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REDUCING NEGATIVE IMPACT OF MACHINE FAILURES ON PERFORMANCE OF FILLING AND PACKAGING PRODUCTION LINE – A SIMULATIVE STUDY

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ABSTRACT

The paper demonstrates the use of a Discrete Event Simulation tool to reduce the negative impact of machine failures on the performance of a filling line. The buffer allocation problem has received a lot of attention, but still there are examples of unreliable production systems for which a buffer can be allocated in order to increase their productivity. The subject of the study is a filling and packaging production line which consisted of seven machines connected by conveyors. Machine failures are registered by maintenance Data Acquisition system. Those data are used to derive statistical distributions for Time To Repair and Time Between Failures. The model is built using FlexSim simulation software and different allocation scenarios are considered. Introduction of buffers results in an increase in mean line throughput by 15%. The initial results indicate that the proposed approach may lead to the reduction of negative effects of machine failures.

1 INTRODUCTION

In modern highly competitive Fast Moving Consumer Goods (FMCG) industry, a company must rapidly adapt to constantly changing customers' requirements and improve the quality of its products in order to achieve business success. Thus, it is important to immediately respond to design or technology changes and demand fluctuations. In addition, stock optimization is also expected but it would require either more accurate sales forecast or an increase of production frequency for maintaining high service level. The latter directly affect performance of the production lines due to higher number of various production batches of lower volume. A production flexibility influences the number of machine changeovers, what may also result in decreasing the capacity of the line. All the aforementioned phenomena explain why optimization of production system performance has recently received such a great attention.

The performance of production line results directly from the performance of the installed machines. Machines are not perfectly reliable and predictable. The unreliability has the potential for disrupting the operations of adjacent machines or even machines further away. One of the approach to improvement of production performance is to prevent machine failures (Jasiulewicz-Kaczmarek and Drożyner, 2011). The other is an introduction of buffers. Buffers decouple machines, and mitigate the effect of a failure of one of the machines on the operation of others. On the other hand, inventory costs money to create and store and it is vulnerable to damage if not stored properly. It also requires space and equipment for buffer operation. Despite all the potential disadvantages buffers can exhibit, it is still beneficial to install them in most of the production lines.

The paper focuses on optimal buffer allocation in the real production line in order to increase its performance.

The objective of this paper is to:

- demonstrate the use of simulation as a beneficial tool to test various improvement scenarios,
- design and build the simulation model that reflects real production line
- create model of machine failures based on real data samples
- show how the model was validated
- present different buffer allocation scenarios:
    - 5 buffers of designed capacities - test via simulation the capacity, utilization of each buffer, evaluate the line performance,
    - check how the removal of particular buffers would affect the line performance,
    - check the influence of buffers in the line throughput.

The subject of the study is the real production systems that is modeled and validated via simulation. Different buffer allocation scenarios are evaluated through simulative experiments.

The main contribution of the paper is to demonstrate use of the validated simulation model in order to determine the efficiency of various buffer allocation in the line in order to increase the productivity.

The paper is organized as follows. We describe the roles of the storage elements called buffers in the production line in Section 2. In addition, related literature is discussed in this section. The problem was defined in section 3 together with production line description. Major ingredients of a simulation model for analyzed real production line and their implementation using simulation engine FlexSim GP and model validation are discussed in Section 4. The description of prepared scenarios and results discussion are showed in Section 5. Finally, we conclude and discuss future research directions.

2 LITERATURE BACKGROUND

A production line is a system of machines, connected by transportation elements and separated by storage zones that are used together for manufacturing process (Gershwin, 1987). The storage elements called buffers, play various roles in the entire system. The main function of the buffer is to prevent the machine from stopping due to fluctuation in production of the precedent machine. There exist two main applications of buffers in the production systems (Amiri and Mohtashami, 2012). In a nonhomogeneous (or nonbalanced) line, machines may take different lengths of time performing operations on parts. In addition, material flow may be disrupted by machines failure (Shi and Gershwin, 2009) or by differences among the service time of the stations. The introduction of buffers leads to an increase of the average production rate by limiting the propagation of distributions, but at the cost of additional capital investments, floor space of the line, and inventory. Thus, a determination of buffer number, their size and location becomes an important problem in order to reduce cost of manufacturing (Massim et al., 2010).

