VERİMLİLİK DERGİSİ
JOURNAL OF PRODUCTIVITY

Evaluation of Production Line Modelling in Qualified Cardboard Production with Reliability Analysis

Aykut Güleryüz[1], Hüseyin Ünözkan[2], Mehmet Yılmaz[3]

ABSTRACT

Purpose: To develop a new model for calculating the long-term production expectation of production lines and to show how this model can be used in production planning and control.

Methodology: The methodology leverages real-world data to assess mechanical unit performance and improvement efforts. By calculating transition probabilities and employing Markov Chain and reliability analysis, it predicts long-term production capacity for the production line.

Findings: It can predict long-term production expectations with high accuracy for a business with six production lines.

Originality: The proposed model and method in this current study are capable of effectively addressing any production line problem where regular data is maintained.

Keywords: Long-Term Expectation, Markov Chain, Production Line, Reliability Analysis, Transition Matrix.

JEL Codes: C13, C15, C44, L23.

Nitelikli Karton Üretiminde Üretim Hattı Modellemesinin Güvenilirlik Analizi ile Değerlendirilmesi

ÖZET

Amaç: Üretim hatlarının uzun vadeli üretim beklentisini hesaplamak için yeni bir model geliştirmek ve bu modelin üretim planlama ve kontrolünde nasıl kullanılabileceğini göstermektir.

Yöntem: Üretim hattında mekanik birimlerin değerlendirilmesi ve performans ölçümü üzerine odaklanarak iyileştirme çabalarını ölçmek için gerçek veri setlerinden yararlanarak geçiş olasılıklarının hesaplanması ve uzun vadeli üretim kapasitesinin belirlenmesini içermektedir. Bu hesaplamalar, Markov Zinciri ve güvenilirlik analizi gibi yöntemler kullanılarak yapılmaktadır.

Bulgular: Altı üretim hattına sahip bir işletme için uzun vadeli bir üretim beklentisini yüksek doğruluk oranı ile kestirebilmektedir.

Özgünlük: Çalışmada önerilen modelin ve metodun, düzenli verinin tutulduğu herhangi bir üretim hattı problemini etkili bir şekilde çözebileceği düşünülmektedir.

Anahtar Kelimeler: Uzun Vadeli Beklenti, Markov Zinciri, Üretim Hattı, Güvenilirlik Analizi, Geçiş Matrisi.

JEL Kodları: C13, C15, C44, L23.

[1] Haliç University, Faculty of Engineering, Department of Industrial Engineering, Eyüpsultan, İstanbul, Türkiye
[2] Fenerbahçe University, Faculty of Engineering, Department of Industrial Engineering, Ataşehir, İstanbul, Türkiye
[3] Ankara University, Faculty of Science, Department of Statistics, Ankara, Türkiye

Corresponding Author: Hüseyin Ünözkan, huseyin.unozkan@fbu.edu.tr

DOI: 10.51551/verimlilik.1465934
Research Article | Submitted: 05.08.2024 | Accepted: 04.11.2024
Cite: Güleryüz, A., Ünözkan, H. and Yılmaz, M. (2025). “Evaluation of Production Line Modelling in Qualified Cardboard Production with Reliability Analysis”, *Verimlilik Dergisi*, 59(1), 167-184.

1. INTRODUCTION

Production lines include many different processes and in production lines, many different resources are scheduled, managed and planned in a continuous process. This result is commonly related to different components that make up the production lines (Duan et al., 2020).

In literature, reliability analysis is popular in production lines. Some of these studies are related to, reliability analysis and optimization with genetic algorithm (Duan et al., 2020), reliability analysis in yoghurt production lines with focus on time between failures (Tsarouhas and Arvanitoyannis, 2014), gaining effectiveness of maintenance processes in purifying systems in the crude oil industry (Savsar, 2016), reliability analysis of an automated pizza production line with descriptive and classical reliability analysis methods (Liberopoulos and Tsarouhas, 2005), analyzing a manufacturer company with reliability analysis included design of experiment and discrete event simulations (Imseitif et al., 2019).

In production lines, two factors are wanted to decrease. They are energy consumption and failure times of components. These two factors are strictly related to maintenance if the components are mechanical. Maintenance is of vital importance in a production line because companies commonly manage limited resources (Yang et al., 2021). The reliability of systems is generally related to equipment and mechanical components unless the biological components or labor force are taken into account.

Like mechanical components maintenance needs, biological components need training. Both component types have similar working conditions such as successfully working, working but not efficiently, and failing. Both component types need resources and consume energy. Administration departments spend time and resources on both types and schedule activities like maintenance, training, meeting, inactive time planning etc.

One of the most important issues for manufacturing companies' sustainability is good recorded data sets for all events in production lines. The data collection quality can increase the success of the studies which depend on these records (Zhang et al., 2019).

Insights from our study are on the evaluation of production line modeling in qualified cardboard production, focusing on reliability analysis. This research combines mechanical unit evaluations with personnel metrics to define performance measurement and ensure a successful production process. By analyzing real lifetime datasets, we uncover transition probabilities that help calculate long-term production capacity and address potential challenges in meeting order demands.

Reliability analysis emerges as a crucial tool in this context, enabling manufacturers to assess and improve the performance of their production lines. By analyzing reliability metrics, companies can identify vulnerabilities within their processes and implement informed maintenance strategies that enhance operational efficiency.

Accurate data collection is fundamental to the success of reliability analyses. High-quality datasets allow for a more precise understanding of production dynamics and facilitate better decision-making. This study aims to develop a comprehensive reliability analysis framework for production lines, utilizing transition probabilities derived from real-life datasets to model production capacity. It will consider both mechanical and personnel factors, recognizing their combined impact on overall reliability.

The findings of this research are significant for manufacturing companies, as they provide insights that can lead to improved production efficiency, reduced costs, and enhanced sustainability. By addressing the complexities of production line reliability, this study contributes to the ongoing efforts to optimize manufacturing operations in a competitive landscape.

