Improving the performance of a filling line based on simulation

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Abstract. The paper describes the method of improving performance of a filling line based on simulation. This study concerns a production line that is located in a manufacturing centre of a FMCG company. A discrete event simulation model was built using data provided by maintenance data acquisition system. Two types of failures were identified in the system and were approximated using continuous statistical distributions. The model was validated taking into consideration line performance measures. A brief Pareto analysis of line failures was conducted to identify potential areas of improvement. Two improvements scenarios were proposed and tested via simulation. The outcome of the simulations were the bases of financial analysis. NPV and ROI values were calculated taking into account depreciation, profits, losses, current CIT rate and inflation. A validated simulation model can be a useful tool in maintenance decision-making process.

1. Introduction

High speed manufacturing involves significant investment. Any change to its operating parameters will have immediate effects. It is important to design and operate this type of facilities at its most efficient condition through continuous improvement efforts. It is necessary to have the ability to carry out “what-if” scenario analyses to sufficient details to evaluate and identify constraints in the production line alternative decisions on improvement plans [1]. These scenarios are characterized by changing the conditions and assessing the compatibility of the system on increased work and reduced waste. This is where computer simulation programs can be very effective. Computer simulation refers to methods for studying a wide variety of models of real-world systems by numerical evaluation using software designed to imitate the systems operations or characteristics, often over a period of time [2]. From a practical point of view, simulation is the process of designing and creating a computerized model of a real or proposed system for the purpose of conducting numerical experiments to give us a better understanding of the behaviour of that system for a given set of conditions.

For the purpose of this paper, we will define simulation as, "the process of designing a computerized model of a system (or process) and conducting experiments with this model for the purpose either of understanding the behaviour of the system and/or of evaluating various strategies for the operation of the system." [3]. Thus we will understand the process of simulation to include both the construction of the model and the analytical use of the model for studying a problem.
This study aimed to evaluate and improve the performance of a filling line based on Discrete Event Simulation (DES).

The paper is organized as follows. In chapter 2 the literature on the use of simulation in maintenance has been reviewed. Next chapter is a brief description of the production which is the subject of our study. In chapter 4, results of machine failure analysis are presented. That analysis constitutes a base of simulation model. Finally, in chapter 5, two different improvement scenarios are presented accompanied by the financial analysis. This paper shows that a validated simulation model can be a useful tool in decision making process.

2. Theoretical background
An increased productivity and better overall efficiency of the manufacturing system are important goals for many companies [4,5]. The disturbance of production to perform the expected outcomes can result in substantial production losses, deteriorated quality, lowered safety, and can affect the financial performance and non-performance of the organisation. Therefore, identification and elimination of constraints or disturbances in manufacturing system is one of the ways to increase efficiency [6, 7].

That is why efficient and reliable disturbance handling is importance for technical as well as economical and human resources [8, 9, 10]. Disturbances in production systems are defined by the several authors [11, 12]. The different definitions of disturbances have many similarities but differ in important details (see Figure 1).

![Figure 1. Differences in Understanding of Disturbances in Literature [13].](image)

The authors of this paper understand a disruption as an expected event that causes machine failure. According to the given definition of a disturbance, several possible disturbance scenarios can arise in a production system. Disturbance can among other things be seen as losses, which can be classified into various types. To describe the efficiency of a manufacturing system, the production disturbance can be classified in downtime, speed and quality losses. Reduction of downtime losses is seen as the most important in order to increase overall efficiency of a system (figure 2).

Disturbance can occur in all system levels in manufacturing and the causes of disturbance in manufacturing systems may be related to many factors, such as: organizational, planning, operational and technical. That’s why efficient and reliable disturbance handling is importance for technical as well as economical and human resources. But the most important is see and assess the possibilities of disturbance reduction. Simulation can be used to support decision-making and to evaluate the impact of various opportunities for improvement.

Manufacturing industry has made extensive use of simulation as a means of modelling the system and trying to model the impact of variability on system behaviour and to explore various ways to cope up with the changes and uncertainty. Using a valid simulation model provides several benefits and advantages in developing a better system and in predicting the system behaviour under varying set of circumstances in order to improve the system performance. The objective of simulation can be that of
quantifying performance improvements which can be expected from effecting changes. Simulation is able to demonstrate the benefits of making some decisions throughout the entire manufacturing system. Finally, simulation through animation can provide a visual and dynamic illustration to management of how the new system would work.

