Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2015, 42 (114), 26–32
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)

Improving the efficiency and reliability of material flow in buffered systems

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Key words: material flow, continuity, reliability, capacitive element, lean, TPM

Abstract

The continuity of the flow of materials needed for correct operation of manufacturing systems can be achieved using different means and control methods. From the perspective of the technical infrastructure, it is important to ensure high reliability of machines, devices, and whole manufacturing lines. These objectives can be achieved through the use of Total Productive Maintenance (TPM). Specific effects can also be achieved by using additional capacitive elements in device systems (manufacturing lines). The focus of this study is limited mainly to continuous flow systems such as complex material flow systems in power plants or mineral pre-processing plants.

Introduction

The variety of manufacturing systems means that each efficiency improvement system requires serious analysis (Bicheno & Hollweg, 2008; Womack & Jones, 2009). One of the major tasks of these systems is to ensure the continuous flow of materials in manufacturing processes (Harris, Harris & Wilson, 2005). One of the methods that can be used in this regard is Total Productive Maintenance (TPM), which can also serve as a basis for other analyses, such as using a capacitive element in the material flow system.

The main goal of TPM is to ensure continuous operation of the equipment and machines performing specific tasks, which also means improving their operational efficiency (Rother & Harris, 2007). The method is based on the use of human resources to analyse the causes of waste and loss in a specified process, and requires a systemic solution of the problems that cause downtime of machinery and equipment (Kornicki & Kubik, 2009; Michlowicz, 2012b). The main objectives for the implementation of the TPM method are:

– reducing the number of equipment failures;
– reducing the time needed to repair and restore efficiency of a unit or line;
– eliminating of micro-stoppages;
– reducing loss.

The TPM method most commonly uses three indicators: MTTR, MTBF and, most distinctively, OEE.

MTTR (*Mean Time to Repair*) represents the average time needed to repair a device in a line.

$$\text{MTTR} = \frac{\sum \text{time for repair}}{\text{number of repairs}} \tag{1}$$

MTBF (*Mean Time Between Failures*) represents the average time between the occurrence of two failures or micro-stoppages.

$$\text{MTBF} = \frac{\sum \text{of time of correct operation}}{\text{number of occurrences of correct operation}} \tag{2}$$

The primary measure of the effects of introducing TPM is the OEE indicator (*Overall Equipment Effectiveness*). OEE means the overall efficiency of equipment, machinery, and devices. This indicator shows the current percentage of theoretically achievable efficiency for a given device or line.

The OEE indicator is usually calculated using this simple formula:

$$\text{OEE} = \text{availability} \cdot \text{performance} \cdot \text{quality} \cdot 100\ [\%] \quad (3)$$

$$\text{OEE} = A \cdot P \cdot Q \cdot 100\ [\%] \quad (4)$$

where:

A – availability: practical availability, or availability factor;

P – performance: performance effectiveness, or performance ratio;

Q – quality: quality factor.

The factors of the product can be determined as follows:

$$D = \frac{D2}{D1} = \frac{\text{operation period time}}{\text{net operating time}} \quad (5)$$

$$P = \frac{P2}{P1} = \frac{\text{actual yield}}{\text{target yield}} \quad (6)$$

$$Q = \frac{Q2}{Q1} = \frac{\text{good yield (number of good products)}}{\text{actual yield}} \quad (7)$$

Loss analysis is the starting point for the whole process of introducing modifications. Based on this analysis, the problem is identified, and the impact of the individual components (A, P, Q) on the functioning of the object in question is evaluated. Based on loss data, activities are prioritised on the basis of loss data, and a plan is set up.

The TPM method requires a systemic problem solution (Michlowicz & Smolińska, 2014; Michlowicz, 2013). Figure 1 shows a sample list of failure durations on different production lines of a plant manufacturing motors for windshield wipers (data taken from the SAP database).

The list shows the total stoppage and failure times of many production lines: P1 to P12, K1 to K13 and L1 to L12. The weakest link, the L5 line, was chosen as a testing ground for TPM implementation in all lines. The line in question was among the most faulty of several dozen lines in the plant. The difference in the total failure duration between line L5 and the average duration for the whole manufacturing unit was almost three-fold, even though many of the lines were equally complex (Michlowicz, 2012a).

