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RELIABILITY ANALYSIS OF RECONFIGURABLE MANUFACTURING SYSTEM STRUCTURES USING COMPUTER SIMULATION METHODS

ANALIZA NIEZAWODNOŚCIOWA STRUKTUR REKONFIGUROWALNEGO SYSTEMU PRODUKCYJNEGO Z WYKORZYSTANIEM METOD SYMULACJI KOMPUTEROWEJ*

Choosing the right production structure (configuration) is one of the most important steps in the process of designing a reconfigurable manufacturing system (RMS). Whether or not a production process to be executed is capable of achieving the assumed performance parameters depends, among others, on the reliability of the machines and technological devices that make up the system under design. Because the individual components of a manufacturing system have different levels of reliability, the reliability of the system as a whole depends to a large extent on the way in which they are configured. This article discusses the process of selecting the structure of a manufacturing system with changing machine reliability, which allows to accommodate these changes to maintain the stability of the production process. The focus of the study was a manufacturing system under design dedicated to the machining of body parts. The experiments were carried out using analytical methods and computer simulation methods. Simulations were performed using Enterprise Dynamics software.

Keywords: *reconfigurable manufacturing system, RMS, configuration, production structure, reliability, simulations, Enterprise Dynamics.*

Wybór odpowiedniej struktury produkcyjnej (konfiguracji) stanowi jeden z ważniejszych kroków w procesie projektowania rekonfigurowalnego systemu produkcyjnego (RMS). Możliwość osiągnięcia zakładanych parametrów wydajnościowych planowanego do realizacji procesu produkcyjnego jest uzależniona m.in. od stopnia niezawodności maszyn i urządzeń technologicznych wchodzących w skład projektowanego systemu. Zróżnicowany poziom niezawodności poszczególnych elementów systemu produkcyjnego powoduje, iż niezawodność systemu jako całości w dużej mierze zależy od sposobu ich konfiguracji. W niniejszym artykule przedstawiono proces wyboru struktury systemu produkcyjnego pod kątem możliwości zachowania stabilności procesu produkcyjnego wraz ze zmianą stopnia niezawodności maszyn technologicznych wchodzących w skład systemu. Jako obiekt badań przyjęto projektowany system produkcyjny dedykowany do obróbki części klasy korpus. Badania przeprowadzono z wykorzystaniem metod analitycznych oraz metod symulacji komputerowej. Jako narzędzie symulacji wykorzystany został system Enterprise Dynamics.

Słowa kluczowe: *rekonfigurowalny system produkcyjny, RMS, konfiguracja, struktura produkcyjna, niezawodność, symulacje, Enterprise Dynamics.*

1. Introduction

Current efforts in the design and installation of manufacturing systems are concentrated on increasing their efficiency, flexibility, and convertibility [2]. This is a result of the growing individualization of customer needs, pressure from global competition, and unprecedented technical and technological progress [14]. The need to meet the growing market demands imposes the necessity of not only developing new methods and techniques of organizing and managing production, but also searching for new forms of organizing maufacturing systems that would allow to achieve these goals [16].

In the light of the prospects for the development of industry in line with Industry 4.0 paradigms, one of the measures that can ensure success for manufacturing companies is the implementation of the concept of reconfigurable manufacturing systems (RMS), which combine the advantages of traditional manufacturing lines and flexible manufacturing systems, thus facing the demands placed on modern manufacturing systems [25, 46]. The idea of a RMS was born in the mid-1990s as a response to the challenges posed by progressing globalization [26]. From that moment on, many scientific, research and industrial centers have been developing methods of designing manufacturing systems with a dynamic production structure adaptable to current market needs [40].

A key issue in designing RMS is the selection of an appropriate production structure that enables the manufacture of products with an assumed efficiency, while allowing to maintain the principles of the reconfigurable manufacturing system [31.33]. This problem has been the subject of numerous studies for over a dozen years now. General assumptions regarding the optimal selection of an RMS configuration are presented in [34, 41, 44]. Methods for the selection of machines for RMS have been proposed by Bensmailne, Dahane and Beouncef [5] and Haddou Benderbal, Dahane and Benyoucef [20]. Reza Abdi developed a model based on the Analytical Hierarchical Process (AHP) method, which allows to structure criteria for selection of layout configuration in RMS [39]. Li, Mitrouchev, Wang, Brissand, and Lu proposed a Petri-net-based method of optimal selection of RMS configuration [30]. Similarly, Petri nets combined with the Lagrange optimization theory were used in the approach proposed by Hsieh [21]. The problem of optimal selection of RMS configuration has also been investigated by Goyal, Jain and Jain, who used NSGA II and TOPSIS multi-criteria optimization methods [19]. The process of selecting the production structure of an RMS viewed from the perspective of maximizing the productivity of the system under design

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** was discussed in paper [17]. The problem of optimization of flowline configuration of selected RMS was also investigated by Dou, Dai and Meng [11, 12] as well as Delorme, Malyutin and Dolgoui [10]. Apart from research on RMS, interesting insights can also be found in studies in the area of analysis and selection of configurations for reconfigurable assembly systems [4, 7].

More and more authors also become interested in the problems of reconfiguration of existing RMS structures, a tendency that reflects the requirement of dynamic change in the production capacity of such systems [18]. An overview of the literature along with a proposal of a general framework for reconfiguration based on the assessment of system life cycle and multiple production levels has been presented in paper [35]. Evaluation criteria and the process of evaluation of reconfiguration of existing systems have been discussed by Wang, Huang, Yan and Du [42] and by Puik, Telgen, Van Moergestel and Ceglarek [37]. An interesting decision-making method for reconfiguration of RMS production structure using the Gale-Shapley model was presented by Renna [38]. Yamana proposed a similar approach based on particle swarm optimization (PSO) [45].

Unfortunately, all the solutions presented in the publications mentioned above assume that the individual machines and technological devices which make up a system under design are characterized by 100% reliability. This fact limits their practical application in industrial settings because in real life, the individual components are never 100% reliable; this means the system as a whole also has a lower than nominal reliability, which directly affects its productivity, efficiency, and production costs [29]. Although in their work [8], Dahane and Benyoucef did draw attention to the issue of reliability in the process of designing RMS, they concentrated solely on the problem of selecting machines for the system under design. Thus, there are no research results showing how a change in the level of reliability of machines affects the level of reliability and expected productivity of an RMS.

This paper focuses on how the production structure of an RMS system being designed affects the level of its reliability and productivity, depending on the level of reliability of the machines that form part of this system. In particular, the article proposes a method for prototyping RMS production structures which uses analytical estimation of system structure reliability and computer simulation. The essence of the proposed approach is to enable the selection of an RMS structure that will correspond to the expected characteristics determining the reliability and productivity of the system under design. The following evaluation criteria for prototyping were adopted: reliability of the system as a whole, system productivity, and utilization rates of the machines and devices making up the manufacturing subsystem of the RMS under design.