Figure 2. Different disturbances category [14].

Simulation has two main approaches; continuous and discrete, both of which depend on the time varying dynamic behaviour. In the continuous approach, the values gradually change throughout the simulation run. The discrete approach uses Discrete Event Simulation (DES) which is based on the assumption that time only exists at determined points, and that events will only take place at these points hence it is more appropriate for detailed operations systems where each item needs to be traced within the organisation dynamics. Simulation in general and discrete event simulation (DES) in particular have been widely used in many manufacturing applications and have proven to be an excellent decision support tool for manufacturing system applications. Discrete-event simulation models have been found to significantly improve the design, management, and analysis of production systems [15, 16, 17].

Machine and equipment breakdowns found in most manufacturing industries and the adverse effects on the overall performance of the organisation ranging from production loss, high production cost, obvious inability to meet production deadlines, poor company’s reputation and loss of integrity which invariably reduces the share capital and the ability to compete with similar industries. However, they create a window of research for possible remedies. Simulation has been the second most widely used technique in operations management after modelling and has the potential to represent the complexity of maintenance systems. The continuous approach is usually used in maintenance of a single machine and only at the high level maintenance operation in an abstract form. DES is particularly relevant to maintenance operation systems. DES shows how the system develops over the time, may be used to answer the question “what if”, and helps explain why certain phenomena occur. Andijani and Duffuaa [18] evaluated simulation studies in maintenance systems in terms of adherence to sound modelling principles such as program verification and validation. According to [18] the purpose of simulation studies in maintenance systems has been classified, evaluated and categorised into: (1) Organisation and Staffing, (2) Evaluation of Maintenance Policies, (3) Maintenance Planning and Scheduling, (4) Spare Parts and Material Management, (5) Shutdown Policies. The authors of this paper prepared a detailed literature review on practical simulative studies of production maintenance (see table 1). It proves that, recently, the range of potential applications of simulation in this field has grown widely.
Table 1. Simulation modeling production maintenance

| Field                        | Related references |
|------------------------------|--------------------|
| Organization and resources   | [19], [20], [21], [22] |
| Maintenance policies / strategies | [23], [24], [25], [26], [27], [28] |
| Maintenance planning / scheduling | [29], [30], [31], [32], [33], [34], [35] |
| Spare parts                  | [36], [37], [38]   |
| Maintenance cost             | [39], [40], [41]   |

This review indicates that simulation has a well-established link in maintenance research, and the use of simulation in maintenance has been increasing. After the literature analysis, following findings can be formulated:

- literature shows the application of DES to evaluate traditional maintenance policies is well addressed,
- simulation has been applied in scheduling preventative activities within manufacturing systems,
- DES has the potential to calculate maintenance operation cost. Yet, there is still very little study about the profitability of new investments into maintenance,
- Models are seldom built based on real data captured from real system working in industrial environment.

In order to address the aforementioned findings, the authors of this paper designed and validated a model based on a real production line. The data were captured from installed DAQ systems collecting the maintenance data from every machine. Two different improvement scenarios were financially evaluated using simulation model as a tool.

3. Characteristics of the model

3.1. Characteristics of the studied object

The subject of study is a technical system, namely a serial manufacturing line, that produces finished cosmetic goods (cosmetic cream). The manufacturing process consists of three main sub-processes (figure 3):

- weighing – where raw materials are weighted in accordance to production recipes,
- mixing – where raw materials are mixed and homogenized in order to produce cream that is transferred to mobile containers or stationary tanks,
- filling and packaging – serial production line which fills cream into primary packaging and subsequently packs them into folding boxes and shipping boxes.

