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## Scalability analysis of selected structures of a reconfigurable manufacturing system taking into account a reduction in machine tools reliability

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### Highlights

- The impact of a decline in the reliability of machine tools on the scalability of a RMS was assessed.
- Two-, three-, four- and five-stage RMS structures were analyzed.
- To identify bottlenecks and evaluate RMS productivity computer simulation methods were used.
- The highest level of scalability was observed for the largest numbers of manufacturing stages.
- The most stable level of reliability of the entire RMS was obtained for the lowest number of stages.

### Abstract

Scalability is a key feature of reconfigurable manufacturing systems (RMS). It enables fast and cost-effective adaptation of their structure to sudden changes in product demand. In principle, it allows to adjust a system's production capacity to match the existing orders. However, scalability can also act as a "safety buffer" to ensure a required minimum level of productivity, even when there is a decline in the reliability of the machines that are part of the machine tool subsystem of a manufacturing system. In this article, we analysed selected functional structures of an RMS under design to see whether they could be expanded should the reliability of machine tools decrease making it impossible to achieve a defined level of productivity. We also investigated the impact of the expansion of the system on its reliability. To identify bottlenecks in the manufacturing process, we ran computer simulations in which the course of the manufacturing process was modelled and simulated for 2-, 3-, 4- and 5-stage RMS structures using Tecnomatix Plant Simulation software.

### Keywords

reconfigurable manufacturing system, RMS, scalability, configuration, production structure, reliability, simulations, Tecnomatix Plant Simulation.

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## 1. Introduction

At the end of the 20th century, manufacturing companies entered a new era, which, on the one hand, offered tremendous technical and IT solutions, but, on the other, brought them into competition with other firms not only on a local and national, but also on a global level [11]. To meet the requirements of the market, enterprises have to manufacture a wide range of products, constantly adjusting their product offerings to the changing demand. In order to maintain an appropriate level of competitiveness, companies must use manufacturing systems that allow to produce good quality commodities at a low production cost and quickly make the necessary changes to adapt to the incoming customer orders [14, 27]. These requirements can only be met by systems that combine the functional features of high-performance distributed manufacturing systems (DMS) and flexible manufacturing systems (FMS), and are, at the same time, scalable and dedicated to the processing of a particular family of products [3].

At the turn of the 21st century, a new concept of reconfigurable manufacturing systems (RMS) was developed to overcome the limitations of DMS and FMS. RMS, by definition, are designed for rapid

change in structure that allows to adjust the system's functionality and production capacity to the current production requirements [22]. RMS, as a modern class of manufacturing systems, have an adaptive structure – both with regard to their hardware and software components, and are characterized by six core features: modularity, integrability, customized flexibility, diagnosability, convertibility, and scalability [7,39]. These characteristics provide a framework for the design of reconfigurable machine tools and reconfigurable controllers, the use of which allows to reduce the time-to-market and the costs of reconfiguring the manufacturing system [6].

Among these six characteristics, scalability is the one that is the most important from the point of view of the possibility of adapting a system to uncertain market changes by adjusting/ reconfiguring machines and/or the structure of the manufacturing processes [8]. Scalability is also a feature that allows to further optimize manufacturing systems and provides a basis for creating new manufacturing system paradigms focused on sustainable development and social welfare [32]. Moreover, scalability can be viewed as a buffer that allows to rapidly adjust a system's productivity in the event of a decrease in

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the reliability of its component machines and devices [9, 34].

Although from a technical and economic perspective, the scalability of a system should be defined at the stage of its design [23], this feature may actually be used for the analysis and optimization of the system's functioning throughout its service life [16]. As a rule, each manufacturing system is designed for a specific lifetime, which means that it should maintain an appropriate level of productivity throughout this period [31]. However, over time, the reliability of any technical system is bound to decrease [4, 21]. Given this, a system should have reserve production capacity as a buffer against a planned decrease in system reliability [38] or be designed so that the missing production capacity can be easily and cheaply offset [25, 29]. What is also important here are issues related to the nature and effectiveness of maintenance activities, which directly affect the dynamics of the decrease in a technical system's reliability level [10, 19].

In the case of RMS, a decline in reliability can be compensated for by adding new machine tools to the system to maintain an appropriate level of productivity [33]. Unfortunately, this type of solution entails costs related to both purchasing machine tools and securing appropriate production space. In this paper, we analyze the impact of reduced machine reliability on changes in the number of machines in a system and the system's reliability level. In particular, we examine selected system structures with different numbers of stages and different flexibility of machine tools. The study was conducted using computer simulation methods which are broadly applied in testing design assumptions in the processes of designing manufacturing systems, identifying bottlenecks, and increasing the efficiency of manufacturing systems (see, e.g. [20, 24]).