In the results and discussion section, the preparation process for the analysis of a Markov chain structure is presented step by step. By using this preparation process, failure timetables are converted to transition probabilities in the transition matrix in the Markov chain. The results of the application in the results and discussion section provide a long-term production expectation for a company with 6 production lines. The results are 97% close to the real yearly productions.

This article initially reviews relevant literature in a dedicated section. Subsequently, the general context of manufacturing lines in qualified cardboard companies is outlined, covering material scope and methodological considerations. Probability and expectation measurement equations, crucial for this study, are then presented. The subsequent application section details the analysis of a real-world dataset. Finally, conclusions drawn from the application are utilized to calculate long-term expectations, and the entire research, including findings and implications, is discussed in the conclusion section.

2. RELATED WORKS

Markov chain structure usage is very popular in manufacturing line modelling studies. In these studies, reliability is one of the most valuable sections of the analysis. The reason behind this comes from the robust probabilistic calculation of the Markov chain with which the transition matrix relies on situation probabilities. In one of these studies, authors proposed a stochastic model that depends on the Markov chain to improve the manufacturing quality of a sub-optimal control policy for vehicle doors (Kang et al., 2017).

Moreover, besides the robust stochastic structure of the Markov chain, new methodologies based on the Markov chain have been proposed by researchers to improve modelling capabilities. For instance, a semi-Markov model was proposed to model cycle time in the production lines (Karishma and Supachai, 2023).

In addition, Markov chain models have been proposed to be used for evaluating the production line’s performance under the detected metrics (Zhao et al., 2017). Performance modelling with stochastic measurement improves reliability in manufacturing activities. With regard to this assessment power, Ballarini and Horvath proposed a discrete state Markov chain model to measure the line’s performance by comparing it to the detected parameters (Ballarini and Horváth, 2021).

Hybrid Markov models have recently been common in manufacturing modelling, especially with using a statistical distribution’s frequency as a transition probability in the matrix which gives another capability to improve calculation quality (Pérez-Lechuga et al., 2021).

Many different production lines have been studied by researchers in many different kinds of manufacturing industries. For instance, the authors studied a textile company to gain an intelligent worker assignment system (Akyol Özer et.al, 2021). The authors used 3 different mathematical model outputs to create decisions.

For serial systems in the production lines, increasing the situational awareness for the biological (employees) and mechanical components, parametric reliability models can be used (Öz et.al, 2023). Especially malfunctions’ frequency and recovery times can be analyzed to increase the successfully working hours.

Another statistical model proposed by the author in a simulation-based study to predict reliable inferences for a key manufacturing company in Istanbul (Ergüt, 2019). The components in the production line are assessed lonely, and the working conditions are modeled by parametric models from statistical distributions.

By using the transition matrix, Markov chain models have been proposed in dynamic performance evaluation of the production lines (Alaouchiche et al., 2020), shipyard’s fabrication line modelling (Hadžić et al., 2021), decision support tools in curve shaped production lines (Ágota, 2023), a system to improve maintenance quality and decrease failure costs (Kozłowski et al., 2023) and success assessment of production systems by utilizing failure signals (Kang et al., 2020).

Despite the widespread use of Markov chains and reliability analyses in modeling production line performance, existing studies have primarily focused on either mechanical components or isolated performance factors. Most research, such as studies on reliability in food production (Tsarouhas and Arvanitoyannis, 2014) or automated systems like pizza production (Liberopoulos and Tsarouhas, 2005), examines production reliability from a single component’s perspective or applies to specific industries without a generalized model adaptable to different production scenarios. Additionally, while statistical models and simulation-based approaches are frequently employed to optimize performance and minimize component failure, these methods do not consistently integrate human and mechanical factors within a unified framework, limiting their applicability to complex production lines where these factors interact continuously (Akyol Özer et al., 2021; Öz et al., 2023).

This study addresses this gap by introducing a comprehensive model that combines both mechanical and personnel metrics to assess long-term production reliability in a broader manufacturing context. By utilizing real-world datasets and calculating transition probabilities through a Markov Chain approach, our model provides a high-accuracy, adaptable solution for various production lines, including those with diverse mechanical and biological elements. This approach fills a critical need in the literature for a model that accounts for both equipment and workforce dynamics, enabling more precise reliability analysis and production planning in a wide range of manufacturing settings.

3. MATERIAL and METHODS

The company, manufactures a sub-product using two different raw materials. The manufactured product is cardboard which has a sealing specialty. The raw materials are cardboard and plastic. The company flows plastic raw material on the surface of a strip shaped cardboard with extruding methodology and the sealing process happens.

For this manufacturing process, company has 6 different production lines located at the factory building. The orders of the lines are given in terms of construction dates. The maximum production speeds of lines in meter/minute units are in the table which is below.

Table 1. Maximum speeds of lines

Lines	*Speeds per minute*
Line 1	250 meters/minute
Line 2	200 meters/minute
Line 3	200 meters/minute
Line 4	400 meter/minute
Line 5	250 meters/minute
Line 6	200 meters/minute

According to Table 1, company produces 1500 meters of cardboard in different wide and lengths with maximum capacity usage. The production line example was created by harmoniously combining many mechanical and electrical components. Each external machine is evaluated as an internal unit on the line. From the starting point of the production line, respectively listed as;

- Unwinder station
- Carton flow regulating station
- 1st surface treatment station
- Laminator station
- Extruder station
- Edge shaving station
- 2nd surface treatment station
- Rewinder station.

In Figure 1 the side view and in Figure 2 the front view are shown as a sample for production lines.