Using a systemic approach to solving the problem of machine downtimes, one can check the influence of other solutions on improving the continuity of flow of materials in manufacturing processes (Nyhuis & Wiendhal, 2009). Such improvement should result in an increase in productivity of the manufacturing system.

Possible improvement of reliability of equipment systems

The performance of typical equipment systems (serial, parallel, mixed) is most often increased by:

- selecting devices with higher reliability;
- improving the reliability of devices or lines (as by applying TPM);
- incorporating redundancy throughout the entire system, a process often referred to as the *parallelisation* of the system, and is often used in control systems (Figure 2);
- adding an additional capacitive element in the system – like a buffer, a small warehouse, or storage tank.

The article draws special attention to the problems associated with the flow of materials in systems with an additional capacitive element.

For this analysis, a serial system of N devices was used, which can be a typical serial system of individual devices or a reduced mixed system consisting of both serial and parallel elements.

The typical structure of serial and parallel devices is shown in Figures 3 and 4, respectively.

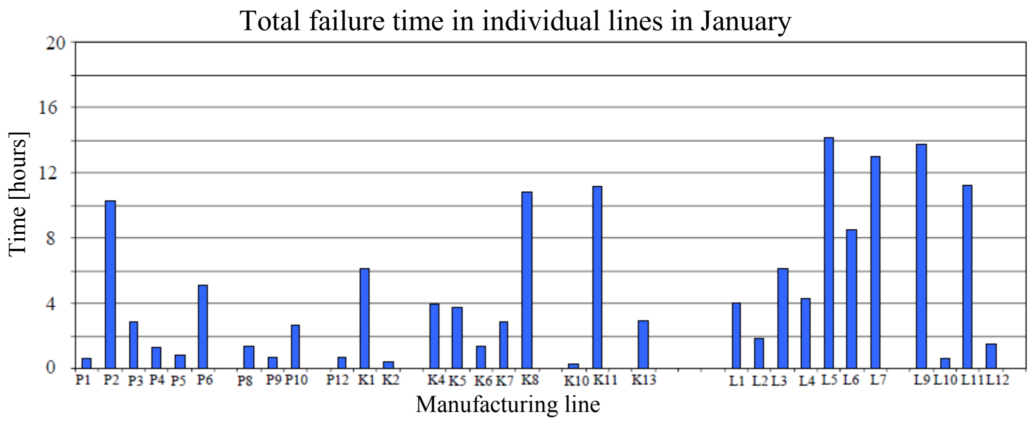


Figure 1. Overview of manufacturing line failures in a selected month

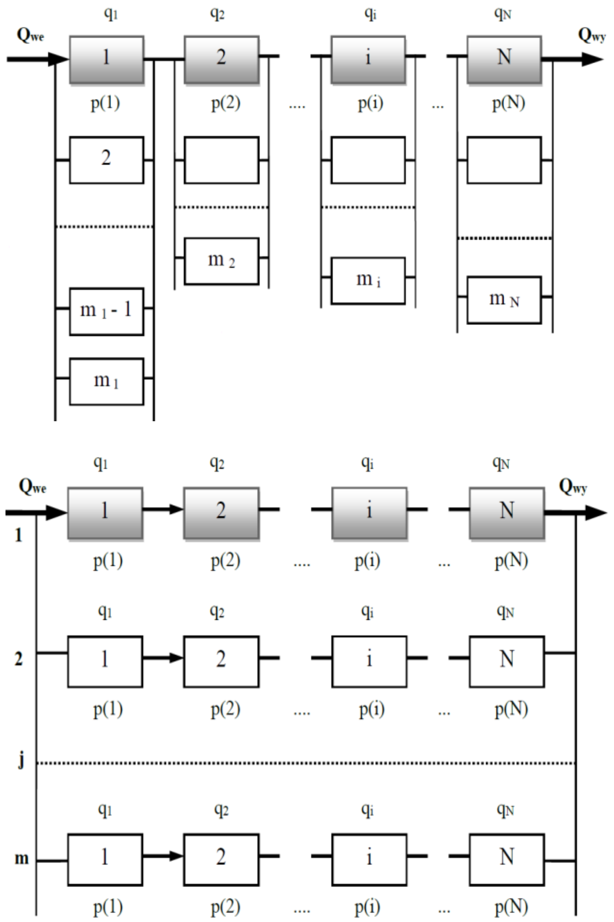
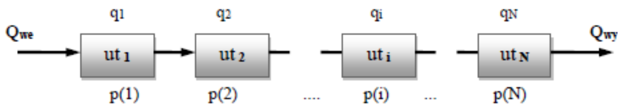


