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Queuing models for production lines on a selected example

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Abstract

In today's production and service systems, the management process plays a primary role. Analysis of the management process allows the detection of weaknesses and strengths in analyzed systems. This paper analyses production line management processes. For one literature example, a queuing model of a selected production line was built, and its performance and reliability were analyzed. The modelling attempt undertaken here was designed to determine whether queuing theory is suitable for modelling production line processes. Confirmation of this thesis would be a novelty in this field.

Introduction

As literature and practice show, production processes are extraordinarily complex cycles of activities that generally cover the production preparation process, the manufacturing process, the distribution process, and customer service. The characteristics of these processes are described in detail in many books (Pająk, 2006; Konsala, 2017; Rogowski, 2018). The main purpose of the production process is to produce a final product (goods or services) and deliver it to consumers. As part of this work, the manufacturing process plays a fundamental role and must be properly analyzed.

The goal of organizing activities in a production process is to complete a customer's order as quickly as possible, using the least capital, and with activities resulting in the quickest return. One way to accomplish these goals is to shorten the production cycle by controlling the production flow. When analyzing the workflow of an object in a production team, the following organizational systems of work stands are distinguished: a) serial, b) parallel, and c) a series-parallel, (Liwowski & Kozłowski, 2011; Grandys, 2013). The essence of a serial system is that workstations are used to their maximum extent, and stops between the operations performed on subsequent copies of a processed product are unacceptable. This means that the entire production batch is processed at the first station, and the next station only takes action after this stage of work is completed. This way of organizing production guarantees continuous work measures. In a parallel system, each individual element of a work item after it completes an operation at a given workstation should be immediately transferred to the next position for the next operation. At this time, it should be free and ready to accept the delivered work object and begin its processing. When choosing a parallel production organization system, it is necessary to take into account stops at work stations due to the implementation of the continuous movement of work objects in a given system. A serial-parallel system has the advantages of both the serial and parallel systems, which makes it possible to maintain a continuous flow of elements of the transport batch at each station.

Capacity planning is the basis for further decisions. At this stage, the goal is to plan the right amount of resources. If an enterprise already has some potential, it can be changed by increasing or reducing it. Having planned the production capacity, one should prepare an aggregate plan and material needs plan (Milewska & Milewski, 2000). Queuing theory can be used in operational production planning.

Queuing systems are currently used in many areas, including transport systems (Woch, 1999; Jacyna, Żak & Gołębiowski 2019), logistics systems (Korzonek & Uhl, 2016; Więckowski, 2017), and telecommunications networks (Eljasz, 2011; Hołyński & Hayat, 2011). It seems useful to verify the applicability of this theory in the production process as well, which is the aim of this paper.

This paper contains five chapters. The first chapter briefly describes the production processes and presents types, forms, and varieties of organizations of the production process. The second chapter describes the production line of the dashboard assembly of a car body presented in the literature. Based on the queuing models of the selected example, the third chapter implements a performance analysis, and the fourth chapter analyzes its reliability for the selected production line. The last chapter summarizes the consequences of this work and outlines ways to create queuing models for other types of production lines.

Selected production line example

The example selected from the literature (Ciszak, 2009) involves the production process of mounting a dashboard on a car body. Figure 1 shows the organization chart of the dashboard installation site to the car body on the final assembly line.

The dashboard assembly process consists of many phases. The graphic in Figure 2 shows the order of operations and tasks during the installation of a dashboard in a car body.

Timing observations were used to determine the proper and rational time for performing assembly operations at a normal rate. Table 1 shows the operating times.