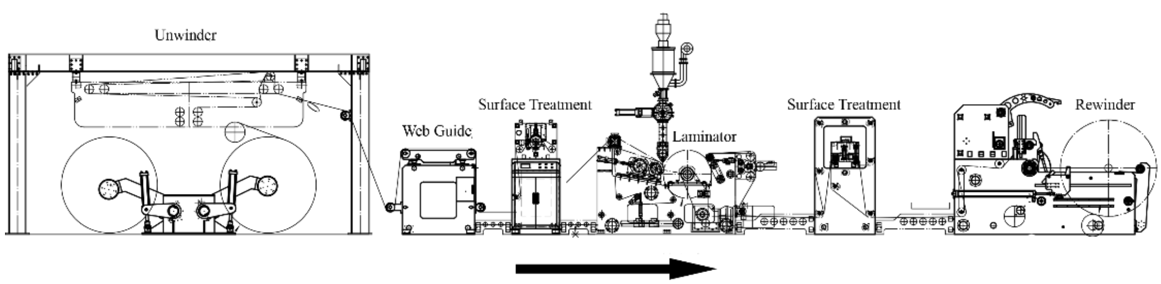

Figure 1. Side view of the sample production line

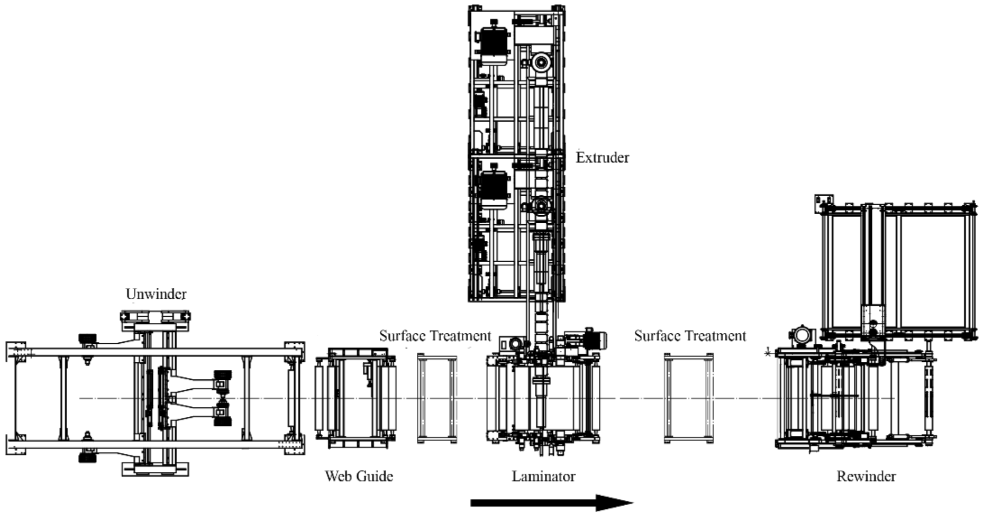

Figure 2. Side view of the sample production line

3.1 Tasks of Stations

Unwinder station: The station in which the coils are to be sealed and attached to the production line. There are two internal area stations for infinite loop production flows. Once the production continues on the coil attached to a station, on the other station the next coil is attached and an operator prepares an additional pass for automatic pass. Once the cardboard on the working line exhaust, the sensors send a comment to the system for additional glueing.

Carton flow regulating station: On the line from the starting point to the endpoint, the cardboard flows with stable strain and constant speed. The unit is combined with two parts in a row. In the lower part, the flow of cardboard is monitored, in the upper part, the two-dimensional correct position is determined with 4 balls.

1st surface treatment station: Just before the sealing process, to make fit the surface strain of the cardboard for plastic covering, the electron bombardment happens in this station. In this process, the surface of the cardboard opens with pores which can never be seen with the eyes without any damage to the cardboard.

Laminator station: The cardboard came from the surface treatment station and is sealed in this station. The laminator station is assessed as the center of the production lines. The components make up of the laminator are the cooling drum, clamping roller, additional cooling roller, idler roller that extends the contact time of the cardboard to the cooling drum, and carrier other idler rollers.

Extruder station: This station places near the laminator station. During the sealing process, the extruder station prepares the plastic material which will be used in covering. The components make up of the extruder are, Motor, Reducer, Feeding Funnel, Hive, Screw, Filter Zone, Transfer Pipe, Pattern and Heaters. A sample of the extruder station side and front views are in Figure 3.

Edge shaving station: In order to obtain smooth bobbin sections for the product produced at this station, the cardboard is trimmed from both sides with a circular knife. The section of the coil wound at the winder station must be smooth and straight.

2nd surface treatment station: This station does the same process as 1st surface treatment station on the other side of the cardboard. The aim of this process is to obtain enough strain on the cardboard surface before the printing press.

Rewinder station: After all the processes are completed, there left only one transaction that the coil, which is unwinded in the unwinder station, and needs to be rewind.

Communication between stations and basic requirements: Each station continually working as long as the operator feeds. There is an operator control panel in the system to provide stations to work compatible with each other.

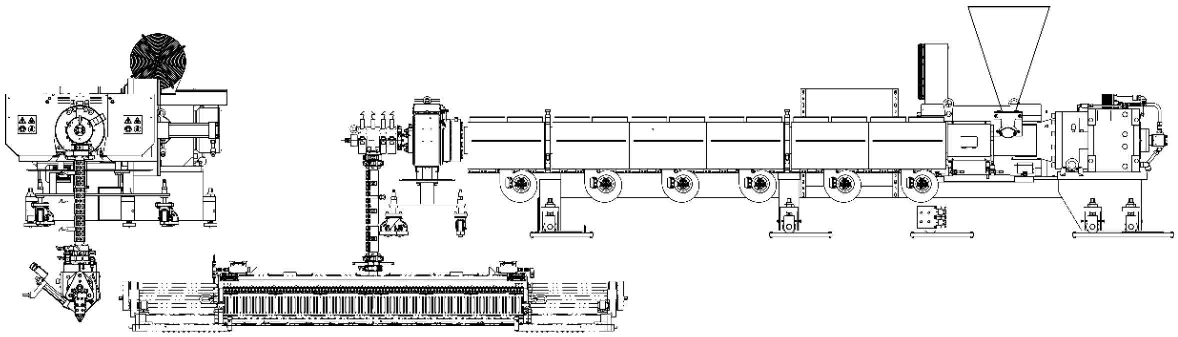

Figure 3. Extruder station views from two sides

3.2. Personnel Distribution on Production Lines

The most critical factor for successfully working of production lines is the optimum conscious labor force. The unit manager determines the personnel number in each shift on production lines. Personnel number optimization has vital importance in the prolific and continuous working of production lines. There are four segments in production lines which are determined operationally.

