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SURVIVAL ANALYSIS METHOD AS A TOOL FOR PREDICTING MACHINE FAILURES

The paper discusses the issues of using survival analysis to predict machines failure. First of all, the description of survival analysis method is presented, along with the idea of creating robust schedules. In the final part the authors offer a concept of developing predictive schedules based on the analysis of previous production processes.
Keywords: *survival analysis method; robust schedule; stable production; machine failure.*

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МЕТОД АНАЛІЗУ ДОВГОВІЧНОСТІ ЯК ІНСТРУМЕНТ ПЕРЕДБАЧЕННЯ ВИРОБНИЧИХ ЗБОЇВ

У статті запропоновано метод аналізу довговічності, за допомогою якого можна передбачати виробничі збої обладнання. Детально описано спосіб застосування даного методу, а також метод складання розкладів надійності. У заключній частині автори представляють варіант розкладу надійності обладнання, що спирається на аналіз минулих виробничих процесів.
Ключові слова: *аналіз довговічності; розклад надійності; стабільне виробництво; збій обладнання.*
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МЕТОД АНАЛИЗА ДОЛГОВЕЧНОСТИ КАК СРЕДСТВО ПРОГНОЗА ПРОИЗВОДСТВЕННЫХ СБОЕВ

В статье предложен метод анализа долговечности, при помощи которого можно предусмотреть производственные сбои оборудования. Детально описан способ применения данного метода, а также метод составления расписания надёжности. В заключительной части авторы представляют вариант расписания надёжности на основе анализа осуществленных производственных процессов.
Ключевые слова: *анализ долговечности; расписание надёжности; стабильное производство; сбой оборудования.*

Problem statement. Prediction of possible manufacturing process disruptions is a largely popular issue today, ensuring stability of the processed jobs results in production progressing in an organized manner with no nervousness involved (Klimek et al., 2008). Awareness of potential disruptions is of great benefit in the course of production, but even more so at the planning stage.

Therefore, literature is increasingly focusing on scheduling under uncertainty (Wojakowski et al., 2014). Numerous authors put forward solutions aimed at obtaining a stable production schedule (Paprocka et al., 2013). The present paper proposes using the survival analysis method to predict possible production process disruptions consisting in machine failure, and employing the obtained knowledge to provide robust production schedule, as economic benefits of stable production are unquestionable.

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Literature review. Production jobs scheduling is developed in numerous research papers. Based on literature analysis, it can be concluded that the subjects of recent research projects are the following:

- scheduling in *job-shop* systems (Thomalla, 2001);
- stochastic job scheduling (Zhang et al., 2012);
- production process dynamism (Adibi et al., 2010);
- practical considerations of scheduling (Wojakowski, 2012).

Analyses of different production processes have revealed the existence of numerous factors hampering scheduling, i.e.: fluctuating number of performed jobs, limitations related to operations and workstations, random events resulting in disturbances of production flow (Kalinowski et al., 2003; Li et al. 2008). These and other factors make it virtually impossible to create a dependable schedule. For this reason, the literature offers an approach called robust scheduling (Lindhard et al., 2012; Klimek et al., 2008). Many authors put forward various solutions related to building robust production sequences. For instance, (Liu et al., 2007) analyse robust job sequencing on a single machine aimed at obtaining a robust schedule. In (Xiong et al., 2013) robust job sequencing in a *flexible job-shop* is analysed, assessing schedule robustness and time of execution. Meanwhile, (Jensen et al., 2007) propose applying redundancy technique based solutions to improve schedule robustness in the job-shop environment.

Increasingly often attention is also focused on predicting potential production process disruptions and applying this knowledge to scheduling process. (Janak et al., 2007) is based on the probability distribution function, while (Paprocka et al., 2007) propose using reliability function, as well as MTTF, MTBF and MTTR.

Robust scheduling as a response to job sequencing problems. The concept of robust production job sequencing is a response to a variety of different problems encountered in the process (Pawlak, 1999). Apart from the basic NP-hard problems, i.e. computational complexity of searching for optimum solutions, literature offers the classification of problems into several categories (Figure 1). The problems occurring result in decreased planning effectiveness, and delayed production (Bubenik, 2011).