Battini, et al. (2009) presented most important functions of the buffer and connected them with its size and position. Besides the aforementioned ones, it can be mentioned that buffers play a role in quality control activities and detection of defected products, material feeding as well as picking activities on the line.

There exist numerous publications related to buffer size design and its influence on the performance of production system. Gershwin and Schor (2000) described an efficient buffer allocation algorithm that applied a primal–dual approach to minimize the total buffer space under a production rate constraint. Huang et al. (2002) considered a flow-shop-type production system and presented a dynamic programming approach to maximize its production rate or minimize its working-process under a certain buffer allocation strategy. Diamantidis and Papadopoulos (2004) also presented a dynamic programming algorithm for optimizing buffer allocation based on the aggregation method given by Lim et al (1990). What is more, there exist other methods used for solving the buffer allocation problem including dynamic programming (historically one of the first methods) (Chow, 1987; Jafari and Shanthikumar, 1989; Yamashita and Altiok, 1998), Powell's method (MacGregor Smith and Cruz, 2005; Yuzukirmizi and MacGregor Smith, 2008), Lagrange-based methods (Cruz et al., 2008), gradient-based search methods (Seong, et al., 1995, Helber 2001), Hooke and Jeeves method (Altiok and Stidham 1983), and the degraded ceiling method (Nahas et al., 2006). Recently, there is trend to use some meta-heuristics that are also employed effectively for solving the buffer allocation problem such as: simulated annealing (Spinellis and Papadopoulos, 2000), tabu search (Shi and Men, 2003; Demir et al. 2012), genetic algorithm (Dolgui et al., 2007), and ant colony optimization (Nourelfath et al., 2005). are examples in this area. Most of those papers bases on the decomposition method proposed by Gershwin. An extensive literature review of current methods on buffer allocation can be found in work by Demir et al. (2014).

The interesting approach was presented by Sorensen and Janssens (2011). They created Petri net model to study buffer allocation problem for the line consisting of three machines and two buffers. Yet, they used failure rates instead of statistical distributions and their study was idealized.

The other approach to buffer allocation problem is using Discrete Event Simulation (DES).

Pehrsson et al. (2015) present a simulation study of manufacturing systems with a view to identifying constraints and optimizing inter-operation buffers. They model machines unreliability by introducing statistical values such as Time To Repair (TTR) or availability. A similar approach is demonstrated by Altuger and Chassapis (2009). Until recently, DES that models system stochastic behaviors has not been applied to the same extent on higher manufacturing systems level (Pehrsson et al., 2011; Beamon ,1998; Maghsoud et al. 2011; Jasiulewicz and Bartkowiak, 2016). In some cases, mathematical methods are considered less accurate and might be more difficult to understand than the DES-based methods (Morecroft, 2007). On the other hand, DES models have some significant drawbacks as they tend to be very time consuming, requiring detailed modeling when considering analysis and optimization of complete factories, and as they often require extensive computing resources and long execution times in such situations. However, it is believed that most of those disadvantages, due to development of computational power, will soon disappear.

From a literature review of the most relevant existing studies it can be noticed that:

- The optimal buffer size problem based on the unreliable machines is a very critical issue, but still has not been yet sufficiently investigated. Most of the machine failures are modeled by statistical parameters such as TTR and Time Between Failures (TBF).
- Great majority of papers studies the model proposed by Gershwin or its variations. Buffers are used to decompose the line into subsystems as it is extremely complex to analyze systems consisting of more than three workstations and buffers. DES that models higher manufacturing systems rarely appears in literature.
- There exist very few papers that show validated models created on real production data. Most papers describe idealized cases, what might be their main barrier in potential application to industrial practice. It is also explained by the fact that there are not many manufacturing companies equipped with reliable maintenance Data Acquisition (DAQ) systems.
- There still very little attention on modeling machine failures by fitting statistical distributions into empirical data and implementation of the devised model in the production line model.