![Figure 3. Stages of production process.](image)

The analysis described in this paper concerns filling and packaging stage only. The process starts with feeding empty jars through the separation & orientation station and a conveyor and ends with
packaging wrapped packets into shipping boxes and weight control. The process takes place on the continuous production line, where machines are connected with conveyors. 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. On average, line is changed-over after filling 20,000 pieces of primary packaging units (jars) - yet it only affects some of the machines in the line. Nominally, the line can produce 120 pieces in 60 seconds. The filling process begins with feeding jars to the depalletizing unit and lids to the lid separation & orientation station. Both machines are located above the other part of the line, namely on 4.75 meter level. Jars and lids are transported to 0.00 meter level by the system of conveyors to the filling machine (see Filling machine in figure 4). Inside the Filling Machine, jars move on two conveyor belts. During filling process there happen four operations:

- filling jars with cream (two jars are filled at the same time),
- putting sealing aluminium foil on a jar and pre-welding,
- welding foil with jar,
- putting and twisting plastic lid on a jar.

Behind the Filling Machine there is a high capacity buffer located. Capacity of the Filling Machine (M.1) is 10 times greater than Labelling Machine which is located behind the buffer. Buffer is installed to ensure production continuity, which may result from failure of the Filling Machine. Next element of the production system is the Labelling Machine (M.2). Its task is to stick labels on the filled jar. Maximal capacity of that machine is 12 pieces. Subsequent machine in the line is the Folding Box Machine (M.3), which packs labelled 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 inside a folded box. Products that leave the Folding Box Machines enter Single Cello Machine (M.4), which task is to wrap a box with cellophane. Production process is then continued on Foil Shrinking Machine (M.5), which groups three items into one packets, wraps each packet with thermo-shrinking foil PE/PO and moves it inside a hot chamber. Next machine is the Shipping Box Machine (M.6). It packs four packets into one shipping box and glues the box to prevent unfolding. Shipping box is moved to Weighing Machine (M.7) which checks its weight and removes items that do not meet the tolerated values. Last machine is Shipping Box Printer and Labeller (M.8) that prints labels, sticks them on shipping boxes and scans the printed barcodes (see End: Labeller in figure 4).

**Figure 4.** Model of the filling and packaging process created in FlexSim.

3.2. _Pareto analysis of the system failures_

There exist two basic definitions of term “failure”: 1) Inability of a product as a whole to perform its intended functions; 2) Inability of particular components to perform its intended functions but a product as a whole can still perform. Those examples constitute an illustration of how certain type of a
failure might not be classified as failure, depending on the definition. In reality, there are numerous definitions of failure. Depending on the competence level and knowledge about the technical systems, companies set their own definitions of failures and their types. Manufacturers that put the emphasis on the effectiveness of their production process, monitor all types of failures and stoppages that impact their technical systems in order to have more control over the manufacturing process. The subject of our analysis is a three-month long observation period of the filling line performance. The data acquisition system installed on that line, collects the data about the failures of particular machine in the line. The failure time is registered only if Filling machine stops. Breakdown is calculated until that machine resumes its operation. If failure lasts longer than 2 minutes it is considered a breakdown and detailed explanation of that problem is required to be provided by the operator directly in the system. The distribution of breakdown time is presented in figure 5.

![Figure 5](image.png)

**Figure 5.** Distribution of breakdown time for all the machines in the line.

It is clearly visible that three out of eight machines in total, are responsible for more than 70% of total breakdown time. Based on that information, a detailed drilldown of causes that initiated those failure is provided for two machines that generated the most of disturbances (figure 6 and 7). Those causes were than divided into categories: organizational problems, minor technical issues, major technical issues. Minor technical issues, contrary to major ones, do not require investment into machine but only minor maintenance action by the maintenance department. Let us focus on M.6 that is located at the bottom of the line. The main problem of this machine is the feeding system that causes most of the problems (see causes A, B, C, G, H). It is believed that this machine is the bottleneck of the entire production line. The technical problems can be solved by installation of the new feeding system that would enable feeding packets into shipping boxes without failures. A simulative study of the financial impact of certain scenarios is present in chapter 4.

### 3.3. Simulation model

Machines that operate in the studied 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 modelling [42].

Figure 6. Distribution of breakdown time for M.1.  

Figure 7. Distribution of breakdown time for M.6.

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 analysed sample was collected during three month long observation of standard production. DAQ gathers data from 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. Table 2 summarizes the modelled objects and estimated statistical distribution that describe breakdowns and micro-stoppages. That table contains the 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.