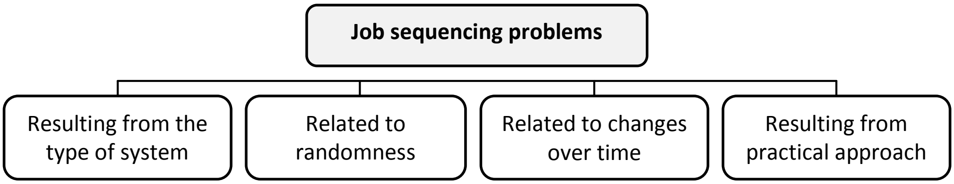

Figure 1. **Classification of job sequencing problems,** *authors' compilation*

As far as the type of system analysed, the problems are grouped into *flow-shop, job-shop* and *open-shop* problems. As for classification according to the randomness of system characteristics, the problems are broken down into deterministic and probabilistic ones. Depending on the change occurring in the analysed production system, problems can be divided into dynamic and static, and the system's relation to practice creates the breakdown into practical and theoretical problems (Sobaszek, 2013).

Upon analysing numerous papers on production scheduling problems, a conclusion can be made that the research covers several groups of problems. Increasingly often, publications employ robust production scheduling in tackling such problems as:

- the influence of the randomness factor on creating schedules;
- dynamism of production processes;
- applying theoretical solutions in practice.

The occurrence of problems from the groups above makes it virtually impossible to create a dependable schedule. This is why applying the robust approach in creating schedules is entirely justified (Gola et al., 2014).

Predictive approach in creating robust schedules. Robust scheduling is a part of the process called predictive-reactive scheduling. This approach to production job sequencing encompasses two phases (Gao, 1996):

- the phase related to the planning stage (predictive scheduling);
- the phase related to carrying out the plan (reactive scheduling).

The predictive scheduling phase is also called the offline phase. It is in the course of this phase that the following are created:

- nominal schedule – taking into account the system's current parameters;
- robust schedule – taking into account process' uncertainty and variability.

However, predicting possible factors that might negatively influence the analysed process remains problematic. The literature presents approaches and techniques aimed at predicting production process disturbances, nevertheless, the issue is sill the subject of numerous research projects and analyses (Haranczyk, 2013). This is why the authors of this paper propose a solution consisting in applying the survival method to predict possible disturbances consisting in failure of machines carrying out the production process. It is part of the concept already presented in (Sobaszek et al., 2014).

The survival analysis method. The term "survival analysis" covers statistical data analysis techniques. Literature provides other names of this type of analysis – *survival data analysis, lifetime data analysis, life testing or analysis of failure time data* (Balicki, 2006).

The survival analysis is connected with duration of processes, defined by two events: the beginning and the end (Sokolowski, 2010). These would be the birth and death in the case of human life, redundancy and hiring in the case of employment, whereas in reference to a machine – the moment of launching an operation and its failure (Miszkiel, 2012).

Time duration is treated as a random variable T belonging to an interval $(0,\infty)$, therefore, mathematical description in the form of appropriate probabilistic functions will constitute an essential element of this method. The basic functions include (Balicki, 2006):

1. Probability density function $f(t)$ – representing the probability of an event occurring in the sense that $f(t)\Delta t$ can be understood as the approximation of probability that an event will occur in duration t.

2. Distribution function $F(t)$, defining that an event will occur in duration $(0, t]$:

$$F(t)=P(T\leq t). \tag{1}$$

3. Duration function $S(t)$ – also called the survival function (Figure 2) is the distribution function complement to the value of one:

$$S(t) = 1 - F(t) = P(T > t). \quad (2)$$

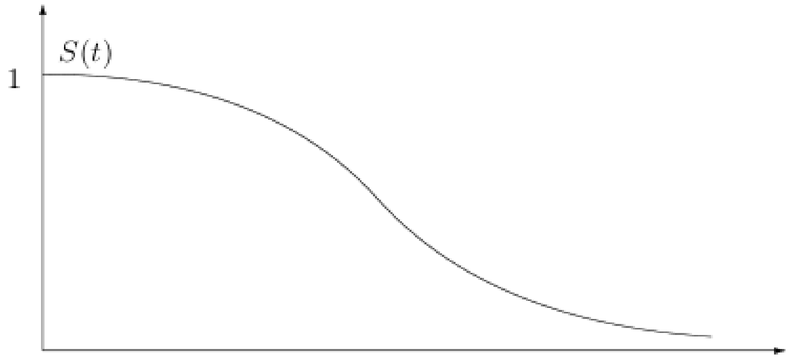

Figure 2. **Shape of survival function** (Magiera et al., 2015)

4. Intensity function $\lambda(t)$ is called the hazard function. It is a local characteristic of a given process, defining its instability in the sense of the time of the event occurrence:

$$\lambda(t) = \frac{d \ln S(t)}{dt}. \quad (3)$$

The survival analysis is a set of analytical techniques and methods. The methods of this type of analysis that can be calculated with the STATISTICA software include (StatSoft, 2006):

1. ***Life tables analysis*** – for grouping data, placing it in an appropriate table, followed by case analysis. The processed data serves, inter alia, to establish the probability density, hazard rate or median survival time.