2. Reconfigurable manufacturing systems – definition and design assumptions

A ***reconfigurable manufacturing system (RMS)*** is one designed to quickly adjust its functionality and production capacity to changing market demand, by changing the structure of the system both with regard to its hardware and software components [23,26]. The concept of RMS was created in the Engineering Research Centre at the University of Michigan College of Engineering (USA) and was implemented in 1999 as a response to new market challenges manifested, among others, by [6]:

- the need to reduce the time of launching a new product in the market,
- customer demand for increasing assortment diversity,
- smaller and variable production volumes, and
- the need to reduce the prices of manufactured goods.

The basic features of RMS include [32]:

- *Modularity* – all the main components of a system (both hardware and software) have a modular structure. Modularity makes it possible to easily change the structure of a system or device in order to adjust it in the best possible way to the current production requirements.
- *Integrability* – the ability to quickly and precisely integrate modules by a set of mechanical, informational and control interfaces that enable their integration and communication.
- *Customization* – system flexibility is designed around the current production needs.
- *Convertibility* – the ability to quickly change the functionality of the existing system, machines and controls to suit new production tasks.
- *Scalability* – the ability to easily change the production capacity of an RMS by changing its structure or the production capacity of its specific components.
- *Diagnosability* – the ability to automatically read the current state of the system and to detect and diagnose the causes of output product defects and take corrective action immediately.

Thanks to customization, the functionality and production capacity of RMS are strictly adjusted to current production tasks. As a consequence, these systems have a minimum required level of flexibility, which limits the investment costs. Owing to their modularity, integrity, scalability and convertibility, however, they can be quickly redesigned to achieve a new, desirable level of functionality and production capacity suited to new market requirements (Figure 1).

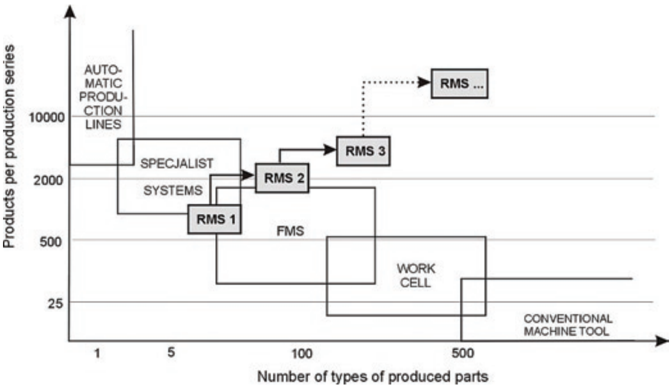

Fig. 1. RMS functionality compared to other manufacturing systems

The basic feature of RMS is their reconfigurable structure, which enables quick rearrangement of hardware and software to obtain a certain level of functionality and production capacity adjusted to current production tasks.

An RMS is composed of workstations which are reconfigurable machine tools, a control system consisting of reconfigurable controllers for the control of the reconfigurable machine tools, and a reconfigurable material transport and handling subsystem, controlled by the control system, for automated transport of materials and workpieces within the RMS. Both reconfigurable process machines and controllers have a modular design that enables fast and reliable integration when a need to change the structure of the system arises.

An example of a reconfigurable manufacturing system is shown in Figure 2.

The system (10) consists of workstations (12) with reconfigurable machine tools (14). The system also contains a control system with the operator's station (16) and reconfigurable controllers (18) which communicate with each other, as shown by the dashed lines. In addition, the system incorporates a handling system consisting of a gantry robot (20), at least one wireless AGV trolley (22), and a system of transmitters and aerial receivers (23) communicating with the AGV

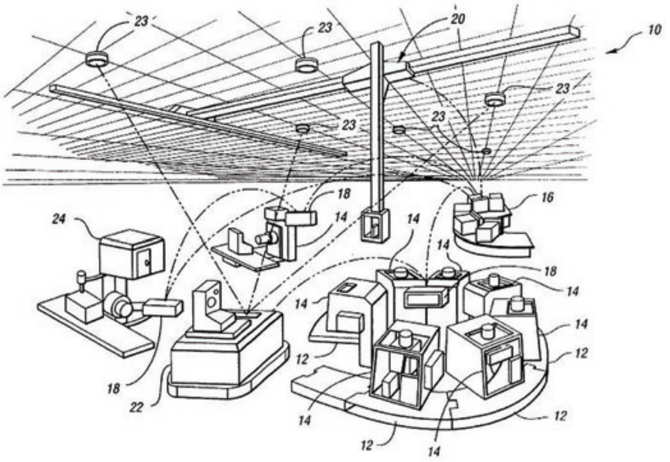

Fig. 2. Reconfigurable manufacturing system [24]

(22). The AGV trolley also communicates with at least one reconfigurable controller (18).

Reconfigurable manufacturing systems enable integration with other modern production devices such as laser processing devices (24) which have their own reconfigurable controllers that communicate with the operator's station (16) and the remaining controllers in the system [24].

3. Problems of designing RMS production structures

Manufacturing systems can be designed in many configurations: serial, parallel or hybrid. The different configurations have a considerable impact not only on the possibility of adapting production to market needs, but also on the reliability, productivity, product quality, and costs of production [27]. For that reason, the right production structure has to be chosen already at the design stage, because the type of structure used cannot be changed during the system's lifetime [25].

According to the definition, a reconfigurable production system is designed for rapid adjustment of its functionality and production capacity to tasks arising from the changing market demand, by changing the structure of the system, both with regard to production hardware and software (see Section 2). In order to make dynamic change of production capacity possible, the structure of the system must be designed so as to enable quick change of the functionality of the existing system in order to adjust it to new production tasks. System structure must therefore be modular, and thus enable easy addition or removal of a process machine without the need to overhaul the production structure and change the functioning of the system [1].

By definition, the structure of RMS is a structure that enables multi-stage machining of workpieces, and simultaneously provides the possibility of replacing machines at the individual stages of the production process [13]. An example of such a structure, utilized by a US powertrain manufacturer, is shown in Figure 3.

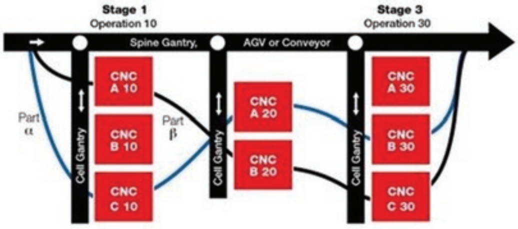

Fig. 3. Functional structure of a reconfigurable manufacturing system [1]

It is a system in which the production process is executed in three stages and enables simultaneous processing of two different parts (a, b). A roller conveyor serves all machines in a particular production stage – it delivers blanks to each machine tool, picks the machined parts and delivers them to an input/output buffer (marked with white dots in Figure 3). The buffer can be a roller conveyor or several AGVs. The machine tools in each stage of the process are always identical [13].

In the present study, we analyzed the process of selecting structures for the reconfigurable manufacturing system discussed in article [28]. The RMS designed in that article was dedicated to the machining of body parts (Fig. 4). The technological process encompassed five technological operations performed on two faces of a part, each face requiring separate fixturing (Fig. 4 b). The design assumed that the system should be capable of producing 500 parts a day. The working time per day for the manufacturing system (F_j) was 60,000 seconds.