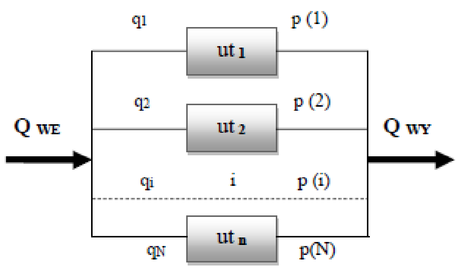
Figure 2. Schemes of parallelization of components in a system



Average performance:

$Q_{av} = P_S(s) \cdot \min q_i; \quad i = 1,2 \dots N$ and $P_S(s) = \Pi\{p(i)\}$

Figure 3. Serial structure schematic



Performance: $Q_{WY} = P_R(r) \cdot \Sigma q_i$; for $i = 1, \dots N$ when $Q_{WE} > \Sigma q_i$
Performance: $Q_{WY} = P_R(r) \cdot Q_{WE}$; for $i = 1 \dots N$ when $Q_{WE} < \Sigma q_i$
Reliability: $P_R(s) = 1 - \Pi[1 - p(i)]$; for $i = 1 \dots N$

Figure 4. Parallel structure schematic

The main problems to solve when using a capacitive element are as follows:

– determining proper buffer capacity;
– determining the proper location of the buffer in the system (*viz.*, the device after which the buffer should be placed);
– determining the number of buffers.

A schematic diagram of a system with a capacitive element is shown in Figure 5.

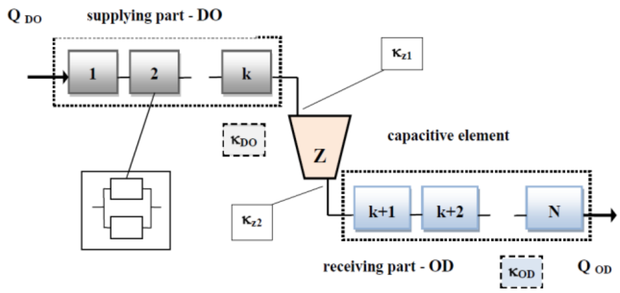


Figure 5. Diagram of a serial system with a capacitive element

Therefore, if:

Q_{DO}, Q_{OD} – performance (flow rate) of the input stream (e.g. an element supplying DO – to) and output stream (e.g. an element receiving OD – from);
q_i – performance of device;
$i = 1, 2 \dots N$ – device number ut_i;
$p(i)$ – the probability of reliability of device ut_i;

then the average performance of the system is:

$$Q_{sr} = \min q_i \cdot P_s(N); \quad i = 1, 2 \dots N \tag{8}$$

with the reliability for a serial system of:

$$P_s(N) = \prod_{i=1}^{N} p(i) \tag{9}$$

Moreover, when $Q_{DO} < \min q_i$, the output performance is:

$$Q_{OD} = Q_{DO} \cdot P_s(N) \tag{10}$$

This analysis assumes that a single device is characterised by a further damage factor κ_l, which is significantly associated with the MTTR (*Mean Time to Repair*) indicator.

It was assumed that the damage factor κ can be estimated by the formula:

$$\kappa = \frac{t_{pn}}{t_p} = \frac{\text{duration of unplanned stoppages (damage)}}{\text{operating time}} \tag{11}$$

The average value was assumed to be:

$$\kappa_{sr} = \frac{t_{pn}}{t_p} \approx \frac{E}{B} \tag{12}$$

where: E is the average duration of stoppage due to damage, and B is the average duration of uninterrupted operation.

It was assumed that the relationship between the damage factor and the probability of reliability of device i is:

$$P(i) = \frac{1}{1+\kappa_i} \quad (13)$$

The damage factor for the system (shown in Figure 5) is:

– $\kappa_{DO} = \Sigma(\kappa_i) + \kappa_{z1}$ for the providing element;
– $\kappa_{OD} = \Sigma(\kappa_j) + \kappa_{z2}$ for the receiving element.