Point A – (Unwinder Station): The station operator takes cardboard coils from the forklift operator the same as the work plan published by the planning unit. The station operator forwards cardboard coils to internal area stations. Each coil has a serial number and the label of the coil which is sent to the internal area is recorded to the system.

Point B – (Laminator area (operator control panel)): The most important segment of the production line. They are responsible for the sealing process and whole the parameters of the process. The machine operator checks the cardboard coils flows at the same time. The operator informs each anomaly situation to the relevant unit as soon as possible.

Point C – (Edge shaving station): They check the final product quality and provide the production process with the correct size.

Point D – (Rewinder station): The personnel at this station performs the packaging, entering the system/preparing the coil label and transporting the wrapped cardboard coil to the shipping area after the coating process has been completed.

Company which includes 6 production lines which manufacture with different speed and capacity needs a different number of personnel. The personnel distribution on lines is in Table 2.

Table 2. Personnel distribution of lines

	Point A	*Point B*	*Point C*	*Point D*
Line 1	1	1	1	2
Line 2	1	1	1	2
Line 3	1	1	1	2
Line 4	2	1	1	4
Line 5	2	1	1	4
Line 6	1	1	1	2

3.3. Reliability Analysis

The reliability function gives the probability of the systems working. The reliability function can be written as below (Equation 1).

$$S(t) = 1 - F(t) = P(T > t), t > 0 \tag{1}$$

$S(t)$ is the survival function and $F(t)$ is the failure function. When a system works only when all components are in working condition, this system is called a serial system. A simple serial system structure is presented in Figure 4.

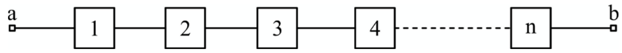

Figure 4. A block diagram for the serial system

When a system works when at least one component is in working condition, this system is called a parallel system. A simple parallel system structure is presented in Figure 5.

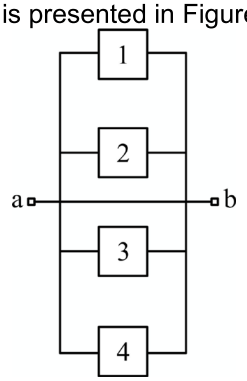

Figure 5. A block diagram for the parallel system

The structure function for the serial system can be written below.

$$\emptyset(x) = x_1 x_2 \cdots x_n = \prod_{i=1}^{n} x_i \tag{2}$$

The structure function for the parallel system can be written below.

$$\emptyset\,(x) = 1 - (1 - x_1)(1 - x_2) \cdots (1 - x_n) = 1 - \prod_{i=1}^{n}(1 - x_i) \tag{3}$$

Markov process with countable or finite event space called a Markov chain. This chain is commonly used for recursive situations. This special process gives an important capability with the transition matrix. This matrix can be used for multiple step calculations.

We can name the step transition probability matrix as a transition matrix. Assume $E = \{0, 1, 2, \dots . m\}$ is an event space, then the transition matrix can be written as below.

$$P = \begin{pmatrix} P_{00} & \cdots & P_{0m} \\ \vdots & \ddots & \vdots \\ P_{m0} & \cdots & P_{mm} \end{pmatrix} \tag{4}$$

Stochastic transactions change the statistical structure of the systems. The components' independency changes calculations in probabilities of the transactions (Ünözkan and Yılmaz, 2021).

Assume X and Y are random variables then the linear combination of expected values of these random variables have some specialties. One of them can be written as below.

$$E\,(X + Y) = E\,(X) + E\,(Y) \tag{5}$$

The proof can be shown below.

$$E\,(X + Y) = \sum_{i,j}(x_i + y_i)\,P\,(X = x_i, Y = y_j) = \sum_j \sum_j (x_i + y_i)\,P\,(X = x_i, Y = y_j) \tag{6}$$

$$= \sum_j \sum_j x_i\,P\left(X = x_i, Y = y_j\right) + \sum_j \sum_j y_j P\left(X = x_i, Y = y_j\right)$$

A note;

$$\sum_j P\left(X = x_i\,, Y = y_j\right) = P\,(X = x_i)\ and\ \sum_i P\left(X = x_i\,, Y = y_j\right) = P\left(Y = y_j\right) \tag{7}$$

Because,

$$\sum_j P(X = x_i) = \sum_i P\left(Y = y_j\right) = 1 \tag{8}$$

Therefore,

$$E\,(X+Y)=\sum_i x_i\,P\,(X=\,x_i)\,+\,\sum_j y_j\,P\big(Y=\,y_j\big)=E\,(X)+E\,(Y) \tag{9}$$

In this proof, X and Y do not need to be independent.

Based on the linear combination of expected values, expectation from event space with two results can be written as follows (Pinsky and Karlin, 2011).

$$E\,(S)=E\,(S_1)+E\,(S_2)=\tfrac{1}{2}\sum_{i=1}^{\infty}P(N\geq i)=+\tfrac{1}{2}\sum_{i=0}^{\infty}P(M>i) \tag{10}$$

$$=\tfrac{1}{2}(P\,(N\,>\,0)\,+\,P\,(N\,>\,1)\,+\,\dots+\,P\,(M>\,0)\,+\,P\,(M\,>\,1)\,+\,\dots)$$

4. RESULTS and DISCUSSION

Under the information in the previous section and the tables in the Appendix, the lost times in the lines from company can be seen in Table 3.

Table 3. Average monthly production lost time table (minute)

Line 1	Line 2	Line 3	Line 4	Line 5	Line 6
2451	2618	2435	2489	2293	2654

The breakdown information in the tables in Appendix can be calculated as personnel based or mechanical based. In Table 4, there are the values of personnel based and mechanical based lost times.

Table 4. Average monthly production lost time table-2 (minute)

Line	Line 1	Line 2	Line 3	Line 4	Line 5	Line 6
Personnel	899	972	568	1037	966	481
Mechanic	1551	1646	1867	1451	1327	2137

By dividing each value by 1440 as daily work time (minute), we can find the lost day calculation on a daily basis. The (Equation 11) can be used to calculate the monthly average lost time in daily basis.