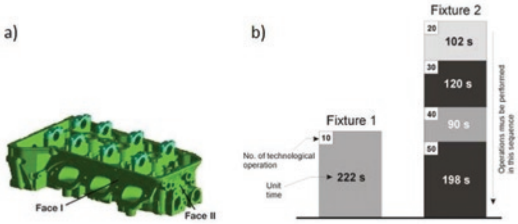

Fig. 4. Engine part : a) general schematic view of the product, b) structure of the technological process [28].

The maximum allowable cycle time for producing 500 parts in 60,000 seconds was $\tau_{max} = 120$ s/part. In designing a system like that, the designer must first establish the minimum number of machines (M) needed to achieve the given production volume. This can be done using formula (1) [28]:

$$M = \frac{Q*t}{F_j*R}\cdot 100\% = \frac{500\ \ szt.*732\ \ s/szt.}{60000\ \ s\cdot 100\%}*100\% = 6{,}1 \tag{1}$$

where: Q – daily demand [parts/day], t – machining time [s/part], F_j – working time per day [s], R – machine reliability [%].

In the analyzed case, in which the machines were assumed to have 100% reliability, the minimum number of machines needed was 7, which corresponded to 64 possible system configurations (calculated using formula (2)):

$$K = \sum_{m=1}^{M}\binom{M-1}{m-1} = 2^{M-1} = 2^{7-1} = 64 \tag{2}$$

where: K – number of possible system configurations, M – number of machines in the manufacturing system, m – number of processing stages

This number can be reduced to 15 configurations by dividing the system into two subsystems (associated with the need to change the way the part is fixed in the workstation) and by taking into account the number of operations that can be performed in each of the stages (Figure 5).

For systems that produce parts in two stages, only one configuration (marked with the symbol A in Fig. 6) is possible. In this configuration, each part is produced at a cycle time of 111 s/part in the first stage and 102 s/part in the second stage. The first stage is a bottleneck and determines the work cycle for the entire system at t_{max} = 111 s/part. The expected productivity of a system with a structure like this is 540 parts.

Theoretically, in the case of systems in which products are manufactured in three stages, four configurations are possible. However,

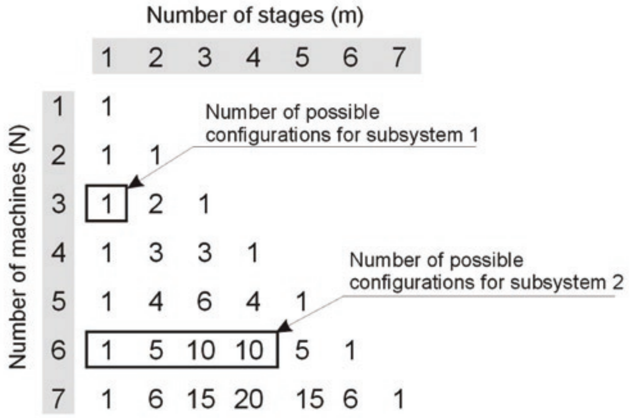

Fig. 5. Pascal's triangle was used to determine the number of system configurations in each production stage

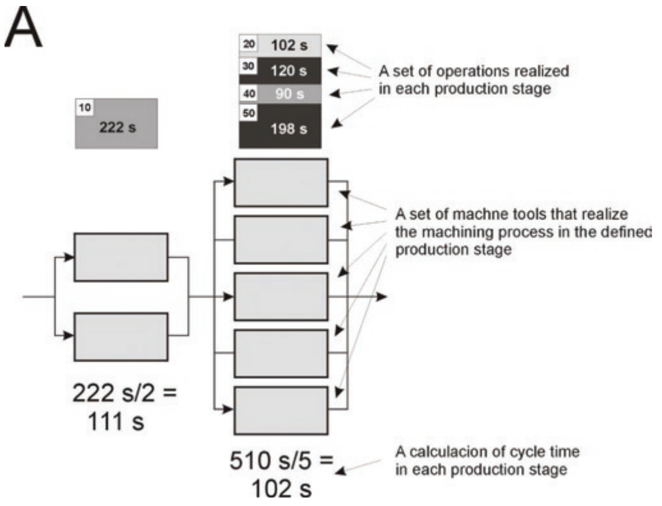

Fig. 6. The production structure of a system in which parts are produced in two stages

only three of them (marked with symbols B, C and D) allow to machine parts at a cycle time lower than or equal to 120 s/part. (Fig. 7). The fourth configuration (marked with the symbol E) has only one machine in the third stage, which is a bottleneck that works at a cycle time of 198 s/part, generating a productivity that is too low to meet the demand.

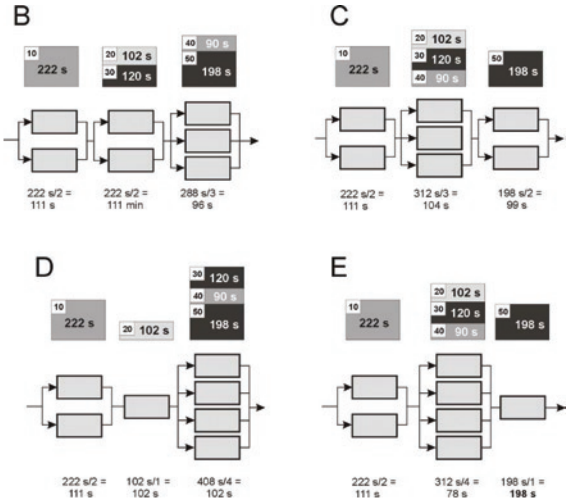

Fig. 7. Production structures of a system in which parts are produced in three stages

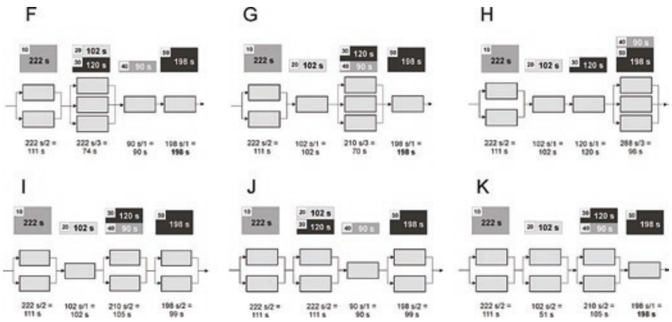

Fig. 8. Production structures of a four-stage-production system

A four-stage-production system may have one of the production structures shown in Fig. 8. However, only three of them meet the requirement that parts be produced at a cycle time lower than 120 s/part, and only these structures will be subjected to further analysis. All the acceptable configurations (marked with the symbols H, I, and J) can operate at a cycle time of 111 s/part. The remaining ones have only one machine in the last stage, which is a limiting link that enables production at a cycle time of 198 s/parts.

Five-stage systems can be configured in four different ways as shown in Fig. 9. Unfortunately, only one of these arrangements (marked with the symbol O) meets the requirements regarding the maximum production cycle time: its cycle time is exactly 120 s/part. In the other three structures, the fifth stage is a bottleneck. Its cycle time of 198 s is insufficient from the point of view of the efficiency requirements of the system under design.