For certain technological processes, simulation studies have been conducted in the literature (Ciszak, 2009) using two variants:

- Variant I – assembly process carried out (currently) manually;

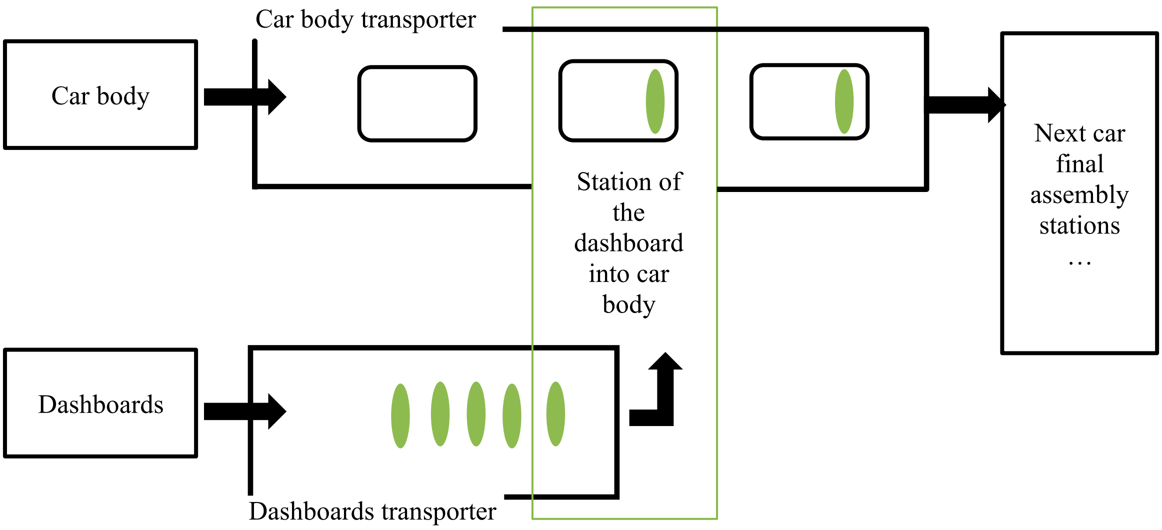

Figure 1. Organization chart of the dashboard installation site to the car body on the final assembly line (Ciszak, 2009)

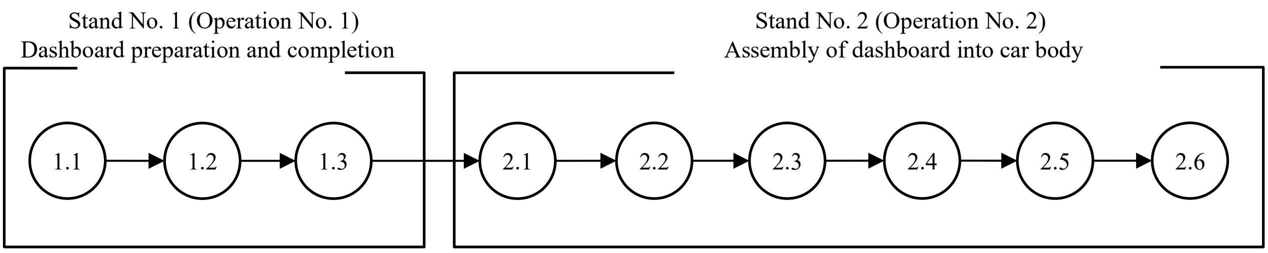

Figure 2. Graphic of the order of operations and tasks during the installation of the dashboard in the car body; operation numbers according to Table 1 (Ciszak, 2009)

Table 1. The timing measurements of the work intensity of operations (Ciszak, 2009)

Operation number	Treatment number	Description of the operation	Effort mean value [min]
1	1.1	Card preparation and completion	0.54
	1.2	Filing the card in the car documentation	0.25
	1.3	Dashboard download	0.70
2	2.1	Card scanning with body documentation	0.16
	2.2	Insertion of the dashboard into the body	0.42
	2.3	Confirmation of dashboard insertion	0.51
	2.4	Dashboard assembly using a manipulator	0.24
	2.5	Execution of the manipulator	0.21
	2.6	Paste the printout WBK (to the car card)	0.16
		Sum	**3.19**

- Variant II – assembly process carried out using a transport manipulator (transponder).

The simulations showed an increase in interoperational transport time using a transport manipulator, which meant that the total number of dashboards fitted into car bodies decreased from 3288 to 2726 pcs. The idle (return) movements of the transport manipulator affected the regression. The transport manipulator worked for 3 shifts per day for 7 days, and its working time analysis is presented in Figure 3.