$Line_{i,j}: ith\ line\ jth\ component\ monthly\ average\ lost\ time\ in\ daily\ basis$

$Lost_{i,j}: ith\ line\ jth\ component\ lost\ minutes$

$$Line_{i,j}=\frac{Lost_{i,j}}{1440},\ \ i=1,2,\dots,6,\ \ j=personnel, mechanic \tag{11}$$

The lost days gained with monthly average lost minutes are in Table 5~~.~~

Table 5. Average monthly production lost time table-3 (daily)

Line	*Line 1*	*Line 2*	*Line 3*	*Line 4*	*Line 5*	*Line 6*
Personnel	0.62	0.68	0.39	0.72	0.67	0.33
Mechanic	1.08	1.14	1.30	1.01	0.92	1.48

Equation 12 can be used to calculate successful working probabilities by using values in Table 5.

$Line_{i,j}: ith\ line\ jth\ component\ successful\ working\ probabilities$

$Lost_{i,j}: ith\ line\ jth\ component\ lost\ days$

$$Line_{i,j}=\frac{(30-Lost_{i,j})}{30},\ \ i=1,2,\dots,6,\ \ j=personnel, mechanic \tag{12}$$

During these calculations we use 30 as constant because of monthly records. We can obtain the probability of successfully working condition by dividing the same constant.

Table 6. Minutely calculated successful working probability

Line	*Line 1*	*Line 2*	*Line 3*	*Line 4*	*Line 5*	*Line 6*
Personnel	0.98	0.98	0.99	0.98	0.98	0.99
Mechanic	0.96	0.96	0.96	0.97	0.97	0.95

For Production Line Reliability Analysis, we can construct a system like in Figure 6 with the values in Table 6. In Figure 6 blue components represent personnel components, and green components represent mechanical components.

The probability of production in the production line system in Figure 6, which means at least one line is working successfully, can be calculated by focusing on the successful working of both personnel and mechanical components probabilities in each production line. One line's successful work is enough for this situation.

In this issue, the successful working probability in each production line can be calculated below.

$$SLine(i) = SLine(i)personnel * SLine(i)mechanic \tag{13}$$

On the other hand, we can calculate the system's general successful working probability with a reliability approach.

$$SSystem = 1 - \prod(1 - SLine(i)) \tag{14}$$

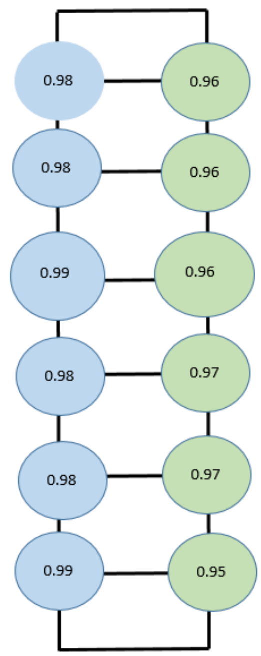

Figure 6. Production lines systematic view

When we gain the system's general successful working probability with a reliability approach, the probability is 0.999999967. This probability is an expectable value for a product line system which is constructed like the system we introduced. Not any company wants to tolerate completely breaking down the whole production system and in addition, does not want to lose the demands of customers.

When we would like to calculate the systems successful working without any halt, we need to take into account the successful working situations' probabilities in all lines. All lines' successful working probability at the same time without any halt is below (Equation 15).

$$SSystem = \prod SLine(i) = 0.704112188 \tag{15}$$

The average lost time for each failure is 32 minutes. (Line 6 is not added to the calculation because of new construction.). We can use this value for constructing a transition matrix. We need transition probabilities in the transition matrix and in our situation, we assume that with the 0.95 probability our failures turn into successful in 32 minutes. Therefore, we find that staying in the failure side probability is 0.91. This probability provides us to generate a transition matrix.

Transition matrix probabilities can be determined from equation (14) by using Figure 6 such as below.

For Line 1, Line 2, Line 3, Line 4 and Line 6;

$$\begin{array}{c|cc} & Success & Failure \\ \hline Success & 0.94 & 0.06 \\ Failure & 0.09 & 0.91 \end{array}$$

For Line 5;

$$\begin{array}{c|cc} & Success & Failure \\ \hline Success & 0.95 & 0.05 \\ Failure & 0.09 & 0.91 \end{array}$$

In the long run in which situation the system will be, can be understood with a recursive repeat of these matrices.

The second step transition matrix can be gained by the square of the first matrix.

For Line 1, Line 2, Line 3, Line 4 and Line 6;

$$\begin{array}{c|cc} & Success & Failure \\ \hline Success & 0.89 & 0.11 \\ Failure & 0.17 & 0.83 \end{array}$$

For Line 5;

$$\begin{array}{c|cc} & Success & Failure \\ \hline Success & 0.91 & 0.09 \\ Failure & 0.17 & 0.83 \end{array}$$

To achieve successful long-term expectations, we need to know in which step the transition matrix does not change with important values. Once we examine the fixed point of the transition matrix;

For Line 1, Line 2, Line 3, Line 4 and Line 6; after 15 steps which means in the 16th minute the matrix is fixed with the matrix below.

$$\begin{array}{c|cc} & Success & Failure \\ \hline Success & 0.63 & 0.37 \\ Failure & 0.56 & 0.44 \end{array}$$

For Line 5; after 16 steps which means in the 17th minute the matrix is fixed with the matrix below.

$$\begin{array}{c|cc} & Success & Failure \\ \hline Success & 0.67 & 0.33 \\ Failure & 0.59 & 0.41 \end{array}$$

Both matrices tell us that for the long-term expectation, each production line stays on the working side. The long-term expectations for Line 1, Line 2, Line 3, Line 4 and Line 6 can be calculated as below.

Probability of being on the working condition $= \frac{1}{2} * 0.63 + \frac{1}{2} * 0.56 = 0.6$

The long term expected value for Line 5 can be calculated with the same method.