2. ***Adjusting distribution*** – consisting in adjusting the distribution to empirical data (Figure 3).

3. ***Kaplan-Meier estimate*** – a solution defining the survival function as the product of consecutive probabilities from the ranges based on formula (4). This method also provides the graphic representation of results in the form of a step chart (Sokolowski, 2010):

$$S_n(t) = \prod_{t_j \le t} \left(1 - \frac{d_j}{r_j}\right), \quad (4)$$

where $S_n(t)$ – estimated survival function; Π – product symbol; r_j – the number of the exposed in period t_j; d_j – the number of events in period t_j.

4. ***Sample comparison*** – consists in comparing survival time or failure-free time in two or more samples, as defined by research.

5. ***Regression models*** – enable the analysis of correlation between variables of different types and the subject's survival time. The most frequently applied models include: Cox proportional model, Cox proportional hazard model, exponential regression model, normal linear regression model, Log-normal linear regression model.

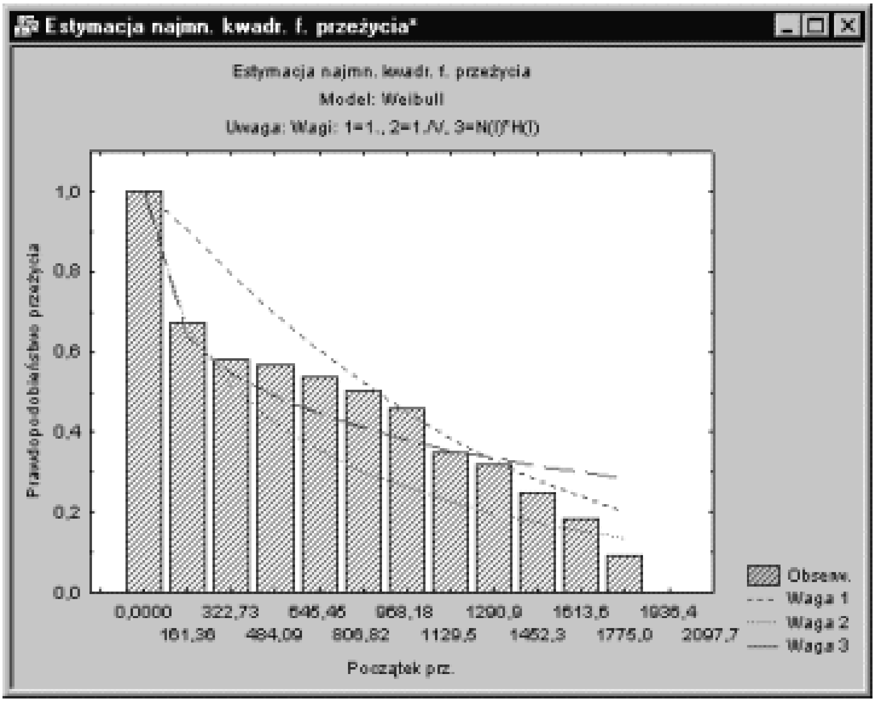

Figure 3. **Distribution adjustment example** (StatSoft, 2006)

