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ECONOMIC ANALYSIS OF MANUFACTURING SYSTEMS CONFIGURATION IN THE CONTEXT OF THEIR PRODUCTIVITY

One of the critical problems in the process of manufacturing system design is to decide which of possible configurations is the most advantageous for a company. This article presents the approach reducing the number possible configurations to maximize the productivity of the system. An example of manufacturing system design is offered.

Keywords: *economic efficiency; manufacturing optimization; system configuration; productivity.*

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ЕКОНОМІЧНИЙ АНАЛІЗ КОНФІГУРАЦІЇ ВИРОБНИЧИХ СИСТЕМ В КОНТЕКСТІ ЇЇ ПРОДУКТИВНОСТІ

У статті показано, що однією з проблем прийняття рішень у процесі проектування виробничих систем є визначення конфігурації спроектованої системи. Наведено результати аналізу впливу типу конфігурації виробничої системи на ефективність виробничого процесу. На конкретному прикладі представлено процедуру проектування виробничої системи для досягнення максимальної продуктивності виробничого процесу для певного продукту.

Ключові слова: *економічна ефективність; оптимізація виробництва; конфігурація системи; продуктивність.*

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ЭКОНОМИЧЕСКИЙ АНАЛИЗ КОНФИГУРАЦИИ ПРОИЗВОДСТВЕННЫХ СИСТЕМ В КОНТЕКСТЕ ЕЕ ПРОИЗВОДИТЕЛЬНОСТИ

В статье показано, что одной из проблем, решаемых в процессе проектирования производственных систем, является определение конфигурации системы. Представлены результаты анализа влияния рода конфигурации на производительность производственного процесса. На конкретном примере представлена процедура проектирования производственной системы с целью обеспечения максимально высокой производительности производственного процесса для определенного изделия.

Ключевые слова: *экономическая эффективность; оптимизация производства; конфигурация системы; производительность.*

Introduction. Manufacturers today face more challenges than ever before due to highly volatile markets, which create large fluctuations in product demand. To remain competitive, companies must design manufacturing systems that not only produce high-quality products at a low cost, but also face market changes in the most economical way (Terkaj et al., 2010; Wang et al., 2012; Gola, 2014). Manufacturing system is usually designed under a set of assumptions on the environment in which the company operates. However, it is frequent that a production system is expanded because of different reasons such as the increasing volumes requested by the market, or the arriving of a new product that has to be manufactured. In order to simplify the design phase of the system, most of configuration parameters (demand, product, costs etc.) are assumed to be constant or, in the best cases, variable in some defined ways (Anglani et al., 2000).

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In large manufacturing systems production is done at many stages. A product is partially processed at one stage and then transferred to the next until all operations are completed. The configuration of a system can facilitate or impede system's productivity, responsiveness, convertibility and scalability, and also impact its daily operations (Spicer et al., 2002; Gola et al., 2009). Multistage manufacturing systems can allow for several operational configurations depending on the way machines are arranged by stages, and connected via the material handling system (Swic et al., 2013).

In this paper we discuss the problem of choice of the best configuration of manufacturing system. In particular, we present a method of reduction possible configurations manufacturing systems when analyzing productivity using the simulation method. Both the method and the example to illustrate it are presented in the article.

Literature review. The problem of manufacturing systems design was reached by many researchers during the last decade and it is still under wide interests of scientific research. Many works present metrological solutions in the area of dedicated manufacturing lines (Chryssolouris, 2006; Brzezinski, 2013), flexible manufacturing systems (Tolio, 2009; Swic et al., 2011) and also reconfigurable manufacturing systems (Bi et al., 2008; Koren et al., 2010).

In particur, research related to the problem of systems' capacity and scalability planning, were provided. An extensive survey on the topic of optimal capacity investment has been provided by (Van Mieghem, 2003). Several studies consider both initial investments and optimal capacity adjustments over time (Katz et al., 2002; Asl et al., 2003).