The described simulation study is a practical contribution to determining the buffer size in unreliable lines, both quickly and quite precisely. The derived models can be easily adjusted for the continuously changing production environment. It may also be a practical tool for manufacturers to easily test and verify different improvement scenarios. The objective of this paper is to bring more attraction to discrete-event simulation tools applied in the field of production maintenance. We strongly believe that DES, due to its undisputed advantages, can be a very useful tool in decision-making process.

3 PROBLEM DEFINITION

Studied object is a technical system (production line) that produces finished cosmetic goods (cosmetic cream filled into jars). The manufacturing process consists of three main subprocesses:

- compounding – where raw materials are weighted according to strict recipes,
- mixing – where raw materials are mixed and homogenized in order to obtain cream of specified parameters,
- filling and packaging – serial production line which fills cream into primary packaging and subsequently packs them into folding boxes and shipping boxes.

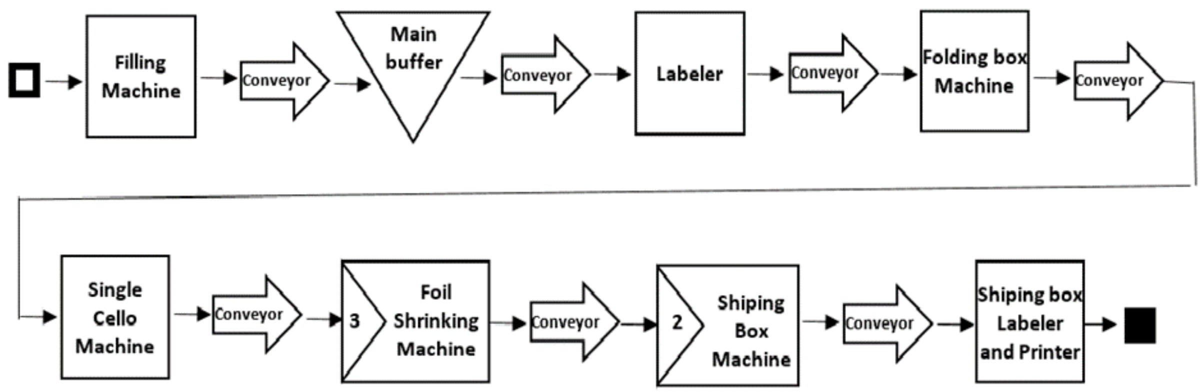

Figure 1: Filling and packaging process operations flow diagram.

The system considered in this paper concerns the filling and packaging stage only, which is shown in Figure 1 using Object Flow Diagram (OFD) notation (Beaverstock et al., 2011). The process begins with feeding empty jars through the transporter and ends with packaging wrapped packets into shipping boxes and weighing. The process takes place on continuous production line, where machines are connected with transporters. Each transporter works as a separate machine. It stops when the number of items on a conveyor exceeds its maximal capacity. During the material flow, there are no stoppages caused by transferring product from one machine to another and the line does not stop from the beginning of the production to its end. Machines are located on two levels: 0.00 and 4.75 meters. On average, the line is changed-over every one or two production shifts, but it only affects some of the machines in the line. Nominally, the line can fill 120 pieces in 60 seconds. The filling starts with feeding jars on the conveyor and lids to the lid buffer. Both machines are located on 4.75 meter level. Jars and lids are transported to 0.00 meter level by transporters to the filling machine. Inside the Filling Machine, jars move on two parallel conveyor belts. During filling process there happen a few operations:

- filling jar with cream,
- putting sealing aluminum foil on a jar,
- welding foil with jar,
- putting and twisting plastic lid on a jar.