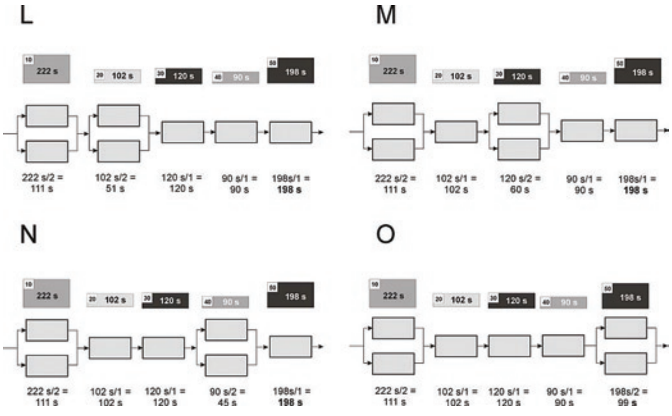

Fig. 9. Production structures of a five-stage-manufacturing system

A detailed analysis of the configurations of a RMS in terms of whether their nominal efficiency complies with the design requirements allows one to substantially reduce the number of feasible arrangements, but not to identify the best design. In designing a system like this, it is necessary to take into account additional criteria that enable one to select a structure that on the one hand will guarantee the fulfilment of the limiting conditions defined in the pre-design phase, and on the other, will take into account factors related to the current operation of the system. As part of the present study, we assessed the reliability and expected productivity of the manufacturing system, taking into account the production structures selected based on the requirement of minimum efficiency. In particular, we evaluated the relationship between changes in the level of reliability of the manufacturing system (R_S) and changes in the level of reliability of its component machines and devices (R) and the expected level of productivity of the system, assuming that the machines that are part of the RMS have different levels of reliability.

4. Analysis of reliability and productivity of RMS system structures

4.1. Evaluation of the reliability of the reconfigurable manufacturing system under design

In general, system reliability (R_s) is understood as the probability that the system will operate continuously throughout its useful life [9]. The total reliability of a system depends on both the reliability of all its components and the way they are arranged [3]. Serial arrangement (Fig. 10 a) reduces the reliability of a system. This is because a system built of elements positioned in a row operates only when all the individual machines are in working order. If the reliability of each machine is R, and the number of machines is n, then the reliability of the system is R^n.

Parallel arrangement of two identical elements increases the overall reliability of a system. More components added in parallel (Figure 10 b) increase the reliability of the system, because the system will stop functioning only when all system components have failed. In this case, the probability that n identical machines arranged in parallel will fail is $(1-R)^n$, and the reliability of the system is $1-(1-R)^n$ [43].

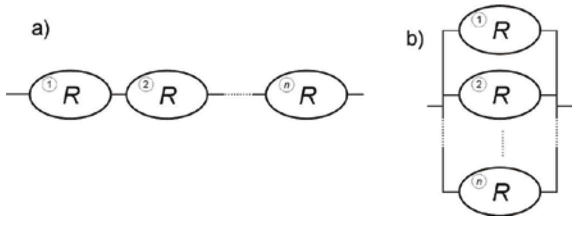

Fig. 10. Basic configurations of manufacturing systems: a) serial (linear) structure, b) parallel structure

All of the structures of the RMS being designed are hybrids that combine the characteristics of both parallel and serial structures. System reliability (R_s) is then a derivative of both the number of production stages as well as the number of machines in each stage, and its value for each configuration can be calculated using the formulas given in Table 1.

Table 1. Manufacturing system reliability formulas for selected structures

Configuration	Formula
A	$R_s = [1-(1-R)^2]*[1-(1-R)^5]$
B	$R_s = [1-(1-R)^2]*[1-(1-R)^2]*[1-(1-R)^3]$
C	$R_s = [1-(1-R)^2]*[1-(1-R)^3]*[1-(1-R)^2]$
D	$R_s = [1-(1-R)^2]*R*[1-(1-R)^4]$
H	$R_s = [1-(1-R)^2]*R*R*[1-(1-R)^3]$
I	$R_s = [1-(1-R)^2]*R*[1-(1-R)^2]*[1-(1-R)^2]$
J	$R_s = [1-(1-R)^2]*[1-(1-R)^2]*R*[1-(1-R)^2]$
O	$R_s = [1-(1-R)^2]*R*R*R*[1-(1-R)^2]$

Reliability levels of the RMS under design for each of the selected structures, at different levels of reliability of the component machines, are shown in Table 2.

As the results show, changes in RMS reliability for each of the structures are disproportionate (Fig. 11). In the case of configuration A, despite the decrease in the reliability level of the individual machines, the reliability of the system as a whole remains relatively stable up to a certain point, after which it sharply drops. A completely different situation takes place in the case of configuration O, where a reduction in machine reliability is accompanied by an immediate, substantial decrease in system reliability.

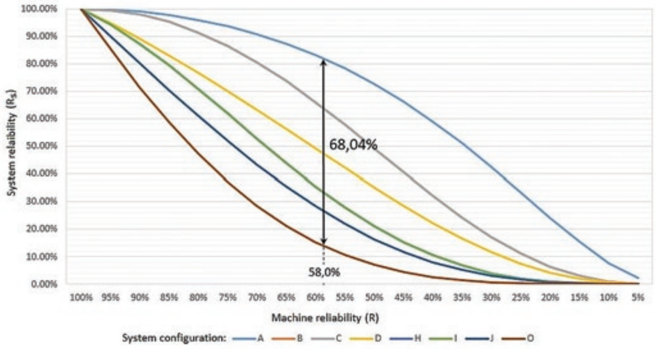

Fig. 11. Relationships between machine reliability (R) and manufacturing system reliability (R_s)

Considering the fact that the reliabilities of machines and manufacturing devices decrease with operation time, the type of configuration used is crucial for maintaining the assumed production capacity within the system's planned life cycle. For example, assuming that the machines operate at a reliability rate of 75%, the reliability of a two-stage system is 93.66%, while a five-stage system (configuration O) has a reliability of 37.08%. Selection of the system's structure already at the design stage can therefore be of key importance for the system's productivity and efficiency in subsequent operational periods. The largest difference (68.04%) in system reliabilities was found when machines operated at 58% reliability: system reliability for configuration A was 81.28% and for configuration O 13.24%

A lower level of machine reliability translates directly into a lower production capacity. Consequently, to reach a specific production volume at a lower level of machine reliability, the manufacturer needs to increase the number of machine tools in the system. To determine the minimum number of machines needed (both for the entire system as well as the subsystems of the RMS being designed), one can use the formula (1) given in Section 3. Assuming that the minimum daily demand is Q = 500 parts/day, working time per day is F_j = 60,000 s, and projected machine reliability is R = 75%, the number of machines in each of the subsystems of the RMS which manufactures the product shown in Figure 4 in five stages is:

- Stage I:

$$M_I = \frac{Q*t}{F_j*R}\cdot 100\% = \frac{500\ \ pc*222\ \ s/pc}{60000\ \ s\cdot 75\%}*100\% = 2.47 \Rightarrow 3 \tag{3}$$

- Stage II:

$$M_{II} = \frac{Q*t}{F_j*R}\cdot 100\% = \frac{500\ \ pc*102\ \ s/pc}{60000\ \ s\cdot 75\%}*100\% = 1.13 \Rightarrow 2 \tag{4}$$