Model was created in simulation program FlexSim (www.flexsim.com). That simulation program was selected due to following benefits it provides:

- production layout can be loaded directly from *.dwg file,
- simple to be used in real 3D dimensions utilizing drag&drop technology,
- simple to model technical systems,
- vast library of statistical models,
- built-in ExpertFit tool for fitting statistical distributions to empirical data.

The model was validated based on the line performance indicator. The details of that process were described in [43].
4. Improving performance

4.1. Return on investment

The best indicator of benefits from the investment is the potential profit it may result in. Therefore it is important to estimate all financial aspects that may concern particular investment. The most commonly used approach, apart from application of simple static methods, are dynamic methods such as: NPV or ROI. In both methods, expenses and gains, together with moments of cash-ins/outs are important factors. The later the money streams into company budget, the lesser value it has due to inflation. Analogically, the loss is less painful when it occurs later in time. Dynamic methods involve discounted cash flows, taking into account a discount rate and number of years. In the paper, the method that is used to evaluate the efficiency of potential investment into technical system in order to improve its performance is discounted cash flow rate of return (DCFROR). The DCFROR of an investment is the discount rate at which the net present value of costs (negative cash flows) of the investment equals the net present value of the benefits (positive cash flows) of the investment.

The calculation process consists of a few stages:

- estimation of net cash flows in all years of the investment
- forecast of consumer price index which will constitute a discount rate,
- checking tax and depreciation rates,
- numerical calculation of internal rate of return

The calculation sheet was created, based on International Financial Reporting Standards (IFRS), to evaluate the efficiency of particular investment scenarios.

### Table 2. Summary of machines and estimated statistical distributions describing breakdowns and micro-stoppages.

| Name of an object | Description | Cap. [pcs.] | Failure distributions |
|-------------------|-------------|-------------|-----------------------|
| Filling machine   | Filling jars with cream | 120 | B:lognormal2(118.16432,68.548549, 1.51485,1) M:empirical(„MAVNapelniaczka MTTR”", 1) |
| Labeller          | Labelling jars | 12 | B:inversegaussian(117.35181,224.26358, 34.06457,1) M:empirical(„MAWEtykieciarzka Pago MTTR”", 1) |
| Folding box machine | Putting jars into folded boxes | 30 | B:johnsonbounded(119.04751, 5432.17052, 2,92705,0.66868,1) M:empirical(„MAWKartoniarkaMTTR”", 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:empirical(„MAWKartoniarka Zbiorcza MTTR”", 1) |
| Shipping box labeller 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) |
4.2. Performance Indicator and its financial effects

In the validation process of production line simulation model, OAE (Overall Asset Efficiency) 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 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:

\[ OAE = \frac{P}{U} \times 100\% \]  

(1)

where:

\[ P = \frac{n}{v_{nom}} \]  

(2)

\[ U = P + B + M + C + CO \]  

(3)

and:

- \( P \) - production time,
- \( n \) - number of filled pieces,
- \( v_{nom} \) - nominal speed 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 change-overs of the machines resulted from change 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 (shown in percentage), which can be noted as

\[ TE = \frac{P}{(P+B+M)} \times 100\% \]  

(4)

By definition, this 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.

Improvement of either OAE or Technical Efficiency would reduce the uptime. As a result, all conversion cost that is dependent on the uptime would be decreased as well. This refers to labor time of operators, energy and their cost. What is more, improvement may lead to decrease of scrapping (if some products are damaged at particular production stage) and maintenance cost. On the other hand, any of this action would require particular expenses which should create greater profits. The devised simulation model will help to evaluate particular scenarios in order to check if they are worth investing in.

4.3. Improvement scenarios and their assessment

4.3.1. Increasing the capacity of the buffer

Buffer design is one of the most important problem the designer is faced with in a serial production line. Most authors have focused on the correct the size and allocation of inter-operational buffers in production lines. Intermediate buffers in production lines are often built also to compensate machines down-times due to maintenance. Consequently, intermediate buffers built between the various machines in an automatic line may represent a relevant resource in increasing the reliability of the whole system by limiting the consequences of micro-down-time and the losses in availability for the whole plant.
In the analysed production line there is a high capacity buffer located between the Filling Machine and Labeller. Its nominal capacity is 468 pieces but it could be expanded up to 600 without major investment. Due to the limitation of space, if more capacity is needed, current buffer should be substituted with new vertical buffer. Thanks to the simulation, we want to assess what is the impact of the buffer on the line performance, namely its Technical Efficiency, and to verify if an expansion of the current device would be beneficial from financial point of view.