Researchers at the NSF Engineering Research Center for reconfigurable manufacturing system developed one of the first algorithm that address the capacity scalability (Son et al., 2001). A more comprehensive approach was presented by (Spicer et al., 2002) where scalability was analyzed as one of the critical issues in designing large, complex machining systems. Capacity scalability may be also achieved by scaling the capacity of individual pieces of equipment (Youssefa et al., 2008), but the most practical approach to system scalability is adding or removing machines to or from existing manufacturing systems, and in this cases the original system layout design is critical for achieving the cost-effective scalability (Ariafara et al., 2009). A scalability planning methodology for reconfigurable manufacturing systems that can incrementally scale the system capacity by reconfiguring an existing system was presented by (Wang et al., 2012).

Defining the research problem. The first step towards the systematic approach to manufacturing system design is to determine the minimum number of machine tools needed to realize the predicted demand. If the daily demand is D (parts/day), and the total production time per part is t (minute/part), the minimum number of machines M, needed in the system is calculated by the equation:

$$M=\frac{D\times t}{A\times R}, \tag{1}$$

where D – daily demand; t – processing time; A – machine availability (minutes a day); R – machine reliability.

The resulting number of machines calculated by equation (1) must be rounded to the next larger integer. For example, if there is a need for 350 parts per day and the processing time for each is 8.5 minutes, for the working time of 900 minutes/day and we assume 90% reliability of all pieces of equipment (i.e. machine reliability = 0.9) there is a need for at least 4 machines in the system.

The next step is to calculate the number of possible manufacturing systems configurations. The basic equations for calculating the number of possible configurations were presented by (Koren, 2010) and are given below. The number of possible manufacturing system's configuration (K) with M machines arranged in up to m stages can be calculated using the equation:

$$K = \sum_{m=1}^{M} \binom{M-1}{m-1} = 2^{M-1}. \qquad (2)$$

The number of possible configurations with M machines arranged in exactly m stages can be calculated using the equation:

$$K = \left(\frac{(M-1)!}{(M-m)!(m-1)!} \right). \qquad (3)$$

For example, for $M = 6$ machines arranged in up to 6 stages equation (2) yields $K = 32$ configurations, and if arranged in exactly 3 stages, the equation (3) yields $K = 10$ configurations.

We can observe that it is easy to calculate the minimum number of machines N required in the system and to calculate the number of possible configurations. However, as shown in Table 1, the number of possible configurations with M machines is enormous, what leads to serious difficulties when designing a system.

Table 1. **Total number of system configurations for different number of machines**

Number of machines (M)	Number of possible configurations (K)
2	2
3	4
4	8
5	16
8	128
10	512
15	16384
20	524288

When we calculate the minimum number of machines for the designed system and analyze the problem of enormous number of possible configurations the research problem can be defined by the following questions:

1. What is the best way to arrange these machines and how to connect them?
2. Should we arrange them, for example, in a serial line, a pure parallel system, or some combination?
3. Which of all possible configurations is the most advantageous one?

The following example answers some of these questions.

The example of manufacturing system configuration analysis. We demonstrate below how to analyze the possible manufacturing system's configuration, both analytically and using the simulation methods.

The analyzed problem can be defined as: *Design a machining system to machine a part requires* $t = 13.6$ *minutes of machining time in 6 machining tasks. The part requires work on 3 faces; each face requires a separate fixturing, and therefore the 3 faces must be* *machined using 3 separate setups. Execution times of the 5 tasks are given in Figure 1. The required daily volume is D = 600 parts/day. The working time per day is 1350 minutes. We assume the machine reliability to be 100%.*