- Stage III

$$M_{III} = \frac{Q*t}{F_j*R}\cdot 100\% = \frac{500\ \ pc*120\ \ s/pc}{60000\ \ s\cdot 75\%}*100\% = 1.33 \Rightarrow 2 \tag{5}$$

- Stage IV

$$M_{IV} = \frac{Q*t}{F_j*R}\cdot 100\% = \frac{500\ \ pc*90\ \ s/pc}{60000\ \ s\cdot 75\%}*100\% = 1.00 \Rightarrow 1 \tag{6}$$

Table 2. Reliability of the system under design (R_S) for various configurations as a function of machine reliability (R)

	Configuration							
R	**A**	**B**	**C**	**D**	**H**	**I**	**J**	**O**
100 %	100.000%	100.000%	100.000%	100.000%	100.000%	100.000%	100.000%	100.000%
95 %	99.7500%	99.4882%	99.4882%	94.7619%	94.2893%	94.2893%	90.0131%	85.3093%
90 %	98.9990%	97.9120%	97.9120%	89.0911%	87.3269%	87.3269%	80.1098%	71.4493%
85 %	97.7426%	95.2281%	95.2281%	83.0454%	79.3906%	79.3906%	70.3860%	58.6800%
80 %	95.9693%	91.4227%	91.4227%	76.6771%	70.7789%	70.7789%	60.9485%	47.1859%
75 %	93.6584%	86.5173%	86.5173%	70.0378%	61.7981%	61.7981%	51.9104%	37.0789%
70 %	90.7789%	80.5741%	80.5741%	63.1840%	52.7500%	52.7500%	43.3861%	28.4038%
65 %	87.2891%	73.6992%	73.6992%	56.1816%	43.9192%	43.9192%	35.4848%	21.1463%
60 %	83.1398%	66.0442%	66.0442%	49.1098%	35.5622%	35.5622%	28.3046%	15.2410%
55 %	78.2784%	57.8050%	57.8050%	42.0639%	27.8968%	27.8968%	21.9260%	10.5816%
50 %	72.6563%	49.2188%	49.2188%	35.1563%	21.0938%	21.0938%	16.4063%	7.0313%
45 %	66.2396%	40.5564%	40.5564%	28.5153%	15.2702%	15.2702%	11.7744%	4.4333%
40 %	59.0234%	32.1126%	32.1126%	22.2822%	10.4858%	10.4858%	8.0282%	2.6214%
35 %	51.0493%	24.1917%	24.1917%	16.6044%	6.7410%	6.7410%	5.1316%	1.4299%
30 %	42.4284%	17.0886%	17.0886%	11.6265%	3.9795%	3.9795%	3.0156%	0.7023%
25 %	33.3679%	11.0657%	11.0657%	7.4768%	2.0935%	2.0935%	1.5808%	0.2991%
20 %	24.2035%	6.3245%	6.3245%	4.2509%	0.9331%	0.9331%	0.7027%	0.1037%
15 %	15.4372%	2.9715%	2.9715%	1.9896%	0.3205%	0.3205%	0.2409%	0.0260%
10 %	7.7807%	0.9783%	0.9783%	0.6534%	0.0686%	0.0686%	0.0515%	0.0036%
5 %	2.2056 %	0.1356%	0.1356%	0.0904%	0.0046%	0.0046%	0.0035%	0.0001%

- Stage V

$$M_V = \frac{Q*t}{F_j*R}\cdot 100\% = \frac{500\ \ pc*198\ \ s/pc}{60000\ \ s\cdot 75\%}*100\% = 2.20 \Rightarrow 3 \qquad (7)$$

Table 3 shows, for each structure, how many machines (including division into subsystems) are needed to produce 500 parts per day, assuming that the machines differ in reliability. As the results show, a decline in machine reliability makes it necessary to expand the machine park (increase the number of machine tools at each stage of the system). Although the structure of the RMS does allow one to add new machine tools to the system, such a procedure generates extra costs related to the purchase of machines, adjusting the transport subsystem, and finding additional space.

As can be seen from Fig. 12, the increase in the number of necessary machine tools is relatively independent of the type of production structure. However, it has (for each configuration) the nature of an exponential function. While in the case of 85% machine reliability, the number of necessary machine tools is 8–9, when reliability drops to 50%, the minimum number of machine tools increases to 16–18.

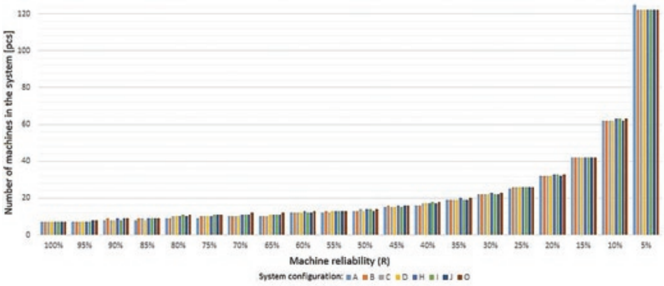

Fig. 12. Relationship between machine reliability (R) and the minimum number of machines in the system (M) required to execute the production plan

This means that there is a certain critical moment at which further expansion of the system becomes uneconomical.

An important issue, from the point of view of system operation in the planned life cycle, is also the reliability of the system which is being expanded as machine reliability declines. System reliabilities for the particular structures are shown in Fig. 13; they were calculated assuming that the system must be expanded to adjust its production capacity to demand (in the analyzed case, 500 parts/day) .

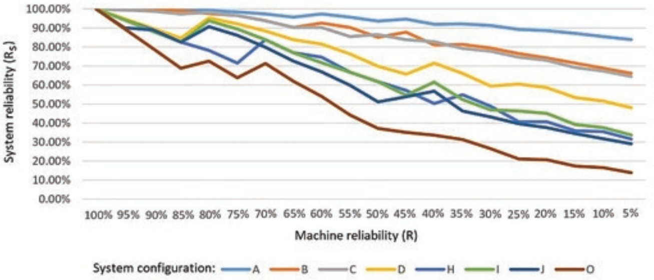

Fig. 13. Relationships between machine reliability (R) and reliability of the manufacturing system to which new machine tools are being added (R_s)

As can be seen from the graph above, despite the fact that new machine tools are being added as machine reliability decreases, the reliability of the system as a whole declines. While in the case of a two-stage system (configuration A), it only decreases to 83.92% (with machine reliability of 5%), in the case of a five-stage system (configuration O), system reliability drops to a dramatic 13.9% . This means that the type of production structure used directly determines the reliability of the reconfigurable manufacturing system being designed. Multi-stage systems are much more susceptible to decreases in reliability.