Probability of being on the working condition $= \frac{1}{2} * 0.67 + \frac{1}{2} * 0.59 = 0.63$

With these probabilities in the long-term expectation for lines, the expected values can be calculated as below. Expected values can be gained from equation (9) by using the transition matrix in equation (16) and equation (17). The results are presented in Table 7.

Table 7. Expected long term production

Lines	Expectation
Line 1	150 meters/minute
Line 2	120 meters/minute
Line 3	120 meters/minute
Line 4	240 meters/minute
Line 5	158 meters/minute
Line 6	120 meters/minute
Total	908 meters/minute

The company's long term production lines' total expectation is below.

$$\sum_{i=1}^{6} E_i = 150 + 120 + 120 + 240 + 158 + 120 = 908\ meter/minute$$

When this expected value is compared with the real manufacturing values yearly, we concluded that this value is 97% close to real manufacturing values.

5. CONCLUSION

Manufacturing companies aim for maximum output with minimum input for the sustainability of their commercial life. According to this aim, with constant improvement studies, they are always dealing with more productivity. With the simulated company's dataset, in this study, reliability analysis for production lines is studied. The dataset includes unplanned failure and breakdown times of 6 months in the company.

Other unplanned halt situations such as energy cuts, earthquakes and other natural disasters did not include the calculations. On the other hand, some precautions can protect production systems; such as Uninterruptable Power Supplies (UPS), generators, water evacuation poles against floods and firefighting systems.

One additional issue for protection is being insured situation of companies against unplanned issues. Thus, companies can be financially insured considering their structures. One of the most important applications in the fight against unplanned halt situations is maintenance.

Companies update their maintenance calendar constantly and planned maintenance times generally at least one-year period. The information about unplanned halt dates, halt periods, and the lifetime events of machines can be used in planning the maintenance times of production line machines.

In this study, a well-planned and working manufacturer company's 6-month production lines datasets were used in reliability analysis. The results of the reliability analysis for this company are very close to real production values.

The successfully working probabilities, the transition matrix, and the long-term expectation values for production lines are calculated. The components of the reliability system in this study are personnel-based components and mechanical based components. Thus, any improvement in the labor force or any maintenance in mechanical components can increase reliability in each manufacturer company.

The results of this study provide valuable insights into the reliability of production lines in the qualified cardboard manufacturing sector. Utilizing a comprehensive dataset that includes unplanned failures and breakdown times over a six-month period, we conducted a thorough reliability analysis. The findings indicate that the reliability metrics calculated for the production lines are remarkably close to the actual production values, achieving an accuracy of approximately 97%.

The analysis involved the conversion of failure time records into transition probabilities, which were then incorporated into a Markov chain model. This approach allowed us to effectively simulate the long-term production expectations for the company's six production lines. The transition matrix derived from the analysis illustrates the probabilities of various operational states, including successful operation, inefficiencies, and failures.

Additionally, the results highlight the critical role of both mechanical and personnel components in influencing overall reliability. Improvements in maintenance practices for mechanical components, alongside enhanced training and management of personnel, can lead to significant gains in production efficiency.

The study also emphasizes the importance of maintaining well-documented records of production events. High-quality data collection not only supports the reliability analysis but also enhances the overall understanding of production dynamics, enabling companies to make informed decisions regarding maintenance and operational strategies.

The dataset used in this study, spanning only six months and originating from a single manufacturing company, may limit the generalizability of the findings. Its specificity to certain industry conditions could constrain its applicability to diverse production environments. Moreover, the study exclusively focuses on mechanical and personnel-related factors, neglecting the influence of external factors like energy outages or natural disasters. The accuracy of predictions derived from the Markov chain model is contingent upon the quality and comprehensiveness of the dataset. Hence, larger and more diverse datasets could enhance the validity of the results.

Future research could bolster the generalizability of findings by employing more extensive and diverse datasets, encompassing data from multiple sectors and geographical locations. Integrating dynamic analysis techniques, such as machine learning algorithms, with the Markov chain model could improve its adaptability to evolving production conditions. Additionally, assessing the impact of external factors would provide a more comprehensive reliability analysis. Further research could explore the effects of emerging technologies on production process reliability. Such advancements could lead to more effective production line management, providing the industry with robust and adaptable solutions for optimizing operational efficiency.

In summary, the results of this study underscore the effectiveness of reliability analysis in predicting production outcomes and improving operational efficiency. By adopting the methodologies outlined in this research, manufacturing companies can better navigate the complexities of production line management and enhance their overall performance.

Author Contributions

Aykut Güleryüz: Literature Review, Conceptualization, Data Curation, Writing-original draft *Hüseyin Ünözkan*: Methodology, Analysis, Modelling, Writing-original draft, Writing-review and editing *Mehmet Yılmaz*: Literature Review, Modelling, Writing-review and editing

Conflict of Interest

No potential conflict of interest was declared by the author(s).

Funding

Any specific grant has not been received from funding agencies in the public, commercial, or not-for-profit sectors.

Compliance with Ethical Standards

It was declared by the author(s) that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement

It was declared by the author(s) that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

REFERENCES

Ágota, B. (2023). “Decision Making in Operator-Machine Assignment Problems: An Optimization Approach in U-Shaped Production Lines”, *Decision Making: Applications in Management and Engineering*, 6(2), 620-638. https://doi.org/10.31181/dmame622023808

Akyol Özer, E., Coşkun, E.E., Bulut, Ö., Toy, E.S. (2021). “Bir Tekstil Fabrikasinda Montaj Hattı Dengeleme ve Performansa Dayalı İşçi Atama Problemi”, *Endüstri Mühendisliği*, 32(2), 235-250. https://doi.org/10.46465/endustrimuhendisligi.868101

Alaouchiche, Y., Ouazene, Y. and Yalaoui, F., (2020). "Economic and Energetic Performance Evaluation of Unreliable Production Lines: An Integrated Analytical Approach," *IEEE Access*, 8, 185330-185345. https://doi.org/10.1109/ACCESS.2020.3029761

Ballarini, P. and Horváth, A., (2021). "Formal Analysis of Production Line Systems by Probabilistic Model Checking Tools", *26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, Vasteras, Sweden, 1-8. https://doi.org/10.1109/ETFA45728.2021.9613494

Duan, W., Dai, W., Wang, Y. and Sun, J. (2020). “Reliability Analysis and Optimization of Production System for Production Scheduling”, *IOP Conference Series: Materials Science and Engineering*, 1043, 032025. https://doi.org/10.1088/1757-899X/1043/3/032025

Ergüt, Ö. (2019). “Üretim Sistemlerinde Bir Simülasyon Uygulaması”, Osmaniye Korkut Ata Üniversitesi İktisadi ve İdari Bilimler Fakültesi Dergisi, 3(2), 244-258.