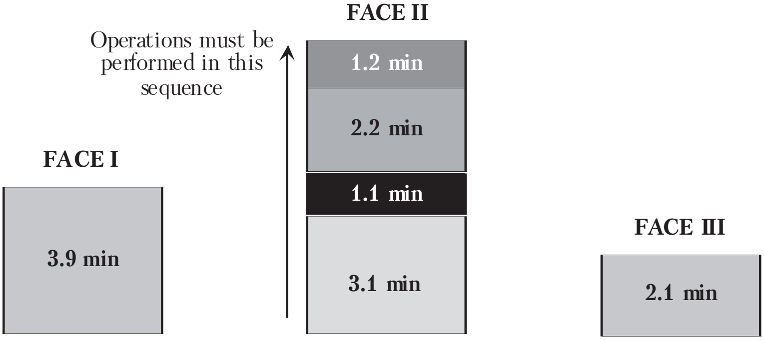

Figure 1. **Machining times**

Producing 600 parts in 1350 minutes requires the cycle time of 2.25 minutes per part. The first step is to determine the minimum number of machines. Equation (1) yields 6.04 machines but we must round the number to the next integer, which gives us M = 7 machines.

According to equation, for 7 machines and the number of possible stages from 1 to 7, we are presented with 64 configurations to analyze. However, 64 configurations is a large number that can be reduced by considering the specific tasks. If a part has 3 faces, we may divide the system into 3 subsystems – first for Face I, second for Face II and third for Face III – and then design 3 separate sub-systems. In the subsystem for Face I (subsystem I) the machining time t is 3.9 minutes per part. According to equation (1) the required number of machines for the first Face is 2:

$$M = \frac{600 \times 3.9}{1350} = 1.73 \Rightarrow 2\,machines. \tag{4}$$

In the subsystem for Face II (subsystem II) the machining time is 7.6 minutes per part. According to equation (1) the required number of machines for the second Face is 4:

$$M = \frac{600 \times 7.6}{1350} = 3.38 \Rightarrow 4\,machines. \tag{5}$$

In the subsystem for Face III (subsystem III) the machining time is 2.1 minutes per part. According to equation (1) the required number of machines for the second Face is only 1:

$$M = \frac{600 \times 2.1}{1350} = 0.93 \Rightarrow 1\,machine. \tag{6}$$

According to equation (2) we can easily calculate that possible number configurations for subsystem I equals 2, for subsystem II – 8 and for subsystem III – only 1. However, when taking into account that in subsystem I we have to realize only one machining task – we have only one possible configuration of subsystem I presented in Figure 2.

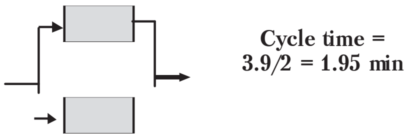

Figure 2. **The only possible configuration for subsystem I**

Therefore, when dividing the system into 3 subsystems we are able to reduce the number of possible configurations from 64 to 8. However, the number of possible configurations is still based on calculations made using the equation (1) which is based on a perfectly balanced system. Indeed, here the system is not necessarily balanced. Therefore, some of these 8 possible configurations will not be able to produce parts with cycle time CT = 2.25 defined by the demand. Our next step is to determine which of these configurations will not supply the demand and eliminate them.

For *3 stages* there is only one possible configuration as shown in Figure 3. In the first stage, one part is produced every 1.95 minutes (between two machines), in the second stage one part is produced (between the 4 machines) every 1.9 minutes and in the third part it is produced every 2.1 minutes. The third stage is the bottleneck, dictating the cycle time of the system is $t_{\max} = 2.1$ minutes. The predicted number of parts per day is, therefore $Q = 1350 / t_{\max} = 642$.

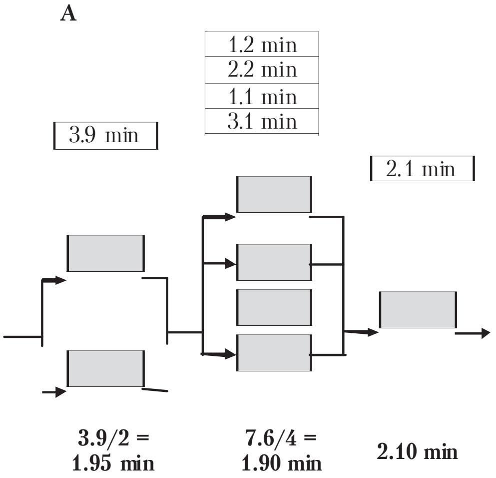

Figure 3. **Configuration with 3 stages**

For 4 stages there are 3 possible configurations, as presented in Figure 4. However, only two of them (configurations B and D) are able to satisfy the cycle time constraint of $t_{\max} \leq 2.25$ minutes. The second configuration (C) has only one machine at the second stage, which becomes a bottleneck with the cycle time of 3.1 minutes, which cannot satisfy the required demand (the minimum cycle time of 2.25 minutes). Therefore, that configuration is unacceptable.