Table 3. Number of machine tools required for the implementation of the planned production program: (a) at individual stages of production, (b) in the entire manufacturing system

		Configuration							
R		**A**	**B**	**C**	**D**	**H**	**I**	**J**	**O**
100%	a)	2+5	2+2+3	2+3+2	2+1+4	2+2+1+2	2+1+2+2	2+1+1+3	2+1+1+1+2
	(b)	7	7	7	7	7	7	7	7
95 %	(a)	2+5	2+2+3	2+3+2	2+1+4	2+2+1+2	2+1+2+2	2+1+2+3	2+1+2+1+2
	(b)	7	7	7	7	7	7	8	8
90 %	(a)	3+5	3+3+3	3+3+2	3+1+4	3+3+1+2	3+1+2+2	3+1+2+3	3+1+2+1+2
	(b)	8	9	8	8	9	8	9	9
85 %	(a)	3+5	3+3+3	3+4+2	3+1+4	3+3+1+2	3+1+3+2	3+1+2+3	3+1+2+1+2
	(b)	8	9	9	8	9	9	9	9
80 %	(a)	3+6	3+3+3	3+4+3	3+2+5	3+3+1+3	3+2+3+3	3+2+2+3	3+2+2+1+3
	(b)	9	9	10	10	10	11	10	11
75 %	(a)	3+6	3+3+4	3+4+3	3+2+5	3+3+1+3	3+2+3+3	3+2+2+4	3+2+2+1+3
	(b)	9	10	10	10	10	11	11	11
70 %	(a)	3+7	3+3+4	3+4+3	3+2+5	3+3+2+3	3+2+3+3	3+2+2+4	3+2+2+2+3
	(b)	10	10	10	10	11	11	11	12
65 %	(a)	3+7	3+3+4	3+4+3	3+2+6	3+3+2+3	3+2+3+3	3+2+2+4	3+2+2+2+3
	(b)	10	10	10	11	11	11	11	12
60 %	(a)	4+8	4+4+4	4+5+3	4+2+6	4+4+2+3	4+2+3+3	4+2+2+4	4+2+2+2+3
	(b)	12	12	12	12	13	12	12	13
55 %	(a)	4+8	4+4+5	4+5+3	4+2+7	4+4+2+3	4+2+4+3	4+2+2+5	4+2+2+2+3
	(b)	12	13	12	13	13	13	13	13
50 %	(a)	4+9	4+4+5	4+6+4	4+2+7	4+4+2+4	4+2+4+4	4+2+2+5	4+2+2+2+4
	(b)	13	13	14	13	14	14	13	14
45 %	(a)	5+10	5+5+6	5+6+4	5+2+8	5+5+2+4	5+2+4+4	5+2+3+6	5+2+3+2+4
	(b)	15	16	15	15	16	15	16	16
40 %	(a)	5+11	5+5+6	5+7+5	5+3+9	5+5+2+5	5+3+5+5	5+3+3+6	5+3+3+2+5
	(b)	16	16	17	17	17	18	17	18
35 %	(a)	6+13	6+6+7	6+8+5	6+3+10	6+6+3+5	6+3+5+5	6+3+3+7	6+3+3+3+5
	(b)	19	19	19	19	20	19	19	20
30 %	(a)	7+15	7+7+8	7+9+6	7+3+12	7+7+3+6	7+3+6+6	7+3+4+8	7+3+4+3+6
	(b)	22	22	22	22	23	22	22	23
25 %	(a)	8+17	8+8+10	8+11+7	8+4+14	8+8+3+7	8+4+7+7	8+4+4+10	8+4+4+3+7
	(b)	25	26	26	26	26	26	26	26
20 %	(a)	10+22	10+10+12	10+13+9	10+5+17	10+10+4+9	10+5+9+9	10+5+5+12	10+5+5+4+9
	(b)	32	32	32	32	33	33	32	33
15 %	(a)	13+29	13+13+16	13+18+11	13+6+23	13+13+5+11	13+6+12+11	13+6+7+16	13+6+7+5+11
	(b)	42	42	42	42	42	42	42	42
10 %	(a)	19+43	19+19+24	19+26+17	19+9+34	19+19+8+17	19+9+18+17	19+9+10+24	19+9+10+8+17
	(b)	62	62	62	62	63	63	62	63
5 %	(a)	37+85	37+37+48	37+52+33	37+17+68	37+37+15+33	37+17+35+33	37+17+20+48	37+17+20+15+33
	(b)	125	122	122	122	122	122	122	122

4.2. Evaluation of expected productivity of the RMS under design

An important issue in designing a manufacturing system, apart from assessing its reliability, is to plan its production capacity, so that it can generate a specified volume of products. Considering the fact that the level of machine reliability decreases over the entire period of operation, both system productivity and the number and utilization rate of machine tools making up the system will also change. These factors may also determine the selection of the production structure of a RMS.

Table 4. Results of simulation experiments for a two-stage manufacturing system

R	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%
Configuration A												
	2+5											
P	500	500	482	455	428	400	372	346	319	293	266	238
M-I	92.50%	92.50%	90.30%	85.10%	80.30%	75.10%	70.30%	65.10%	60.30%	55.10%	50.30%	45.10%
M-II	85.00%	85.02%	82.38%	77.80%	73.08%	68.38%	63.96%	59.42%	54.86%	50.30%	45.70%	40.90%
	2+5	2+5	3+5	3+5	3+6	3+6	3+7	3+7	4+8	4+8	4+9	5+10
P	500	500	500	500	500	500	500	500	500	500	500	500
M-I	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-II	85.00%	85.02%	85.00%	85.00%	70.87%	70.87%	60.73%	60.73%	53.15%	53.15%	47.24%	42.50%

R – machine reliability, P – number of manufactured products, M-I – mean workload of machine tools in the first production stage, M-II – mean workload of machine tools in the second production stage,

Table 5. Results of simulation experiments for a three-stage manufacturing system