Hadžić, N., Ložar, V., Opetuk, T.İ. and Cajner, H. (2021). “Improvability of the Fabrication Line in A Shipyard”, *Brodogradnja*, 72(3), 13-28. https://doi.org/10.21278/brod72302

Imseitif, J., Tang, H. and Smith, M. (2019). “Throughput Analysis of Manufacturing Systems with Buffers Considering Reliability and Cycle Time Using DES and DOE”, *Procedia Manufacturing* 39, 814-823. https://doi.org/10.1016/j.promfg.2020.01.423

Kang, N., Zhao, C., Li, J. and Zheng, L. (2017). "A Sub-Optimal Control Policy in a Two-Product Door Manufacturing Line with Geometric Reliability Machines", *IEEE Robotics and Automation Letters*,2(1), 157-164, https://doi.org/10.1109/LRA.2016.2582925

Kang, Y., Yan, H. and Ju, F. (2020). "Performance Evaluation of Production Systems Using Real-Time Machine Degradation Signals", *IEEE Transactions on Automation Science and Engineering*, 17(1), 273-283. https://doi.org/10.1109/TASE.2019.2920874

Karishma, A. and Supachai, V., (2023). “A Hidden Semi-Markov Model for Predicting Production Cycle Time Using Bluetooth Low Energy Data”, *Advances in Technology Innovation*, 8(4), 241–253.

Kozłowski, E., Borucka, A., Oleszczuk, P. and Jałowiec, T., (2023). “Evaluation of the maintenance system readiness using the semi-Markov model taking into account hidden factors”, *Eksploatacja i Niezawodnosc – Maintenance and Reliability,* 25(4). http://doi.org/10.17531/ein/172857

Liberopoulos, G. and Tsarouhas, P. (2005). “Reliability Analysis of An Automated Pizza Production Line”, *Journal of Food Engineering*, 69, 79-96. https://doi.org/10.1016/j.jfoodeng.2004.07.014

Öz, D., Edizkan, R. and Yazici, A. (2023). “Seri Üretim Hatlarinda Güvenilirlik Analizi Ile Durumsal Farkındalığın Artırılması”, *Eskişehir Osmangazi Üniversitesi Mühendislik Ve Mimarlık Fakültesi Dergisi*, 31(2), 630-643. https://doi.org/10.31796/ogummf.1192034

Pérez-Lechuga, G., Venegas-Martínez, F. and Martínez-Sánchez, J.F. (2021). “Mathematical Modeling of Manufacturing Lines with Distribution by Process: A Markov Chain Approach”, *Mathematics,* 9(24), 3269. https://doi.org/10.3390/math9243269

Pinsky, M.A. and Karlin, S. (2011). “An Introduction to Stochastic Modeling” (Fourth Edition), Elsevier.

Savsar, M. (2016). “Reliability and Availability Analysis of A Manufacturing Line System”, *Journal of Applied and Physical Sciences*. 2(3), 96-106. https://doi.org/10.20474/japs-2.3.5

Tsarouhas, P.H. and Arvanitoyannis, I.S. (2014). “Yogurt Production Line: Reliability Analysis”, *Production & Manufacturing Research*: 2(1), 11-23.

Ünözkan, H. and Yılmaz, M. (2021). “A Stochastic Approach to a Combined Parallel System”, *International Journal of Applied Mathematics and Statistics,* 60(1), 81-87.

Yang, Z., Li, J., Chen, C., He, J., Tian, H. and Yu, L. (2021). “A Study on Overall Line Efficiency (OLE) Centered Production Line Maintenance Prioritization Considering Equipment Operational Reliability”, *The International Journal of Advanced Manufacturing Technology*, 124, 3783-3794. https://doi.org/10.1007/s00170-021-07547-9

Zhang, Y., Cheng, Y., Wang, X.V., Zhong, R.Y., Zhang, Y. and Tao, F. (2019). “Data-Driven Smart Production Line and Its Common Factors”, *The International Journal of Advanced Manufacturing Technology*, 103, 1211-1223. https://doi.org/10.1007/s00170-019-03469-9

Zhao, C., Li, J., Huang, N. and Horst, J.A., (2017) "Flexible Serial Lines with Setups: Analysis, Improvement, and Application," in *IEEE Robotics and Automation Letters*, 2(1), 120-127, https://doi.org/10.1109/LRA.2016.2556078

APPENDIX

Table A.1. Lost times in Line 1

		Lost time /minute	*Times in month*	*Total*
Personnel lines	Transaction with wrong coil	30	4.67	140.00
	Not controlling deformations on the coil	30	7.67	230.00
	Incorrect insertion at the solvent station	30	2.50	75.00
	Entering an incorrect value on the control panel	11	1.50	16.50
	Incorrect position of the edge razor	11	4.67	51.33
	Incorrectly dimensioned bobbin at the winder station	11	2.83	31.17
	Insufficient glue	30	3.00	90.00
	Excess glue	11	3.33	36.67
Mechanical and electrical halts	Heater replacement	300	1.00	300.00
	Heating equipment replacement	45	1.00	45.00
	Print roller replacement	120	1.50	180.00
	Screen change in the filter area	30	9.00	270.00
	Bearing or roller replacement	60	2.00	120.00
	Edge razor replacement	30	3.00	90.00
	Edge limiter change in die	30	4.00	120.00
Labor lost	Staff absenteeism or momentary loss of workforce	98	2.33	228.67
Measure change	Pauses in work orders that cannot be directly accessed	20	21.33	426.67
	Total Values	897	75.33	2451.00