## 2. Scalability of RMS – a literature review

In designing manufacturing systems, designers focus on optimal selection of the systems' physical components, such as machine tools and means of in-plant transport, and their optimal arrangement, in order to meet pre-defined production requirements [2]. In the case of an RMS, these requirements may include optimization of the system's modular structure (which allows to reconfigure the system), optimal selection of the system's structure, and development of a system design that can accommodate changes in production demand.

A typical RMS consists of up to 20 stages with the machine tools of each stage having identical functional features (Fig. 1). In the machining process, parts are moved from one stage to the next using conveyors or overhead cranes. They are processed using CNC machine tools and/or RMS [8].

In order to adjust a system's production capacity (throughput) to changes in the needs of the market, the structure of the system must be reconfigured quickly and cost-effectively [1]. Production capacity is scaled in small and frequent discrete steps to smoothly adjust the system's functionality and throughput to match changes in customer demand [30]. As demonstrated by Putnik and colleagues [32], in practice, scalable capacity can be achieved by adding

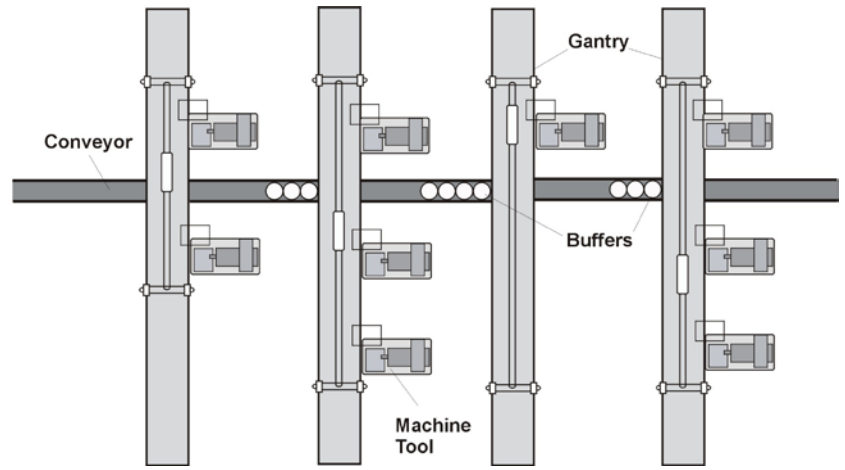


Fig. 1. Schematic of the arrangement of the structural components of an RMS (diagram prepared by the authors based on: [13])

or removing specific machines, which is possible due to the parallel arrangement of the components of an RMS structure (Fig. 2).

Production capacity planning, understood as a problem of optimal adjustment of production capacity to the existing production needs and tasks, has been the subject of interest of numerous researchers in the last 40 years. The first studies on increasing systems' production capacity were carried out by Manne [28], and later elaborated on by Luss [26] and many other scholars (see e.g. [17, 41]). Their approach, however, was static. Considering that modern production systems have to deal with a rapidly changing and uncertain demand and that there are constant advancements in methods of designing manufactur-