Behind the Filling Machine there is a high capacity buffer. Capacity of the Filling Machine is 10 times bigger the Labeling Machine which is located behind the buffer. Buffer ensures production continuity. Next element of the system is the Labeling Machine. Its task is to stick labels on the filled jar. Maximal capacity of that machine is 12 pieces. Subsequent machine in the line is Folding Box Machine, which packs labeled jars into the folded boxes. That machine also prints batch number, expiration and production date. It can also fold and put a leaflet with the jar. Products that leave the folding machines enter to Single Cello machine, which task is to wrap a box with cellophane. Production process is then continued on Foil Shrinking Machine, which groups three items into one packets, wraps each packet with thermo-shrinking foil PE/PO and moves it inside hot chamber. Next machine is Shipping Box Machine. It packs four packets into one shipping box and glues the box so it cannot unfold. Shipping box moves to Weighing machine which checks its weight and removes items do not meet the tolerated values. Last machine is Shipping Box Printer and Labeler that prints labels, sticks them on shipping boxes and scans the printed barcodes. Every machine is characterized by constant net processing time, which might be affected by occurring failures.

Machines that operate in the examined filling and packaging line can be characterized by failures that can be described parametrically by TTR and TBF distributions. In the model two kinds of failures are considered. Failure of first kind are called breakdowns and they result from serious machine malfunctions such as bearing failure, short circuit, damage of the actuator etc.. These problems often require assistance of the maintenance department or 3rd party service and last significantly long. Failure of a second kind, called micro-stoppage, are caused by operational reasons (lack of packaging materials, product stuck in the machine etc.) or easy to fix technical problems. In the model, the criteria value differing those two failures is assumed to be constant and equal to 120 seconds. It is derived directly from the manufacturers practice. Neglecting the different natures of each failure kind can lead to misleading results that can impact further stages of modeling (Bartkowiak and Gessner, 2014).

4 BUILDING SIMULATION MODEL AND VALIDATION

Distributions of TTR and TBF for breakdowns and micro-stoppages are devised based on data collected by installed DAQ system that monitors those types of events. The analyzed sample concerned three month long observation of standard production. DAQ gathers data from Programmable Logic Controllers (PLCs) of every machine that operates in the line when it stops and resumes. Apart from time stamp, monitoring system provides information about the code of the failure. In addition, failures that last longer than 120 seconds have to be described manually by mechanic or operator. Time resolution of a single failure is 1 second. Based on the collected data, distributions of time to repair and time between failures can be easily calculated. In the described case, ExpertFit® distribution-fitting software is used to determine the best distribution for the given data. More details about the software can be found in (Law, 2011). For some data sets, no candidate model provided an adequate representation. In this case, as recommended by software developer, an empirical distribution is used.

Table 1 summarizes the modeled objects and estimated statistical distribution that describe breakdowns and micro-stoppages. That table contains abbreviations standing for the following statistical distributions describing breakdowns (B) and micro-stoppages (M):

- lognormal – log-normal (Galton) distribution,
- cempirical – empirical distribution,
- inversegaussian – inverse Gaussian distribution,
- Johnsonbounded – Johnson bounded distribution,
- Beta – Beta distribution.

Table 1: Summary of machines and estimated statistical distributions (TTR) describing breakdowns and micro-stoppages. source: own work.

Name of an object	Description	Capacity [pcs.]	Failure distributions (TTR distributions)
Filling machine	Filling jars with cream	120	B:lognormal2(118.16432,68.548549, 1.51485,1) M:cemprical(„FillingMachineMTTRTab",1)
Labeler	Labelling jars	12	B:inversegaussian(117.35181,224.26358, 34.06457,1) M:cempirical(„LabellerMTTR", 1)
Folding box machine	Putting jars into folded boxes	30	B:johnsonbounded(119.04751, 5432.17052, 2.92705,0.66868,1) M:cempirical(„FoldingBoxMTTR", 1)
Single cello machine	Cellophaning	40	B:johnsonbounded(130.30733,341.62041, 0.65679,0.48126,1) M:beta(1.62103,129.69863,0.62559, 1.93504,1)
Foil shrinking machine	Wrapping and shrinking foil over 3 item packets	40	B:lognormal2(119.39103,64.85981, 1.83399,1) M:johnsonbounded(1.52013,125.63919, 0.83745,0.63815,1)
Shipping box machine	Packing 4 packets into shipping box	48	B:lognormal2(117.15510,69.26997, 1.42784,1) M:cempirical(„ShippingBoxMTTR",1)
Shipping box labeler and printer	Printing and labelling of shipping boxes	24	B:lognormal2(121.26295,78.87534, 1.24878,1) M:johnsonbounded(1.51009,154.43555, 1.38520,0.56123,1)