Table A.2. Lost times in Line 2

		Lost time /minute	*Times in month*	*Total*
Personnel lines	Transaction with wrong coil	30	5.17	155.00
	Not controlling deformations on the coil	30	12.00	360.00
	Incorrect insertion at the solvent station	30	2.00	60.00
	Entering an incorrect value on the control panel	11	0.83	9.17
	Incorrect position of the edge razor	11	3.67	40.33
	Incorrectly dimensioned bobbin at the winder station	11	5.83	64.17
	Insufficient glue	30	4.00	120.00
	Excess glue	11	0.67	7.33
Mechanical and electrical halts	Heater replacement	300	1.00	300.00
	Heating equipment replacement	45	0.83	37.50
	Print roller replacement	120	2.17	260.00
	Screen change in the filter area	30	11.67	350.00
	Bearing or roller replacement	60	2.67	160.00
	Edge razor replacement	30	1.83	55.00
	Edge limiter change in die	30	5.67	170.00
Labor lost	Staff absenteeism or momentary loss of workforce	78	2	156.00
Measure change	Pauses in work orders that cannot be directly accessed	20	15.6667	313.33
	Total Values	877	77.67	2617.83

Table A.3. Lost times in Line 3

		Lost time /minute	Times in month	Total
Personnel lines	Transaction with wrong coil	30	0.83	25.00
	Not controlling deformations on the coil	30	4.67	140.00
	Incorrect insertion at the solvent station	30	3.00	90.00
	Entering an incorrect value on the control panel	11	0.67	7.33
	Incorrect position of the edge razor	11	2.83	31.17
	Incorrectly dimensioned bobbin at the winder station	11	5.67	62.33
	Insufficient glue	30	2.00	60.00
	Excess glue	11	2.00	22.00
Mechanical and electrical halts	Heater replacement	300	1.67	500.00
	Heating equipment replacement	45	1.67	75.00
	Print roller replacement	120	0.83	100.00
	Screen change in the filter area	30	6.67	200.00
	Bearing or roller replacement	60	3.83	230.00
	Edge razor replacement	30	3.17	95.00
	Edge limiter change in die	30	5.00	150.00
Labor lost	Staff absenteeism or momentary loss of workforce	78	1.66667	130.00
Measure change	Pauses in work orders that cannot be directly accessed	20	25.8333	516.67
	Total Values	877	72.00	2434.50

Table A.4. Lost times in Line 4

		Lost time /minute	Times in month	Total
Personnel lines	Transaction with wrong coil	30	1.50	45.00
	Not controlling deformations on the coil	30	4.33	130.00
	Incorrect insertion at the solvent station	30	5.17	155.00
	Entering an incorrect value on the control panel	11	0.67	7.33
	Incorrect position of the edge razor	11	1.83	20.17
	Incorrectly dimensioned bobbin at the winder station	11	2.00	22.00
	Insufficient glue	30	1.67	50.00
	Excess glue	11	0.17	1.83
Mechanical and electrical halts	Heater replacement	300	0.17	50.00
	Heating equipment replacement	45	0.67	30.00
	Print roller replacement	120	1.67	200.00
	Screen change in the filter area	90	4.17	375.00
	Bearing or roller replacement	50	2.00	100.00
	Edge razor replacement	20	1.83	36.67
	Edge limiter change in die	30	0.67	20.00
Labor lost	Staff absenteeism or momentary loss of workforce	158	3.83	605.67
Measure change	Pauses in work orders that cannot be directly accessed	20	32.00	640.00
	Total Values	997	64.33	2488.67

Table A.5. Lost times in Line 5

		Lost time /minute	*Times in month*	*Total*
Personnel lines	Transaction with wrong coil	30	1.83	55.00
	Not controlling deformations on the coil	30	2.67	80.00
	Incorrect insertion at the solvent station	30	5.00	150.00
	Entering an incorrect value on the control panel	11	2.83	31.17
	Incorrect position of the edge razor	11	2.83	31.17
	Incorrectly dimensioned bobbin at the winder station	11	8.67	95.33
	Insufficient glue	30	11.50	345.00
	Excess glue	11	1.33	14.67
Mechanical and electrical halts	Heater replacement	300	0.00	0.00
	Heating equipment replacement	45	2.17	97.50
	Print roller replacement	120	1.00	120.00
	Screen change in the filter area	20	7.83	156.67
	Bearing or roller replacement	60	2.17	130.00
	Edge razor replacement	30	1.83	55.00
	Edge limiter change in die	30	5.17	155.00
Labor lost	Staff absenteeism or momentary loss of workforce	98	1.67	163.33
Measure change	Pauses in work orders that cannot be directly accessed	20	30.67	613.33
	Total Values	887	89.17	2293.17

Table A.6. Lost times in Line 6

		Lost time /minute	*Times in month*	*Total*
Personnel lines	Transaction with wrong coil	30	0.67	20.00
	Not controlling deformations on the coil	30	5.67	170.00
	Incorrect insertion at the solvent station	30	1.33	40.00
	Entering an incorrect value on the control panel	11	0.33	3.67
	Incorrect position of the edge razor	11	0.33	3.67
	Incorrectly dimensioned bobbin at the winder station	11	2.00	22.00
	Insufficient glue	30	4.67	140.00
	Excess glue	11	0.33	3.67
Mechanical and electrical halts	Heater replacement	300	2.00	600.00
	Heating equipment replacement	45	2.00	90.00
	Print roller replacement	120	2.67	320.00
	Screen change in the filter area	30	10.67	320.00
	Bearing or roller replacement	60	1.33	80.00
	Edge razor replacement	30	1.67	50.00
	Edge limiter change in die	30	11.33	340.00
Labor lost	Staff absenteeism or momentary loss of workforce	78	1.00	78.00
Measure change	Pauses in work orders that cannot be directly accessed	20	18.67	373.33
	Total Values	877	66.67	2654.33