process can be obtained. These two random variables are: the time to stop the weaving process because of a breakage (a warp or a filling breakage), and the time to remedy a yarn breakage. Let λ and μ be the stop and the remedying rate, respectively. Assuming that both random variables are exponentially distributed, the weaving process with m weaving machines can be modeled by a reduced Markov chain with m+1 states, as presented in Fig. 4. The steady–state probabilities are given by the Eqs. (9) and (10), where $\rho = \dfrac{\lambda}{\mu}$.

$$p_1 = \frac{1}{1+\sum_{i=1}^{m}\left(\rho^i \prod_{k=0}^{i-1}(m-k)\right)}. \tag{9}$$

$$p_i = \rho^{i-1} p_1 \prod_{k=0}^{i-1}(m-k),\ i = 2, 3, ..., m. \tag{10}$$

The following notations are introduced: md_m – the mean number of machines down in a certain time; λ_m – the mean stop rate in the group of m weaving machines; tr_m – the mean remedying time for a yarn breakage; td_m – the mean down time of a weaving machine because of a breakage; ti_m – the mean interference time. The following equations can be written:

$$md_m = \sum_{i=2}^{m+1}(i-1)p_i\ ,\ \lambda_m = \sum_{i=1}^{m}(m-i+1)\lambda p_i \tag{11}$$

$$tr_m = \frac{1}{\mu}\ ,\ td_m = \frac{md_m}{\lambda_m}\ (\textit{Little}\ \text{formula}) \tag{12}$$

$$td_m = ti_m + tr_m. \tag{13}$$

It follows that, $$ti_m = \frac{\sum_{i=2}^{m+1}(i-1)p_i}{\sum_{i=1}^{m}(m-i+1)\lambda p_i} - \frac{1}{\mu}. \tag{14}$$

Let c_v be the coefficient of variation for time to remedy a weaving machine, obtained by simulation. As shown in [5, pp.170], the estimation of ti_m can be improved by applying a correction factor, so that

$$ti_m^* = ti_m \frac{1+c_v^2}{2}. \tag{15}$$

It follows that, $md_m^* = (ti_m^* + \frac{1}{\mu})\lambda_m$, and finally,

$$EF = 1 - \frac{md_m^*}{m}. \tag{16}$$

Symbol * is used to denote the estimation when the correction factor is considered.

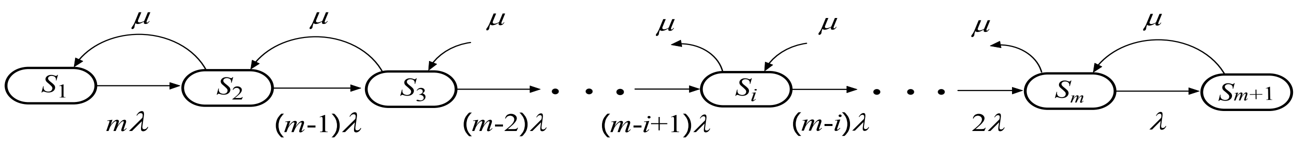

Fig. 4 – Reduced Markov chain for m weaving machines served by one weaver.

The work loading for the weaver is equal to

$$WL = \sum_{i=2}^{m+1} p_i . \quad (17)$$

5 Case Study

In this section, analytical and simulation results are compared in order to verify the effectiveness of the reduced model presented in this paper.

Take the weaving process with filling break tolerance and automatic filling repair as presented in section 3.1. Remember the parameters of the weaving process: λ_W =4.77, λ_F =2.05, λ_{PP} =1.37 breakages/h and μ_W =58.88, μ_F =220.02, μ_{PP} = 43.20 remedies/h. Note that, in this case study, the weaver does not suspend the remedying process of a broken yarn between a spare package and the prewinder, when other breakage occours, as considered in section 3.1.

In order to evaluate the loom efficiency when m looms are allocated to the weaver, the method in two steps will be applied.

Step 1. In this stage, the filling breakages into the shed are ignored. A reduced Markov model with only two random variables is obtained by applying a parallel and a serial transformation, as proposed in [1]. Thus, for a weaving machine, the breakage rate λ and the remedying rate μ are given by Eq. (18) and Eq. (19), respectively.

$$\lambda = \lambda_W + \frac{\lambda_{PP}^2}{\lambda_{PP} + \mu_{PP}} . \quad (18)$$

$$\mu = \frac{\lambda_W + \dfrac{\lambda_{PP}^2}{\lambda_{PP} + \mu_{PP}}}{\dfrac{\lambda_W}{\mu_W} + \dfrac{\lambda_{PP}^2}{\mu_{PP}(\lambda_{PP} + \mu_{PP})}} . \quad (19)$$

With these values of λ and μ, the loom efficiency EF^1 and the work loading WL can be estimated by using Eqs. (11) – (17).

Step 2. Only the filling breakages into the shed are considered. The loom efficiency EF^2 is given by Eq. (6), where $RTS = \frac{1}{\mu_F}$.

When all types of yarn breakages are considered, the loom efficiency is $EF = EF^1 \cdot EF^2$. Numerical results when one weaver serves up to eight weaving machines are presented in Table 2. For simulation, a model of stochastic coloured Petri net has been used ([1], [4]). Note the good accordance between the analytical and the simulation results.

Table 2 – Anaytical and simulation results (expressed as %).

Weaving machines allocated to the weaver	Machine efficiency (*EF*)		Percentage of working time (*WL*)	
	analytical results	simulation results	analytical results	simulation results
M=1	91.37	91.39	11.14	11.14
M=2	90.55	90.58	22.15	22.14
M=3	89.70	89.71	32.81	32.81
M=4	88.71	88.70	43.27	43.28
m=5	87.55	87.56	53.41	53.42
m=6	86.25	86.27	63.19	63.18
m=7	84.77	84.79	72.48	72.47
m=8	83.12	83.11	81.10	81.11

6 Final Remark

An approximate analytical method able to predict with accuracy the efficiency of the weaving machine with automatic filling repair and filling break tolerance is proposed. This work improves the result presented in [1], where a similar problem is treated. In this paper, all random variables describing the weaving process are exponentially distributed. But, as shown in [5, pp.169], in many cases it is necessary to consider a normal or gamma distribution for the remedying time. This point will be the subject for upcoming papers.

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