Hence, the overall damage factor for the system is:

$$\kappa_c = \kappa_{DO} + \kappa_{OD}$$

The probability of the up state of a system without a buffer is:

$$P(N) = \frac{1}{1+\kappa_c} \quad (14)$$

The probability of the up state of a system with a buffer is:

– *element providing material* DO:

$$P_{DO}(k) = \frac{1}{1+\kappa_{DO}} \quad (15)$$

– *element receiving material* OD:

$$P_{OD}(N-k) = \frac{1}{1+\kappa_{OD}} \quad (16)$$

The probability of a down state of a system with a buffer is:

– *element providing material* DO:

$$PI_{DO}(k) = PI(DO) = \frac{\kappa_{DO}}{1+\kappa_{DO}} \quad (17)$$

– *element receiving material* OD:

$$PI_{OD}(N-k) = PI(OD) = \frac{\kappa_{OD}}{1+\kappa_{OD}} \quad (18)$$

The states in which the system can be found are summarized in Table 1.

Average system performance (the amount the receiver is able to handle) is:

$$Q_{av} = Q_{OD} \cdot [P_I(N) + P_{II}(N)] = = Q_{OD}\left[\frac{1}{1+\kappa_{DO}} \cdot \frac{1}{1+\kappa_{OD}} + \frac{\kappa_{DO}}{1+\kappa_{DO}} \cdot \frac{1}{1+\kappa_{OD}}\right] \quad (19)$$

Analysis of systems with a capacitive element

The purpose of this analysis is to determine the impact of the capacitive element on the performance of the system (Michlowicz, 2012a; 2013). A serial system was reduced to a replacement system, whose diagram is shown in Figure 6.

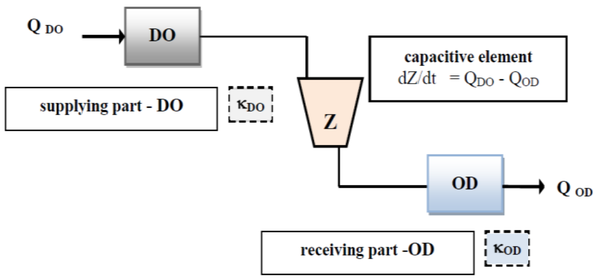


Figure 6. Diagram of the reduced system

Decision variables in this analysis are:

– the capacity of the element;
– the location of the capacitive element in the device structure.

For the purpose of analysing the impact of buffer parameters on the efficiency of the system, it was assumed that the *supplying and receiving elements* can be in the following states:

S – operational (working);
A – failure (damaged);
P – forced to stop.

State *P* – forced stoppage – occurs when the device is in standby mode, but cannot perform its tasks due to the failure of other devices.

The third part – *the buffer* – may adopt one of the three following states: 1 – empty, 2 – partially full, 3 – full.

The generalisation of the above assumptions for the entire system allows us to conclude that the total number of possible states for the system is:

$$3^n = 3^3 = 27$$

Table 1. Possible states of the system

State	The name and description of the state	Probability of state
I	NORMAL OPERATION (DO and OD elements), – the flow of material through the buffer	PI(N) = P(DO) · P(OD)
II	DAMAGED “DO” PART, “OD” PART OPERATING NORMALLY, – buffer emptying	PII(N) = PI(DO) · P(OD)
III	DAMAGED “OD” PART, “DO” PART OPERATING NORMALLY, – filling the buffer	PIII(N) = P(DO) · PI(OD)
IV	BOTH PARTS DAMAGED – “DO” AND “OD”, – no flow of material	PIV(N) = PI(DO) · PI(OD)

An example description of the state:

P3A – means that there is no flow of material in the system, because:

- the receiving element "OD" is in a failure state "A";
- the buffer is full;
- thus, the supplying element "DO" is in the forced stoppage state "P".

Simplifying assumptions made it possible to reduce the number of possible states to eight, which have been summarised in Table 2, together with the possible transitions between them.