![Graph](image.png)

**Figure 8.** Results of 30 simulations, lasting 455 (1 production shift), indicating the influence of Shipping Box Machine failures on average TE indicator. Note the figure on the right is the zoomed area of the left graph.

30 simulations, lasting 455 and 910 minutes (1 and 2 production shifts) were conducted for different scenarios that included various size of the buffer. The results of those simulation are presented in Figure 8. It can be seen that the existence of current buffer is beneficial for the line performance. If the buffer is removed, its estimated TE value would decrease by 33 and 34pp on average, what is a significant difference. The increase of buffer size effects the line performance only up to 600 pcs no matter the simulation time. This upgrade is possible due to current modular design and would require investment of 15 000 EUR in total. Assuming that the line produces 20 million pcs per annum and that its variable hour rate that includes energy and staff related expenses is 80 EUR per hour, ROI and NPV can be calculated as presented in Table 3.

|                      |                  |
|----------------------|------------------|
| **ROI**              | 26.1%            |
| **NPV**              | 14 TEUR          |
| **Return in**        | 48 months        |

**Table 3.** Summary of ROI and NPV calculation of buffer expansion.

Buffer expansion is an engagement that should provide 26.1% ROI and returns in 4 years. Therefore it might be beneficial to consider that solution in order to decrease cost of manufacturing as well as increase line performance.

4.3.2. Investment into reduction of failure time

Based on provided Pareto analysis and the knowledge about the actual causes of breakdowns that occur during the manufacturing process, we selected one machine and identified a set of problems that
can be solved by modifying one of its technical module. This would result in major investment which is estimated to reach 100 000 EUR. On the other hand, it should entirely eliminate failures initiated by that module. As a consequence, the distribution of TTR and TBF would change as well. In order to measure potential benefits that investment would provide, 30 simulations were conducted which results are depicted in figure 9.

![Figure 9](image)

**Figure 9.** Results of 30 simulations, lasting 455 (1 production shift), indicating the influence of Shipping Box Machine failures on average TE indicator.

We first checked the performance of that line if the machine would be free of any failures. As a result, an increase by 16 pp was noticed. That value is more than machine itself generates, which can lead to the conclusion that is a major bottleneck in the line. If breakdowns were removed completely, the performance by 6pp. If a new module was installed, that would lead to growth of TE by 5.3pp. This value can be monetized, as it was described in section 4.3.1 into 20 000 EUR per annum. Taking into account both expenditures and benefits, that engagement should return in 89 months, and its ROI is 12.6%.

| Table 4. Summary of ROI and NPV calculation of buffer expansion. |
|----------------------------------------------------------------|
| ROI | 12.6% |
| NPV | 24 TEUR |
| Return in | 89 months |

However, please bear in mind a fact that FMCG business frequently changes its product range which means that 10 year perspective cannot be applied to all examples as a potential expected lifetime of particular machine or its subsystem might be less than 10 years.

5. Conclusions
In this paper, a simulation model of packaging line was described. The model was designed to be compared with the real packaging line. Model parameters were collected during 3-month long observation. Statistical distributions of time-to-repair and time-between-failures were approximated
based on samples acquired from installed maintenance data acquisition systems. The results obtained via simulations demonstrated a good agreement of the proposed model with reality regarding the line efficiency.

A validated model can be an extremely useful tool in maintenance decision-making process. Two improvement scenarios were selected and evaluated through simulation. Potentially most profitable solution can be selected thanks to simulation testing. We strongly believe that such simulative tool can be easily implemented in the company and can be extremely useful in making the decision regarding the investment or maintenance strategy. Together with the growing computational power and popularity, the problem of time-consuming simulation and its cost will be solved. The development of new heuristic and meta-heuristic methods, in order to optimize system performance, would be a very promising direction for the further research in this area.

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