In the validation process of production line simulation model, Overall Asset Efficiency (OAE) key performance indicator was used. This measure was devised in the corporation in which the analyzed production facility exists as a part of its supply chain. OAE was chosen as a main indicator in validation of the modeled line. OAE differs from the commonly used Overall Equipment Effectiveness (OEE) as it only concerns inefficiencies due to technical and organizational reasons, speed reduction, losses due to cleaning and change-overs of the machines that are parts of the line. OAE value is presented in percentages and calculated by applying the following formula:

$$OAE = P/U \cdot 100\% \quad (1)$$

where:

$$P = n/vnom \quad (2)$$

$$U = P + B + M + C + CO \quad (3)$$

and:

P - production time,
n - number of filled pieces,
vnom - nominal production rate of the filling machine (pcs per min),
U - uptime,
B - time losses due to machine breakdowns,
M -time losses due to machine micro-stoppages,
C - time losses due to cleaning of the machines,
CO - time losses due to machine change-overs resulted from changes of packaging type or language version for the same type of packaging.

What is more, the company developed and uses its own performance measure called Technical Efficiency (TE) (shown in percentage), which can be noted as:

$$TE = P/(P+B+M) \times 100\% \quad (4)$$

By definition, this Key Performance Indicator (KPI) is supposed to measure only technical and organizational causes that initiate the breakdown and micro-stoppages. It is explained by the fact that, time losses due to cleaning and change-over depend primarily on the production plan and resulted number and required time to be spent on those activities. The presented indicators were implemented in the described simulation model.

In order to verify the model, results obtained from simulation were compared with actual values. 30 simulations were conducted for each scenario: lasting 1 production shift (455 minutes) and 2 production shifts (910 minutes) and values of Technical Efficiency KPI were calculated. Those simulation times were selected as, on average, per every one or two production shifts there occurs a line change-over and all products are removed from the line.

Those values were confronted with actual figures that referred to the same period that was used for analysis of TTR and TBF. Those results demonstrate a good agreement between the model and the actual real object. Relative error did not exceed 2 percentage points, whereas absolute error was below 2% (Pawlewski et al., 2016).

5 REDUCTION OF MACHINE FAILURES BY BUFFER ALLOCATIONS

The reduction of negative effects resulted from machine failures were studied by setting the following scenarios:

- 5 buffers of designed capacities - test via simulation the capacity, utilization of each buffer, evaluate the line performance – see Figure 2,
- identify buffers that are more utilized than others and remove buffers which present little utilization,
- check how the removal of particular buffers would affect the line performance,
- check the influence of buffers on the line throughput.