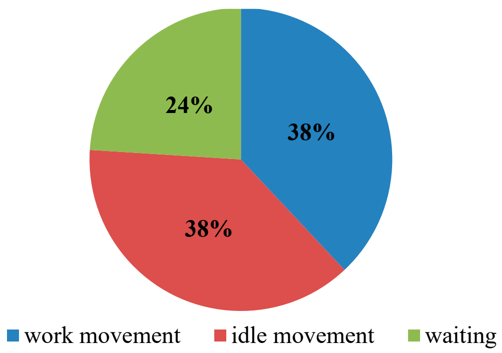

Figure 3. The shares of individual movements during the work shift of a transport manipulator that transfers dashboards to the body of a passenger van on the final assembly line (Ciszak, 2009)

The diagram illustrated in Figure 3 forms the basis for creating a queuing model for the selected assembly line.

Queuing model of the selected production line

The progress of the dashboard assembly phases can be symbolized using a queuing system (Figure 4), which is generally described by Kendall's notation (Uhl, 2015, p. 36) and is defined as follows: $A|B|m|n$ – buffer handling strategy. The letter A characterizes the type of arrival process, B is the service process, m is the number of service stations, and n is the buffer capacity. The most common buffer handling strategy is FIFO. These types of systems will be used later in this paper to analyze the operation of the selected production line. At the beginning of the analysis, it is assumed that the production line queuing system is of the general type: $G|G|m|n$ – FIFO.

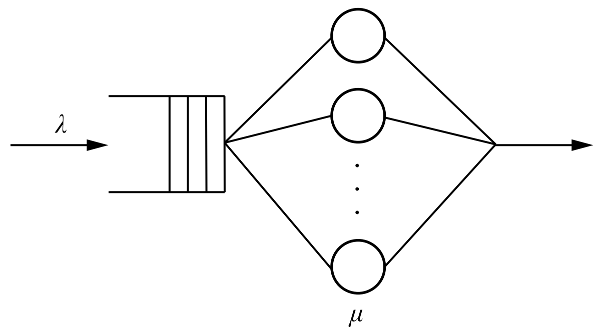

Figure 4. Model of the queuing system

The arrival and service processes are generally stochastic processes. Measurements carried out in practice allow the parameters of these processes to be calculated, as well as their distributions. The value λ is the average rate of events at the entrance of the queuing system, and μ is the average service rate. Knowing these quantities makes it possible to determine other quality parameters of a queuing system in subsequent steps, e.g., the utilization factor ρ, the average number of orders $\bar{k}$ in the system, and others.

The basis for numerical analysis is the queuing model for the selected variant of the production line operation. Figure 5 shows the queuing model for variant I of the production line.

The average time to perform operations at the first position, referred to in Figure 5 as "admission", is t_1 = 0.79 min/order. Downloading the dashboard is the activity carried out at the second stand, and it required an average of t_2 = 0.7 min/order. The operations carried out at the third station, referred to as "assembly", required the most time, t_3 = 1.7 min/order (times calculated based on the values in Table 1).

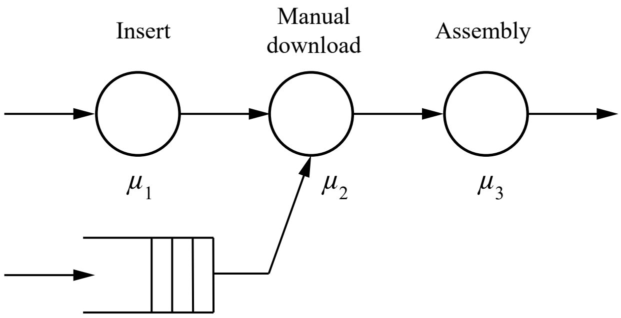

Figure 5. Queuing model for variant I of the production line

The first calculation step was to determine the average time, which according to the adopted queuing model, was equal to the sum of t_1, t_2, and t_3.