R	**100%**	**95%**	**90%**	**85%**	**80%**	**75%**	**70%**	**65%**	**60%**	**55%**	**50%**	**45%**
Configuration B												
	2+2+3											
P	500	500	479	450	422	388	357	331	310	273	264	238
M-I	92.50%	92.50%	90.30%	85.10%	80.30%	75.10%	70.30%	65.10%	60.30%	55.10%	50.30%	45.10%
M-II	92.50%	92.50%	89.60%	84.60%	79.60%	74.60%	69.60%	64.60%	59.60%	54.60%	49.60%	44.60%
M-III	80.03%	80.00%	76.83%	72.13%	67.77%	62.27%	57.43%	53.27%	50.03%	44.20%	42.50%	38.20%
	2+2+3	2+2+3	3+3+3	3+3+3	3+3+3	3+3+4	3+3+4	3+3+4	4+4+4	4+4+5	4+4+5	5+5+6
P	500	500	500	500	498	500	500	500	500	500	485	500
M-I	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-II	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-III	80.03%	80.00%	80.03%	80.03%	80.03%	60.00%	60.00%	60.00%	60.00%	47.98%	46.94%	39.97%
Configuration C												
	2+3+2											
P	500	500	481	454	430	400	373	346	319	292	265	238
M-I	92.50%	92.50%	90.30%	85.10%	80.30%	75.10%	70.30%	65.10%	60.30%	55.10%	50.30%	45.10%
M-II	86.63%	86.67%	84.03%	79.30%	74.90%	69.97%	65.27%	60.50%	55.87%	51.13%	46.47%	41.80%
M-III	82.50%	82.50%	79.60%	75.15%	71.15%	66.25%	61.70%	57.25%	52.75%	48.25%	43.85%	39.35%
	2+3+2	2+3+2	3+3+2	3+4+2	3+4+3	3+4+3	3+4+3	3+4+3	4+5+3	4+5+3	4+6+4	5+6+4
P	500	500	500	500	500	500	500	489	500	496	500	500
M-I	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-II	86.63%	86.67%	86.63%	65.00%	65.00%	65.00%	65.00%	64.97%	52.00%	52.00%	42.77%	43.37%
M-III	82.50%	82.50%	82.50%	82.50%	55.00%	55.00%	55.00%	53.87%	55.00%	54.80%	41.25%	41.25%
Configuration D												
	2+1+4											
P	500	500	481	452	427	396	372	345	318	288	263	237
M-I	92.50%	92.50%	90.30%	85.10%	80.30%	75.10%	70.30%	65.10%	60.30%	55.10%	50.30%	45.10%
M-II	85.00%	85.00%	82.50%	77.90%	73.30%	68.70%	64.10%	59.50%	54.90%	50.30%	45.70%	41.10%
M-III	85.00%	85.00%	82.05%	77.35%	72.87%	68.00%	63.65%	59.05%	54.47%	49.60%	45.22%	40.65%
	2+1+4	2+1+4	3+1+4	3+1+4	3+2+5	3+2+5	3+2+5	3+2+6	4+2+6	4+2+7	4+2+7	5+2+8
P	500	500	500	495	500	500	500	500	500	500	500	500
M-I	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-II	85.00%	85.00%	85.00%	85.00%	42.50%	52.50%	42.50%	42.50%	42.50%	42.50%	42.50%	42.50%
M-III	85.00%	85.00%	85.00%	84.70%	68.00%	68.00%	68.02%	56.67%	56.65%	48.59%	48.59%	42.50%

R – machine reliability, P – number of manufactured products, M-I–M-III – mean workloads of machine tools in production stages I to III,

Table 6. Results of simulation experiments for a four-stage manufacturing system

R	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%
Configuration H												
	2+2+1+2											
P	500	500	480	451	421	390	360	329	297	267	242	218
M-I	92.50%	92.50%	90.30%	85.10%	80.30%	75.10%	70.30%	65.10%	60.30%	55.10%	50.30%	45.10%
M-II	92.50%	92.50%	89.60%	84.60%	79.60%	74.60%	69.60%	64.60%	59.60%	54.60%	49.60%	44.60%
M-III	75.00%	75.00%	72.20%	68.10%	64.10%	60.20%	56.10%	52.10%	48.10%	44.00%	40.00%	35.90%
M-IV	82.50%	82.50%	79.20%	74.00%	69.65%	64.55%	59.50%	54.55%	49.25%	44.25%	40.30%	36.30%
	2+2+1+2	2+2+1+2	3+3+1+2	3+3+1+2	3+3+1+3	3+3+1+3	3+3+2+3	3+3+2+3	4+4+2+3	4+4+2+3	4+4+2+4	5+5+2+4
P	500	500	500	500	500	490	500	500	500	461	484	488
M-I	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-II	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-III	75.00%	75.00%	75.00%	75.00%	75.00%	75.00%	37.50%	37.55%	37.50%	37.50%	37.50%	37.50%
M-IV	82.50%	82.50%	82.50%	82.50%	55.00%	54.13%	55.00%	55.00%	55.00%	50.83%	40.30%	40.60%
Configuration I												
	2+1+2+2											
P	500	500	481	454	427	400	372	345	318	291	262	238
M-I	92.50%	92.50%	90.30%	85.10%	80.30%	75.10%	70.30%	65.10%	60.30%	55.10%	50.30%	45.10%
M-II	85.00%	85.00%	82.50%	77.90%	73.30%	68.70%	64.10%	59.50%	54.90%	50.30%	45.70%	41.10%
M-III	87.50%	87.55%	84.60%	79.90%	75.20%	70.40%	65.65%	60.95%	56.20%	51.50%	46.55%	42.00%
M-IV	82.50%	82.55%	79.45%	75.00%	70.55%	66.10%	61.60%	57.15%	52.70%	48.20%	43.50%	39.35%
	2+1+2+2	2+1+2+2	3+1+2+2	3+1+3+2	3+2+3+3	3+2+3+3	3+2+3+3	3+2+3+3	4+2+3+3	4+2+4+3	4+2+4+4	5+2+4+4
P	500	500	500	494	500	500	500	500	489	498	500	500
M-I	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-II	85.00%	85.00%	85.00%	85.00%	42.50%	42.00%	42.50%	42.50%	42.50%	42.50%	42.50%	42.50%
M-III	87.50%	87.55%	87.50%	58.37%	58.37%	58.37%	58.37%	58.37%	58.37%	43.80%	43.80%	43.80%
M-IV	82.50%	82.55%	82.50%	81.75%	55.00%	55.03%	55.00%	55.00%	54.10%	55.00%	41.27%	41.30%
Configuration J												
	2+1+1+3											
P	494	472	447	421	396	371	343	307	279	270	245	205
M-I	92.50%	92.50%	90.30%	85.10%	80.30%	75.10%	70.30%	65.10%	60.30%	55.10%	50.30%	45.10%
M-II	85.00%	85.00%	82.50%	77.90%	73.30%	68.70%	64.10%	59.50%	54.90%	50.30%	45.70%	41.10%
M-III	99.50%	95.00%	90.20%	85.20%	80.20%	75.10%	70.10%	65.00%	60.00%	54.90%	49.90%	44.90%
M-IV	79.33%	75.70%	71.90%	67.83%	63.67%	59.57%	55.10%	49.43%	45.03%	43.57%	39.57%	33.30%
	2+1+1+3	2+1+2+3	3+1+2+3	3+1+2+3	3+2+2+3	3+2+2+4	3+2+2+4	3+2+2+4	4+2+2+4	4+2+2+5	4+2+2+5	5+2+3+6
P	494	500	500	495	498	500	500	498	493	500	465	500
M-I	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-II	85.00%	85.00%	85.00%	85.00%	42.50%	42.50%	42.50%	42.55%	42.50%	42.50%	42.50%	42.50%
M-III	99.50%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	49.90%	50.00%	49.90%	33.30%
M-IV	79.33%	80.00%	80.03%	79.36%	80.03%	60.00%	60.00%	59.95%	59.45%	47.98%	45.10%	39.98%

R – machine reliability, P – number of manufactured products, M-I–M-IV – mean workloads of machine tools in production stages I to IV