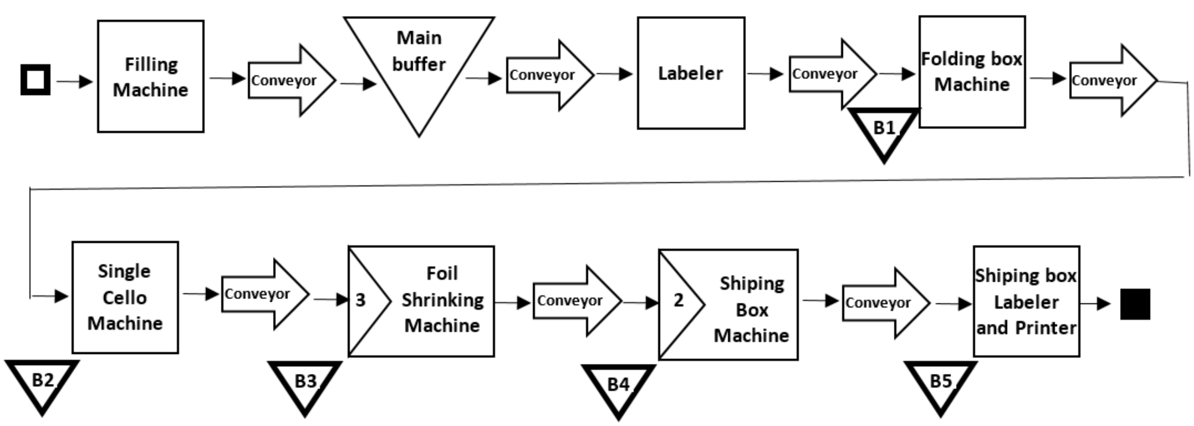

Figure 2: The allocation of five buffers on the studied production line.

In all of the conducted experiments the objective function is the line throughput, namely number of finished products that leave the system during the experiment. It is assumed that the each experiment lasts 600 minutes. The decision variables are the sizes of the buffers: 1, 10, 20, 50,100, 200, 400, 600, 800, 1000 pieces.

It is the first study, we conducted and we assume that in our future work, buffers sizes will be sought for which different objective function – defined by financial measures – will be considered (see section 6). In this paper, six various scenarios were analyzed (see Table 2). The first scenario represents "as-is" situation, which means that the line possesses one buffer behind the Filling Machine. The other ones concern allocations of single buffers between two neighboring machines (X marks the allocation of particular buffer, empty field means that there is no buffer).

Table 2: Six analyzed scenarios.

Scenario	B1	B2	B3	B4	B5
1					
2	X				
3		X			
4			X		
5				X	
6					X

The results obtained for Scenario 1 ("as-is") are presented in Figure 3. Ten replications for each scenario were performed – those scenarios were defined in order to understand the system behavior. Scenarios represent various buffer sizes: from 1 to 1000 pieces. It was noticed that 10 replications were enough to analyze the system performance and more replications did not provide any important contribution. Namely, for analyzed scenarios, the widths of confidence intervals for throughput were stabilized for number of replications greater than ten. In further studies the number of replications will be adjusted according to the defined cost-based objective function (see section 6).