$$\bar{t} = 0.79 + 0.7 + 1.7 = 3.19 \text{ min/items} \quad (1)$$

The value of the average time $\bar{t}$ is necessary to calculate the average number of items carried out by the system per hour $\bar{k}_h$. On the other hand, knowledge of the working dimensions of the adopted example allows the determination of the average number of items per day $\bar{k}_{\text{day}}$ and during a week $\bar{k}_{\text{week}}$.

$$\bar{k}_h = 60 : 3.19 = 18.8 \text{ items/h} \quad (2)$$

$$\bar{k}_{\text{day}} = 18.8 \cdot 24 = 451 \text{ items/day} \quad (3)$$

$$\bar{k}_{\text{week}} = 451 \cdot 7 = 3159 \text{ items/week} \quad (4)$$

The calculated number of items per week was $\bar{k}_{\text{week}} = 3159$ pcs, while the total number of installed dashboards for car bodies in the simulated assembly process example was 3288 pcs. This small difference was probably due to the randomness in every simulation and was within the confidence interval of ≤ ±5% of the mean value.

The queuing model for variant II of the production line coincides with the model in Figure 5, except the second operating unit (marked as "manual download") was replaced by a "transponder".

The operation times at the first and third positions t_1 and t_3 were identical in both variants since the operations were not changed. The difference between the two variants of the example technological process was attributed to the use of a transport manipulator (transponder), which affected the transport time t'_2. Time t'_2 was determined by analyzing the manipulator's working time, the results of which are presented graphically in Figure 3. The working movement of a given manipulator constitutes only 38% of the share of all its movements during the shift; however, the remaining 62% are movements that increase the interoperational transport time t'_2.

$$t'_2 = 0.7 \cdot 1.62 \approx 1.13 \text{ min/order} \quad (5)$$

The times used above for the production line servicing units made it possible to determine the average time $\bar{t}$ for variant II.

$$\bar{t} = 0.79 + 1.13 + 1.7 = 3.62 \text{ min/items} \quad (6)$$

The average service time was used to calculate the average number of items carried out per hour $\bar{k}_h$, day $\bar{k}_{\text{day}}$, and week $\bar{k}_{\text{week}}$.

$$\bar{k}_h = 60 : 3.63 = 16.57 \text{ items/h} \quad (7)$$

$$\bar{k}_{\text{day}} = 16.57 \cdot 24 = 397 \text{ items/day} \quad (8)$$

$$\bar{k}_{\text{week}} = 397 \cdot 7 = 2784 \text{ items/week} \quad (9)$$

The calculated number of items per week was $\bar{k}_{\text{week}} = 2784$ pcs. On the other hand, the total number of installed car body dashboards in the simulated developed assembly process was 2726 pcs. The above difference can be explained by the dispersion of variables in the method simulation, which were within the confidence interval of < ±5% of the mean value.

Queuing theory can also be used to determine the average arrival rate at a selected service station. This is possible when the number of items carried out in the assumed work period is known. Assuming a result of 3000 items per week, the average order execution time $\bar{t}$, the average duration of the second position operation (transponder) $\bar{t}'_2$, and the average rate of service for a given position μ'_2 can be determined in turn.

$$\bar{k}_{\text{week}} = 3000 \text{ items/week} \quad (10)$$

$$\bar{k}_{\text{day}} = 3000 : 7 = 428 \text{ items/day} \quad (11)$$

$$\bar{k}_h = 428 : 24 = 17.8 \text{ items/h} \quad (12)$$

$\bar{k}_h$ symbolically indicates the average number of items carried out per hour; however, the average time to complete the order $\bar{t}$ is described in minutes.

$$\bar{t} = 60 : 17.8 = 3.37 \text{ min/items} \quad (13)$$

The duration of operations at the first and third service stations (t_1 and t_3, respectively) remains unchanged, therefore:

$$\bar{t}'_2 = 3.37 - 1.7 - 0.79 = 0.88 \text{ min/order} \quad (14)$$

The average rate of service at the second station μ'_2 is the inverse of the average duration of the operation at this station $\bar{t}'_2$.