For 5 stages there are 3 possible configurations (configurations E-G presented in Figure 5). However, two of them (configurations F and G) do not satisfy the cycle time constraint of $t_{\max} \leq 2.25$ minutes and have been omitted from consideration.

The only acceptable configuration (E) has the cycle time of $t_{\max} = 2.20$ minutes. The two omitted configurations have only one machine at the second stage, which becomes a bottleneck with the cycle time of 3.1 minutes that cannot produce the required demand.

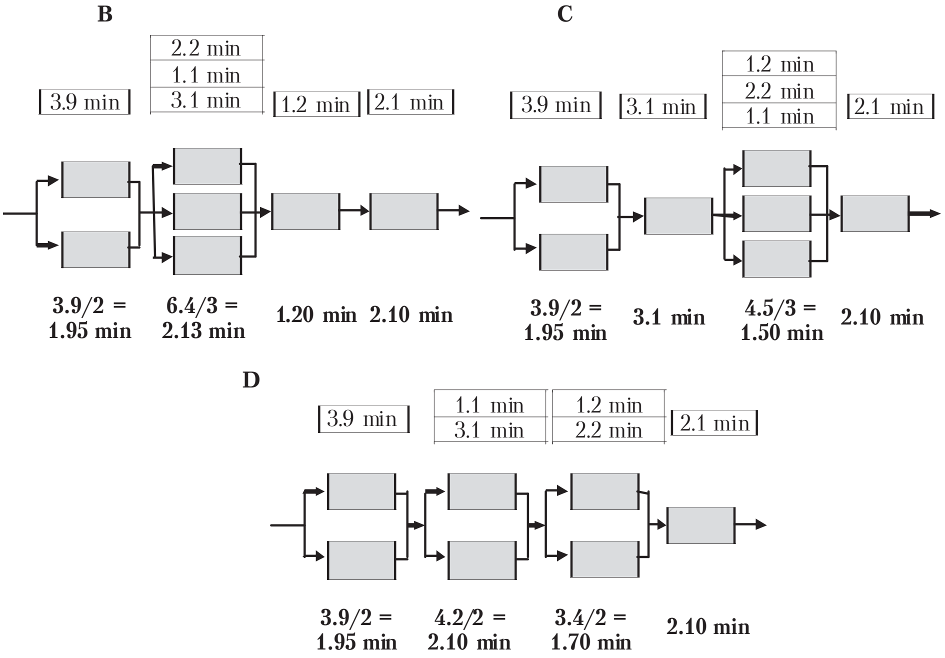

Figure 4. **Configurations with 4 stages**

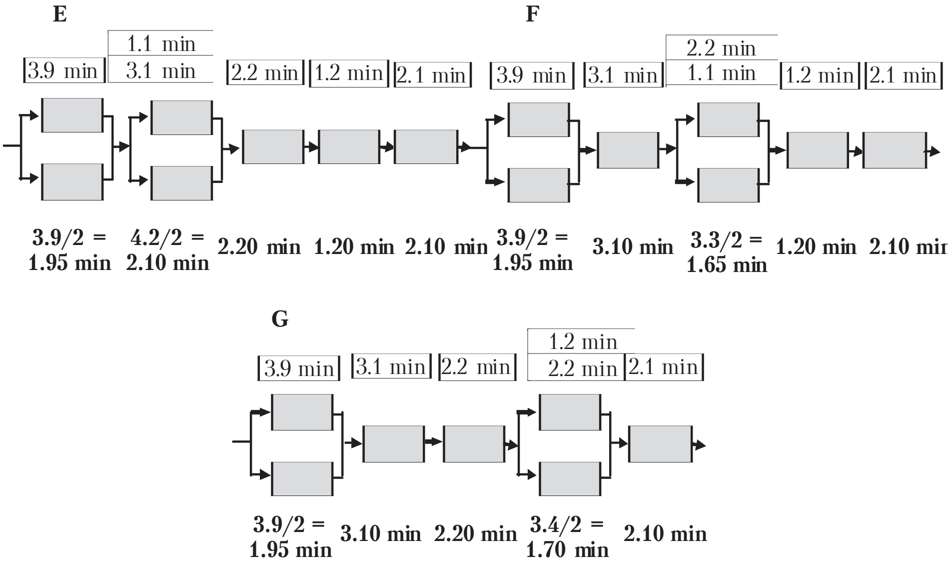

Figure 5. **Configurations with 5 stages**

For 6 stages there is only one possible configuration as presented in Figure 6. Unfortunately, this configuration cannot produce the required demand (the cycle time for that configuration equals 3.1 minutes).

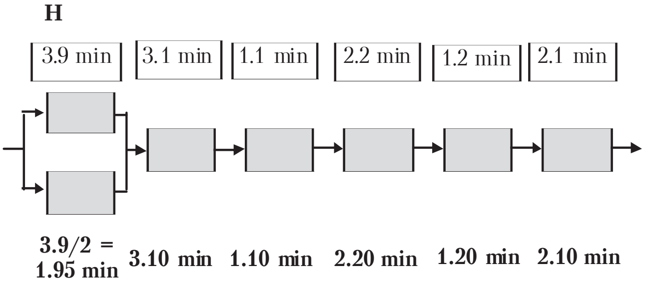

Figure 6. **Configuration with 6 stages**

We can see that because of the cycle time requirement, the number of configurations is reduced from 8 to 4. Altogether, the number of possible RMS configurations to consider was reduced from 64 to 4. Four configurations is a manageable number to compare.

System configurations analysis within the productivity parameter. In order to make the final decision a designer has to compare the selected configurations using the defined parameters. For the purpose of this paper we analyzed the selected configurations in the aspect of the designed system productivity. The measured parameter was throughput of the system in each configuration.

To solve the presented above problem the computer simulation method was used. Simulation methods are very widely used in manufacturing systems' design (Cwikla, 2006; Klosowski, 2011; Sobaszek, 2013). In particular, the simulation model was built and analyzed in the Tecnomatix Plant Simulation Software. During the modelling process it was assumed the system works in 3 shifts with a 30-minutes break during each shift. Finally, the calculated time of designed system's work time (mirrored in the developed model) equals 1350 minutes. Models were built and analyzed for each of the selected configurations. An example of developed model for B configuration is presented in Figure 7.

The obtained results in realized simulations are summarized in Table 2. As we can see, there are two configurations (A and D) with the highest productivity of 637 parts per day – and these ones are the most preferable for the designer.

Conclusions and further studies prospectives. The choice of the best manufacturing system configuration is a strategic decision that companies have to face when designing a new system.

The presented approach offers a method for classification of configurations based on system productivity. Although, the presented example is quite simple, a methodic approach which allows whittling down the range of possibilities and making logical decisions based on facts and data to find the optimal system configurations can be used for more complex systems. Important conclusions that we draw from this example are as follows:

- it is simple to calculate the minimum number of machines needed in a system based on the total processing time per part and the required daily quantity;