Table 2. Table of possible states and transitions

No.	Current state	Previous state	Next state
1	S1S	4	4, 6
2	S2S	5, 6	5, 6
3	S3S	8	5, 8
4	A1P	1, 5	1
5	A2S	2, 3, 7	2, 7, 4
6	S2A	1, 2, 7	7, 2, 8
7	A2A	5, 6	6, 5
8	P3A	3, 6	3

Figure 7 shows an illustration of possible states and the transitions between them. For simplicity, the normal states of operation (S1S, S2S and S3S) were combined into a single peak.

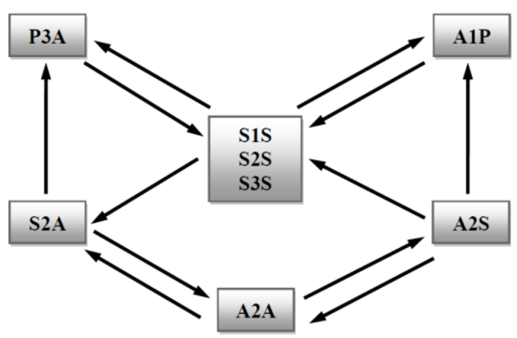


Figure 7. Graphic depiction of states and transitions

These theoretical considerations were the basis for carrying out simulation studies.

Calculation algorithm for systems with a buffer

In order to test the possible effects achievable by using a capacitive element, a calculation algorithm was created, accompanied by a computer program (written in C++), which simulates the operation of a serial system with one capacitive element.

In the calculations, both the supplying and receiving parts are characterised by the time to repair and the time of operation before a failure. Eight basic states of the system were analysed. Both operation time and time to repair are random variables described by an exponential distribution.

Designation of used values (as shown in Figure 5) are as follows:

P – production state (relative value);
Q – full capacitive element state;
W – relative efficiency of the system;
N – number of devices i, $i = 1,2,...N$;
V – relative volume of the capacitive element;
κ_i – damage factor for device i;
B(I) – the average working time before damage of device I (supplying element DO);
B(II) – the average working time before damage of device II (receiving element OD);
E(I) – mean time to repair of device I (supplying element DO);
E(II) – mean time to repair of device II (receiving element OD);
TX – state starting moment;
TK – state end moment;
TU(I) – moment of damage of device I;
TU(II) – moment of damage of device II;
TN(I) – moment of repair of device I;
TN(II) – moment of repair of device II;
CP – stoppage duration;
CRS – operation duration;
CR(I) – time of operation of device I;
CR(II) – time of operation of device II;
CN(I) – time to repair of device I;
CN(II) – time to repair of device II;
CV – time to fill the capacitive element.

The following describes the steps of the algorithm for example state S2A.

STATE S2A

Time to fill the buffer CV: $\text{CV} = (V - Q) / W$

End moment of state:

$\text{TK} = \min(\text{TU(I)}, \text{TU(II)}, \text{TX} + \text{CV})$

Duration of state: $\text{CP} = \text{TK} - \text{TX}$

Time to fill buffer Q: $Q = Q + W \cdot \text{CP}$

Time generation for:

- **repair**, if TK = TU(I), **then** $\text{CN(I)} = -E\text{(I)} \cdot \ln C$;
- moment of completion of repairs: TN(I) = TU(I) + CN(I);
- **operation**, if TK = TN(II), **then** $\text{CR(II)} = -B\text{(II)} \cdot \ln C$;
- end moment of operation: TU(II) = CT + CR(II)

Beginning of the next state: TX = TK.

Transition to the next state:

TK = TU(I)	TK = TN(II)	TK = TX + CV
A2A	**S2S**	**P3A**

Table 3. Sample simulation results

$W_{V/j}$	$\kappa = 0.05$; $V = \{0, 1, 2, 4, 8, 16\}$, $j = \{1, 2, \ldots 9\}$									
	V_i	j	P	TP_{DO}	TP_{OD}	TU_{Do}	TU_{OD}	κ_{DO}	κ_{OD}	η
$W_{0/1}$	0	1	7915.4	11488.9	7948.6	561.6	3573.5	0.0489	0.4496	**0.6596**
……					……					**……**
$W_{0/9}$	0	9	7928.7	8311.5	8092.7	3740.1	393.7	0.45	0.0486	**0.6607**
$W_{4/1}$	4	1	8190.6	11512.3	8173.1	570.8	3663.6	0.0496	0.4482	**0.6826**
……					……					**……**
$W_{4/9}$	4	9	8076.9	8274.2	7787.4	3650.3	381.2	0.4412	0.049	**0.6731**
$W_{8/1}$	8	1	8283.6	11604.3	8166.0	567.3	3636.0	0.0489	0.4453	**0.6903**
……					……					**……**
$W_{8/5}$	8	5	9375.8	9599.1	9599.1	2450.8	2348.7	0.2553	0.2447	**0.7813**