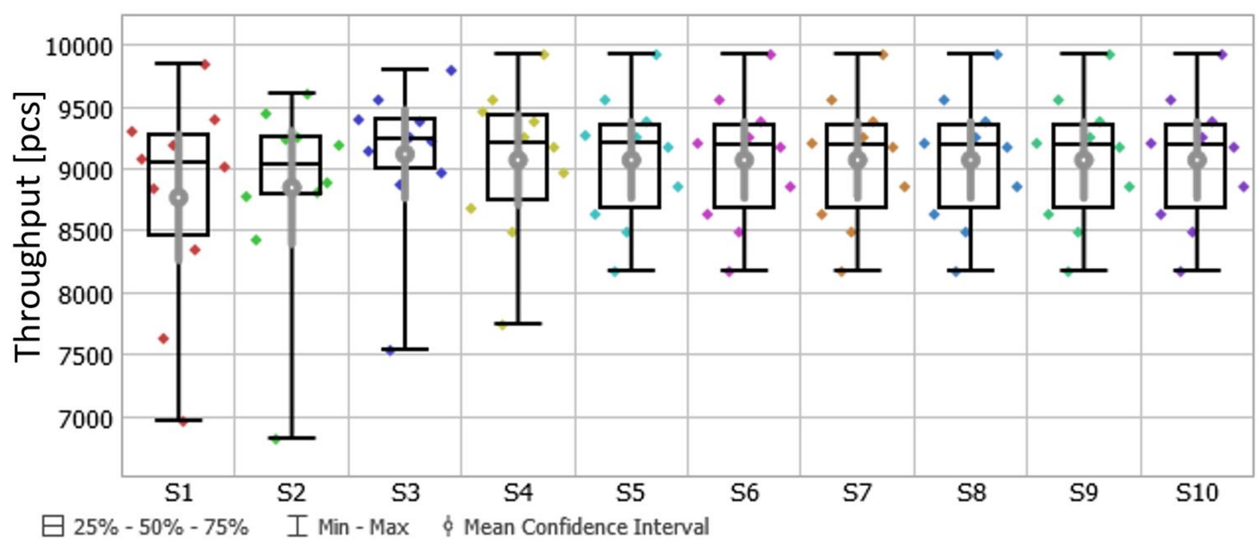

Figure 3: Results obtained by simulation experiments for Scenario 1 („as-is"). Please note that S1, S2,…, S10 are different scenarios varying in buffer capacity from 1 to 1000 pieces, gray circle indicates mean throughput for each scenario based on 10 replications.

Those results were the reference for other tested scenarios. In order to check if certain buffer allocation would provide any benefits for the line performance, mean and median throughput were calculated for "as-is" situation with the real size of the existing buffer. Some statistical parameters i.e. mean and median were calculated – they took values of 8977 and 9106 pieces, accordingly.

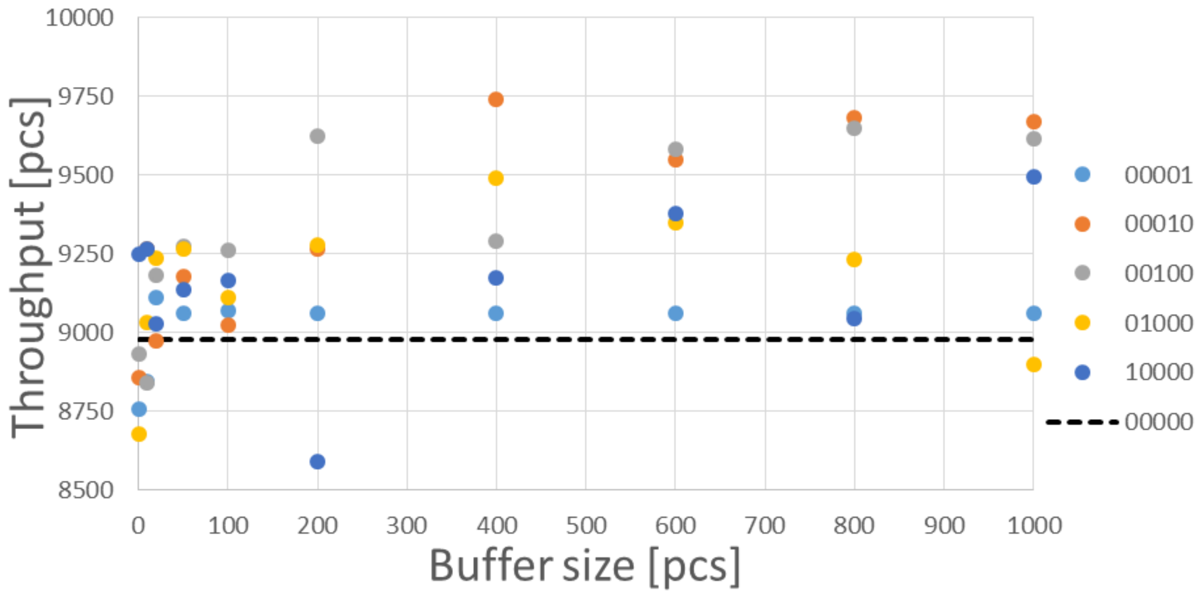

Figure 4: Results of simulative experiments for different buffer allocations – mean throughput calculated for ten replications. Please note that "as-is" result is presented as a dash line.