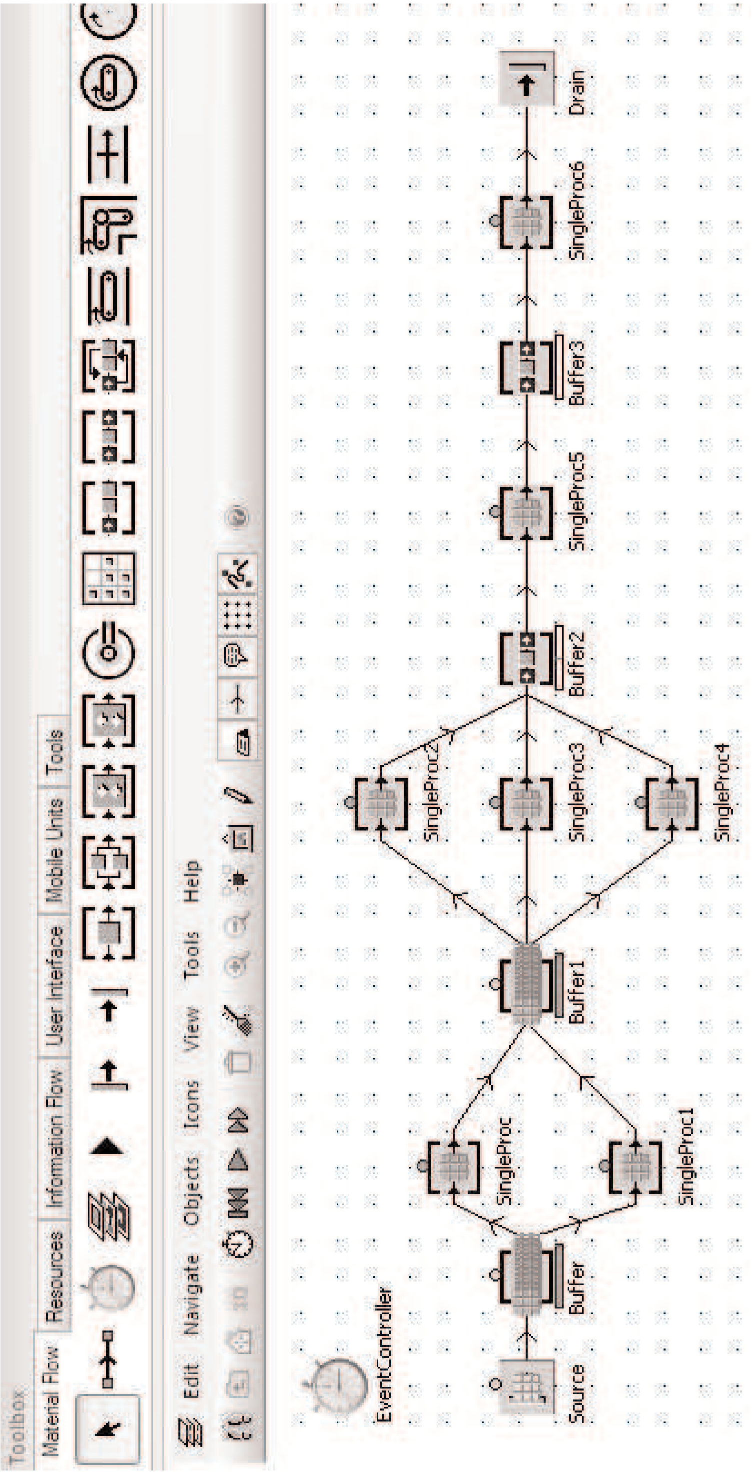

Figure 7. **Manufacturing system model with configuration B**

- the number of possible configurations is bounded by (i) the number of tasks on the part and (ii) the number of faces on the part, and it is always smaller than 2^{M-1};
- the number of possible manufacturing system's configurations is reduced dramatically when considering the daily requirement that must be met;
- although, the analysis of system's productivity allows reducing the number of the most desired configurations it cannot be the only criterion when choosing the best configuration.

Table 2. **Simulation results**

Symbol of configuration	Throuput of the system	
	Parts per day	Parts per hour
A	637	28
B	627	28
D	637	28
E	609	27

As a consequence of the obtained results, future research will be provided in the area of manufacturing systems configuration optimization taking into account the following parameters:

- system throughput with reliability less than 100%;
- investment cost;
- scalability – the increment of production capacity gained by adding a machine;
- floor space, which may be roughly calculated by configuration length (i.e. the number of stages), times its maximum width (i.e. the maximum number of machines at a stage).