$$\mu'_2 = \frac{1}{\bar{t}'_2} \quad (15)$$

$$\mu'_2 \approx 1.13 \text{ order/min} \quad (16)$$

The basic parameters that determine the performance of a queuing system are the probabilities of state $p(k)$, which depend, among other things, on the system utilization coefficient ρ, for which the following equation applies:

$$\rho = 1 - p(0) \tag{17}$$

The variable $p(0)$ indicates an idle (no orders) queuing system. In the analyzed case, ρ_2 can be calculated by assuming the value of $p_2(0)$, e.g. $p_2(0) = 0.05$. Then:

$$\rho_2(0) = 1 - p_2(0) \tag{18}$$

Since the system utilization coefficient ρ is equal to $\rho = \lambda/\mu$, the following is obtained:

$$1 - \frac{\lambda_2}{\mu_2'} \leq 0.05 \tag{19}$$

Since $\mu'_2 = 1.13$, we obtain:

$$\lambda_2 \geq 1.07 \ \text{order/min} \tag{20}$$

The obtained result is accurate for the analyzed technological process of installing the dashboard in a car body using a transport manipulator with a capacity of 3000 pcs and a probability of $p_2(0) = 0.05$. This is just one example of using queuing theory to analyze a selected production line.

Reliability of the selected production line

To determine the reliability of the production line, the reliability parameters of individual service stations should be used. These parameters will be further designated by $p_{i,\text{reliability}}$, $i = 1,2,\ldots,m$ and will be interpreted as probabilities for the reliable operation of a service station. The structure of the line also plays an important role in calculating the reliability of the line. In the example analyzed here, the production line has a serial character (Figure 6).

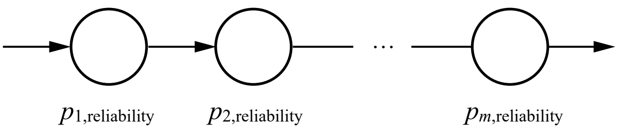

Figure 6. Serial production lines

According to probability theory, the reliability parameter of the entire $p_{\text{line,reliability}}$ is:

$$p_{\text{line,reliability}} = \prod_{i=1}^{m} p_{i,\text{reliability}} \tag{21}$$

To make the calculation process more specific, concrete values of reliability parameters of individual service stations in the selected example were adopted, so:

$$p_{1,\text{reliability}} = 0.9 \tag{22}$$

$$p_{2,\text{reliability}} = 0.9 \tag{23}$$

$$p_{3,\text{reliability}} = 0.9 \tag{24}$$

Further, $p_{\text{line,reliability}}$ can be determined as the product of the above parameters, and $p_{\text{line,reliability}} = 0.729$ was obtained here. In the case of a parallel production line structure or a series-parallel structure, determining $p_{\text{line,reliability}}$ is a more complicated task. Here, a tree structure can be used to pass between service stations, and this structure can be determined based on the structure of a specific production line.

Conclusions

The purpose of this paper was to assess the efficiency and reliability of production lines using queuing models. Queuing theory allows the creation of mathematical models of real and planned systems, while also considering their downtime and possible losses. The first chapter characterized the production process, the components of which constituted the basis for the attempt to apply the selected research method. After the theoretical presentation of the production process (detailing the manufacturing process), queuing models were created for the selected production line, and calculations were carried out to assess their effectiveness and reliability.

The calculated results showed that queuing theory can also be used in the production process to create a queuing model that shows the structure of the analyzed production line and, in more complex systems, organize individual service units and design a simplified model. The activities presented in this paper show that the queuing model used for the production line can also be used to determine its reliability. Queuing analysis makes it possible to link several production-related aspects. To date, however, this method has rarely been applied to production processes. Most often, it is used in areas such as transport, service systems, various shops, airports, seaports, and communications networks; however, this paper showed that this method is also useful for production systems. The functioning of a production process consists of many factors and only by depending on all of them can a queuing model be created for an operating system to be analyzed. It would be worth continuing further research in this direction.

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