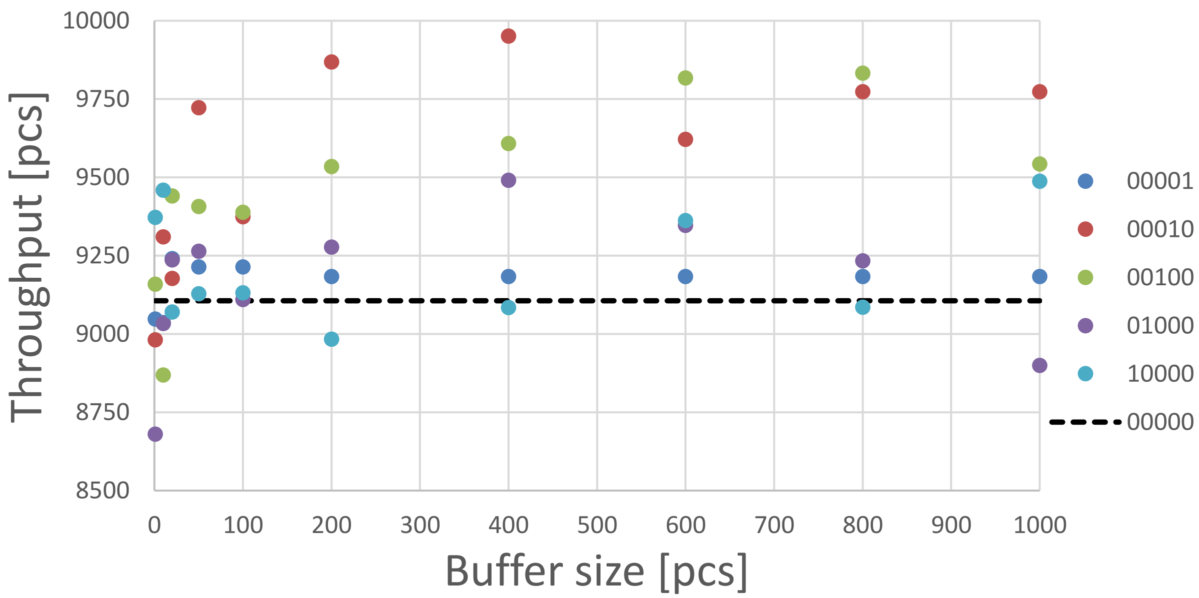

Figure 5: Results of simulative experiments for different buffer allocations – median throughput calculated for ten replications. Please note that "as-is" result is presented as a dash line.

The results obtained for other buffer allocation scenarios are depicted in Figure 4 (mean values of ten replications for each simulation variant) and Figure 5 (median values of ten replications for each simulation variant).

It can be noticed that both mean and median throughput are affected by buffer size. In most cases (except B1) throughput increase for buffer capacity between 100 and 800. For all allocation scenarios, it is evident that relation between mean and median throughput is not monotonous for analyzed sizes. Namely, as an example, mean and median line throughput take the highest values for B4 buffer which capacity is 400 pieces. The increase of buffer capacity in that case did not lead to the increase of line performance. It might also be noticed that allocation of B5 buffer generally does not improve the productivity much. Impact of B2 and B1 is size dependent and appears to be less beneficial than B3.

6 CONCLUSIONS AND FURTHER WORKS

Based on this simulation study, promising results are obtained which indicate that it is possible to reduce the negative impact of machine failures on the performance of filling and packaging production lines. It was found out that mean throughput could be increased by almost 15 percent. The proposed method can be beneficial in decision-making process that concerns company that wants to optimize its productivity.
However, from practical point of view, the primary criterion of every decision is the return on funds spent or invested into the company. The authors want to develop this method in two directions:

- the first one is the further analysis of the proposed production system model – study into various combinations of buffer sizes and finding possibly smaller buffers for which line productivity increases by 15 percent; distinction between effects of breakdowns and micro-stoppages on the system – for which failure type the proposed method is the most perspective,
- the latter one is related to financial aspects of the solution – development of business model for analyzed production line, cost estimation for particular improvement scenarios, feasibility of proposed solution and developing the objective function based on profits vs. cost.

The primary objective of further research in this field is to answer the question of how long it would get to have a return on an investment into additional buffers, which parameters will be found as a result of simulation study as well as how attractive the proposed solution it will be from financial perspective.

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