References:

Anglani, P., Caricato, A., Grieco, A, Nucci, F., Matta, A., Semeraro, Q., Tolio, T. (2000). Evaluation of Capacity Expansion by Means of Fuzzy-Devs. Proceedings of the 14th European Simulation Multiconference on Simulation and Modelling: Enablers for a Better Quality of Life, pp. 129–133.

Ariafara, S., Ismail, N. (2009). An improved algorithm for layout design in cellular manufacturing system. Journal of Manufacturing Systems, 28(4): 132–139.

Asl, F.M., Ulsoy, A.G. (2003). Stochastic optimal capacity management in reconfigurable manufacturing systems. Annals of the CIRP, 52(1): 371–374.

Bi, Z.M., Lang, S.Y.T., Shen, W., Wang, L. (2008). Reconfigurable manufacturing systems – the state of the art. International Journal of Production Research, 46(4): 967–992.

Brzezinski, M. (2013). Organizacja produkcji w przedsiebiorstwie. Wyd. PLACET, Warszawa.

Chryssolouris, G. (2006). Manufacturing Systems: Theory and Practice. Springer.

Cwikla, G. (2006). Zastosowanie systemu Enterprise Dynamics do modelowania procesu montazu samochodow. Technologia i Automatyzacja Montazu, 1: 10–16.

Gola, A. (2014). Economical Aspects of Manufacturing Systems Design. Actual Problems of Economics, 6(156): 205–212.

Gola, A., Swic, A. (2009). Computer Aided FMS Machine Tools Subsystem Selection – Conception of Metodology. Applied Computer Science, 5(1): 27–39.

Katz, R., Duenyas, I., Narongwanich, W., Koren, Y. (2002). Economic benefits of reconfigurable manufacturing systems. Global Powertrain Conference, Ann Arbor, MI.

Klosowski, G. (2011). Zastosowanie symulacji komputerowej w sterowaniu przeplywem produkcji mebli. Zarzadzanie Przedsiebiorstwem, 2: 29–37.

Koren, Y. (2010). The Global Manufacturing Revolution. Product-Process-Business Integration and Reconfigurable Manufacturing Systems. Wiley, New Jersey.

Koren, Y., Shpitalni, M. (2010). Design of reconfigurable manufacturing systems. Journal of Manufacturing Systems, 29: 130–141.

Sobaszek, L. (2013). Computer Programming as a Tool for the Engineering Problems Analysis. Applied Computer Science, 9(2): 57–71.

Son, S.Y., Olsen, T.L., Yip-Hoi, D. (2001) An approach to scalability and line balancing for reconfigurable manufacturing systems. Integrated Manufacturing Systems, 12(7): 500–511.

Spicer, P., Koren, Y., Shpitalni, M. (2002). Design principles for machining system configurations. CIRP Annals, 51(1): 276–280.

Swic, A., Mazurek, L. (2011). Modeling the reliability and efficiency of flexible synchronous production line. Eksploatacja i Niezawodnosc – Maintenance and Reliability, 4(52): 41–48.

Terkaj, W., Tolio, T., Valente, A. (2010). A stochastic programming approach to suport the machine tool builder in designing Focused Flexibility Manufacturing Systems (FFMSs). International Journal of Manufacturing Research, 5(2): 199–229.

Tolio, T. (2009). Design of Flexible Production Systems. Methodologies and Tools. Springer-Verlag, Berlin Heidelberg.

Van Mieghem, J.A. (2003). Capacity management, investment and hedging: Review and Recent Developments. Manufacturing & Service Operations Management, 5(4): 269–302.

Wang, W., Koren, Y. (2012). Scalability planning for reconfigurable manufacturing systems. Journal of Manufacturing Systems, 31: 83–91.

Youssefa, A., ElMaraghy, H.A. (2008). Performance analysis of manufacturing systems composed of modular machines using the universal generating function. Journal of Manufacturing Systems, 27(2): 55–69.

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