Table 7. Results of simulation experiments for a five-stage manufacturing system

R	100%	95%	90%	85%	80%	75%	70%	65%	60%	55%	50%	45%
	Configuration O											
	2+1+1+2											
P	494	472	442	413	386	361	334	305	280	256	226	200
M-I	92.50%	92.50%	90.30%	85.10%	80.30%	75.10%	70.30%	65.10%	60.30%	55.10%	50.30%	45.10%
M-II	85.00%	85.00%	82.50%	77.90%	73.30%	68.70%	64.10%	59.50%	54.90%	50.30%	45.70%	41.10%
M-III	99.50%	95.00%	90.20%	85.20%	80.20%	75.10%	70.10%	65.00%	60.00%	54.90%	49.90%	44.90%
M-IV	74.50%	71.10%	67.50%	63.70%	59.30%	54.90%	50.60%	64.20%	42.20%	38.60%	35.10%	31.70%
M-V	81.70%	77.95%	73.10%	68.40%	64.00%	59.90%	55.30%	50.00%	46.20%	42.25%	37.45%	33.10%
	2+1+1+1+2	2+1+2+1+2	3+1+2+1+2	3+1+2+1+2	3+2+2+1+3	3+2+2+1+3	3+2+2+2+3	3+2+2+2+3	4+2+2+2+3	4+2+2+2+3	4+2+2+2+4	5+2+3+2+4
P	494	500	500	485	500	496	500	500	500	459	452	488
M-I	92.50%	92.50%	61.67%	61.67%	61.67%	61.67%	61.67%	61.67%	46.30%	46.30%	46.30%	37.00%
M-II	85.00%	85.00%	85.00%	85.00%	42.50%	42.50%	42.50%	42.50%	42.50%	42.50%	42.50%	42.50%
M-III	99.50%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	50.00%	49.90%	33.30%
M-IV	74.50%	75.00%	75.00%	75.00%	75.00%	75.00%	37.55%	37.55%	37.50%	37.50%	35.10%	37.50%
M-V	81.70%	82.00%	82.50%	80.30%	55.00%	54.70%	55.03%	55.00%	55.00%	50.77%	37.50%	40.60%

R – machine reliability, P – number of manufactured products, M-I–M-V – mean workloads of machine tools in production stages I to V

To assess how the decrease in machine reliability affects the expected productivity of the RMS under design, computer simulation analyses were conducted, which are one of the basic tools used in this type of problems [15,36]. Simulations were performed using Enterprise Dynamics 7.0 software from Incontrol Simulation Solutions. A model of the system was developed for each of the production structures (Figure 14), and simulation of production was performed for a period corresponding to the working time per day (60,000 seconds), in which the reliability of machine tools was reduced in 5% increments. Aspects related to the operation of the transport and storage subsystems were ignored.

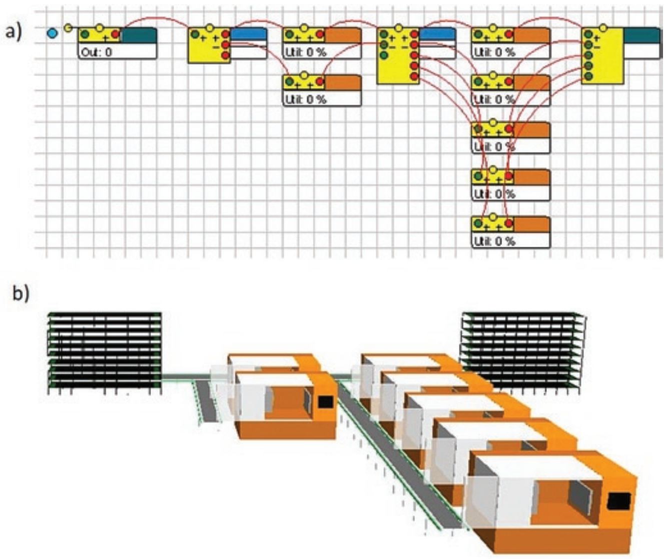

Fig. 14. Example of a simulation model for configuration A developed using Enterprise Dynamics software: a) a 2D model of the machine tool sub-system , b) 3D visualization of the system

Productivity analyses were carried out for:

- systems with a baseline structure in which all machines and devices were characterized by 100% reliability (see Section 3).
- expanded systems to which new machine tools were added as the reliability of the machines and devices already in use decreased (see Table 3).

In the case of the "expanded" systems, simulation experiments were carried out for structures containing a maximum of 16 machine tools with reliabilities of not less than 45%. To assess the reproducibility of the obtained results, the simulation experiments were carried out in five replicates for each system. Mean results are shown in Tables 4–7.

As the results show, the expected system productivity decreases with the declining reliability of the machines in the machine tool subsystem (Fig. 15). Nevertheless, in contrast to system reliability, the decrease in expected productivity is similar for each of the analyzed structures and is almost proportional (see Fig. 10). This means that

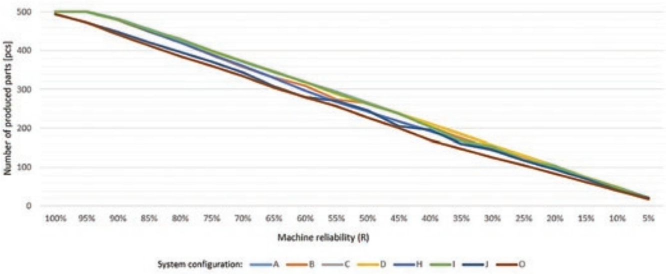

Fig. 15. Relationship between the number of manufactured products (P) and the reliability of the machines in the machine tool subsystem (R)

in designing an RMS, it is not enough to analyze system reliability alone, because such an analysis does not provide a full picture of attainable productivity, which is a fundamental issue from the point of view of system operation.

The key problem is the fact that expansion does not always allow the system to generate a specified volume of products. It is possible then that despite methodological correctness of the design, the system will not have enough production capacity to meet the current demand. This means that the analytical methods used at the stage of system design are insufficient, and the results obtained with their use must be verified using simulation methods.

In the case under analysis, the only configuration that ensures a required production capacity is configuration A. Taking into account the results of the reliability analyses (Section 4.1) – this structure is the preferred one as it guarantees stable production over the entire lifetime of the system.

5. Conclusions and further research

Selection of the right production structure is the key element in the process of designing any manufacturing system as what structure is used has long-term implications for the efficiency, productivity and operating costs of the system being designed. This also applies to reconfigurable manufacturing systems, which are currently one of the main focuses of research in the area of designing modern production systems.

In the present study, an attempt was made to assess the structures of a designed RMS system from the point of view of changes in the reliability of its component machines. As the analyses show, the type of system configuration has a direct impact on the reliability of the system as a whole. System reliability changes in a disproportionate way along with changing reliability of the machines and production equipment which make up the system. Importantly, as demonstrated by the simulation experiment, changes in system reliability are not reflected in the system's expected productivity, which (although it does decline with decreasing machine reliability) is relatively independent of the type of production structure. Importantly, a system which theoretically can reach the required level of efficiency may not be able to attain the assumed production volume. To verify the productivity of the designed system and eliminate errors which cannot be identified using analytical methods, one needs to perform simulation tests.

The present results also show that RMS structures with fewer production stages are the preferred type of structure because they ensure process stability. Unfortunately, these structures are based on multitask machine tools, which automatically makes them more expensive. Therefore, the process of selecting production structures should be accompanied by multicriteria analyses, which make it possible to minimize the costs of constructing and operating the system, while taking into account the required performance characteristics as well as operational, technical and organizational limitations.

As part of further research, we plan to carry out performance analyses taking into account the varied reliability of machines and devices (especially in the process of expanding an RMS) and the impact of the reliability of means of internal transport on the productivity of a designed reconfigurable manufacturing system.

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