Example calculation

The following parameters were adopted as input data:

- the damage factor for each device: κ_i; $i = 1,2,\ldots,10$;
- buffer capacity $V = \{V_0, V_1, V_2, V_4, V_8\}$;
- average time of operation of each device: B(I), B(II);
- mean time to repair each device: $E(\text{I}) = B(\text{I})\,\kappa_\text{I}$, $E(\text{II}) = B(\text{II})\,\kappa_\text{II}$;
- actual state durations (work, repair) are calculated from the exponential distribution density:

$$f(t) = \lambda e^{-\lambda t} \quad t = -\lambda \ln C$$

where:

λ – the average value B(IS), E(IS);

$C \in (0, 1)$ – a random variable from uniform distribution (0, 1).

Sample simulation results for the damage factor $\kappa = 0.05$ are shown in Table 3.

where: $W_{V/j}$ – means a variant with buffer volume V_I and is located after device j.

Figure 8 shows performance variability depending on the volume and location of the buffer.

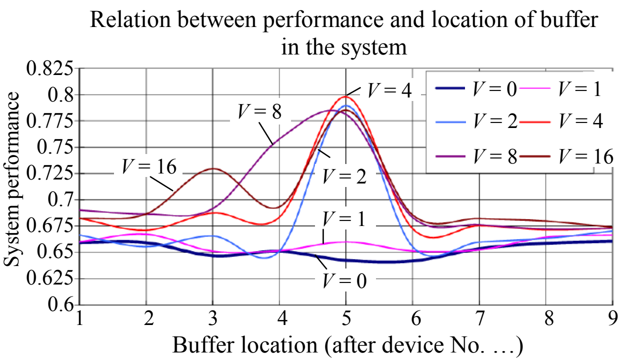


Figure 8. A plot of performance variability as a function of buffer volume and location

The performance curve for $V = 0$ (a system without a buffer) should, of course, be a straight line. The irregularity is caused by an imperfect distribution of quasi-random numbers generated by a computer program. To simplify the discussion, it was assumed in this example that all devices have the same damage factor. As a result, the biggest performance gains should occur in variants where the buffer is located in the centre of the system (after the 5th device). The results shown in the graph confirm this prediction. The largest gain was obtained for variant $W_{16/5}$, i.e., with a buffer capacity of $V = 16$ located after device 5. The relative performance was $W = 0.8$. The performance gain compared to a system without a buffer ($W_{0/5} = 0.66$) amounts to over a ten per cent increase. Such a large gain results from the high damage factor of elements ($\kappa = 0.05$). With low damage factors ($\kappa = 0.01$), the achievable performance gains are in the range of 3 to 5%. Research has also shown that gains achieved above $V = 4$ are insignificant. Therefore, due to the cost concerns, buffers with a relative capacity (relative to the flow rate) of $V = 2$ to $V = 4$ should be used.

Conclusions

The continuity of the flow of materials needed for correct operation of manufacturing systems can be achieved using different means and control methods. As far as the technical infrastructure is concerned, ensuring high reliability of machines, devices and whole manufacturing lines is an important task. These objectives can be achieved through the use of Total Productive Maintenance (TPM). Specific effects can also be achieved by using additional capacitive elements in device systems (manufacturing lines). Even though this case may be debatable in view of recommended flow control measures without storage, the additional performance gains in systems make it worthwhile to include this method of continuity improvement in company strategies. The case presented in this study is limited mainly to continuous flows (e.g. complex material flow systems in power plants or mineral pre-processing plants). In the case of systems with a serial structure, the achievable performance gains amount to several percent (3–5%) with a relative capacity of $V = 2$ to $V = 4$ of the element (buffer) in relation to the average flow rate.

Acknowledgments

This work was supported funded by research project AGH Univ. of Science and Technology Krakow 11.11.130.957.

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