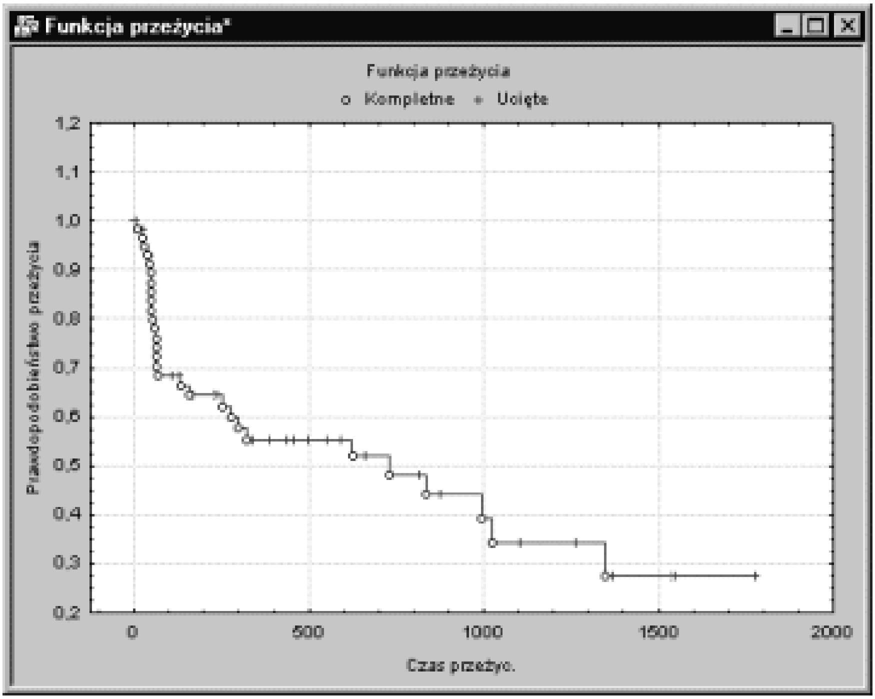

Figure 4. **Estimated survival function chart,** *authors'*

Despite offering great potential, the survival analysis method is not widely popular in technical research; nevertheless, it does provide researchers with plenty of interesting information on processes and objects that can serve as a basis for predicting their behaviour. It can be assumed that such knowledge may be helpful in production scheduling. Thus, the next chapter presents the concept of applying the survival analysis in predicting failures of machines performing production processes.

Applying survival analysis in predicting production process disturbances. Numerous research papers touch upon the job sequencing issues. Recent literature offers scheduling under uncertainty solutions (Wojakowski et al., 2014; Rahmani, 2014). Various random factors are analysed, the occurrence of which impede further production processes. Failures of machines processing individual jobs are certainly among them.

That is why the previous papers presented the concept of robust production scheduling, the key element of which is using historical data on the process to identify potential process disturbances. The historical data accumulated can serve as a basis for analysing and identifying machines potentially threatened by failure. Figure 5 presents the idea of applying the survival analysis.

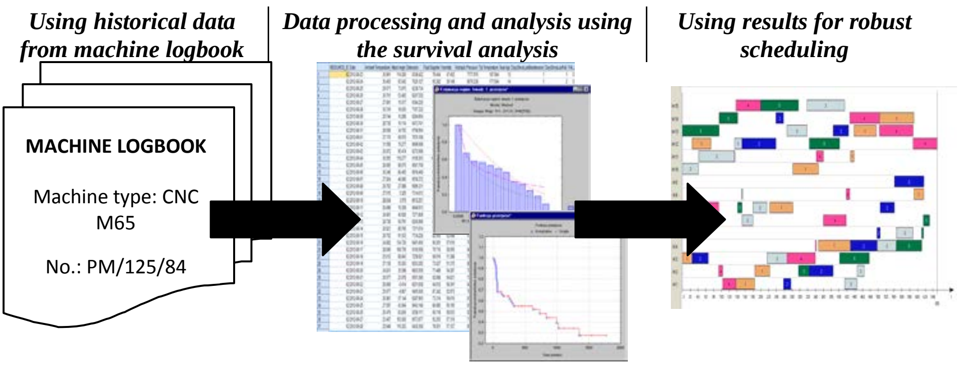

Figure 5. **Using the survival analysis method to obtain a robust schedule,** *authors'*

The historical failure rate data can be obtained from such documents as the machine/tool job card, or the maintenance log. Such documentation contains information on machine operation history. At today's enterprises, this type of data is also stored using specialized software (Plecka et al., 2013), allowing obtain data on failure occurrence time necessary to perform the Survival Analysis.

STATISTICA software, offering the survival analysis option, can be used for this purpose. Conducting the analysis can include applying the selected techniques. Table 1 presents an appropriate method that can be used for this purpose.

The analysis results can find their further application in the process of robust production scheduling. Establishing the probability of failure-free machine operation at given intervals may be helpful in identifying periods of no threat of process interruption. Based on the duration analysis, machines posing the highest threat of failure can also be identified and paid attention to in the course of scheduling and production process. To ensure job sequencing stability, redundant time buffers can be placed in sensitive portions of the schedule – in time *t* identified based on the survival analysis of machinery.

Table 1. **Using survival analysis techniques,** *authors'*

Survival analysis technique	Application
Life table analysis	Establishing the failure rate of machines within the analysed periods.
Adjusting the distribution	Defining the character of disturbances occurring.
Kaplan-Meier estimate	Calculating the survival function to compare with the failure rate tables.
Sample comparison	Comparing failure cases in different periods of time (e.g. in times of higher or lower production workload).
Regression models	Assessing what factors influence failure occurrence. (e.g. What is the influence of machine inspections frequency? What is the influence of the type of process conducted on the rate of failure?).

Summary and prospects for further research. Ensuring the stability of production performed is a valid and current issue. Negative influences on the production process should be considered as early as the planning stage. That is why, more and more papers on job sequencing under uncertainty are being published. The literature analysis suggests that the survival analysis can be used in the process of robust sequencing, and appropriate use of historical data can bring measurable effects. The authors of this paper are conducting research of real data obtained from a production company. The results of research using the survival analysis will be published in future papers.

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