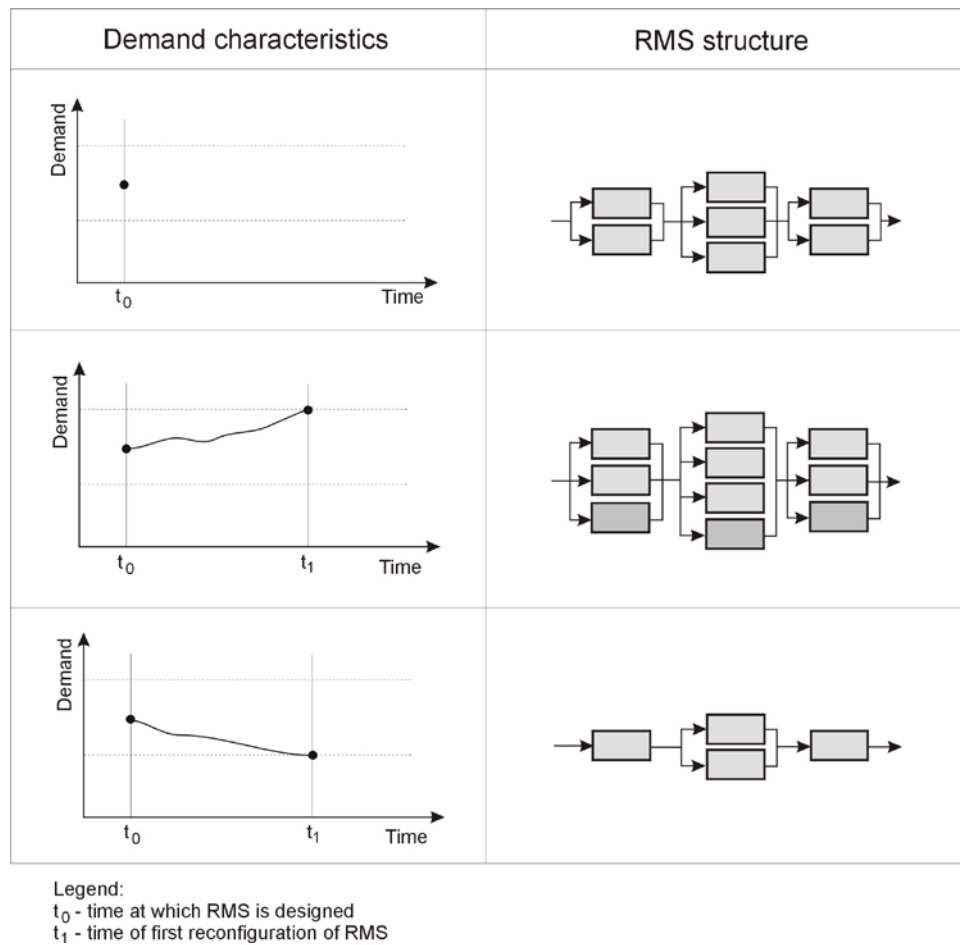


Fig. 2. Graphical illustration of RMS scalability based on [13]

ing systems, the problem of production capacity planning must be analyzed using a dynamic approach.

A review of the literature on scalability of manufacturing systems shows that there are two main lines of research in this area [8]:

1. design of RMS focused on increasing their scalability level, and
2. capacity planning using the scalability of RMS to adapt their production throughput to the existing demand.

Research on RMS design has been conducted, among others, by Spicer et al. [36], who investigated the problem of the impact of different system configurations (i.e. different degrees to which machines are arranged in parallel in a system's  $n$ -stage structures) on the system's productivity and production capacity. Son et al. studied the problems of stage paralleling and line balancing from the point of view of productivity and scalability of a production line. They showed that a completely balanced production line and an RMS could achieve an almost identical throughput, and that even an unbalanced RMS system generated smaller steps of production capacity changes than a balanced production line. Based on the results of a simulation study, Deif and ElMaraghy [12] proposed a new model for assessing system structures for different changing market demand scenarios. Wang and Koren [40] defined the scalability of a production system as its smallest possible incremental capacity change, and determined the relationship between the magnitude of this change and a system's scalability. Putnik et al. [32] conducted an extensive literature review in which he showed how Wang and Koren's method could be used to assess *a posteriori* the scalability level of different configurations of RMS by comparing the throughput gain obtained for a specified number of additional machines or the cost needed to achieve a given level of productivity. Their conclusion was that a system's throughput and gain were higher in structures with a smaller number of stages. More recently, Hu et al. [18] analyzed the problem of joint optimization of production planning and adjustment of a system's production capacity based on product specifications, delivery time constraints and reconfigurable machine capabilities for assembly systems. Finally, Cerques et al. proposed their own metrics to evaluate the scalability of RMS by taking into account the parameters used for balancing operations on each stage of a production system [8].

The review of the literature shows that there are a large number of studies devoted to the problem of selecting an appropriate system structure in designing RMS. However, the focus of these studies is on the optimization of productivity and production capacity and their adaptation to the changing market demand. Unfortunately, the existing literature does not offer any empirical analyses of the impact of the decrease in the reliability of machine tools on the scalability of RMS over the system's entire service life, which is a large research gap.

To fill in this gap in research, we addressed the decision-making problem of choosing an appropriate RMS structure in experiments in which we evaluated selected RMS structures, taking into account the

decrease in the level of reliability of machine tools during the system's service life. We used computer simulation methods and techniques for calculating the reliability of complex systems with hybrid structures, which permit to verify research assumptions without the need to build a physical model (a demonstrator). The goal of the study was to answer the question of how a decrease in the reliability of machine tools affects the need for expanding a scalable RMS and how it influences its reliability depending on the system's functional structure.

### 3. Research problem

In this study, which is a continuation of our earlier research reported in [15], we considered the problem of selection of the production structure of an RMS. As part of this study, we analyzed the structures of the RMS dedicated to the machining of body-type parts presented in article [22]. The decision-making problem under study can be formulated in the following way:

*A machine manufacturing company that provides machining services is planning to launch a new RMS production line for machining parts. The goal is to design an RMS dedicated to the machining of a body-type part (Fig. 4) which is produced in a technological process that encompasses five operations performed on two faces of the part, each face requiring separate fixturing (Fig. 4 b). The system under design should be capable of manufacturing a minimum of 500 parts a day. The working time per day for the RMS ( $F_j$ ) is 1000 seconds.*

*Over time, the reliability of the individual machines decreases, which leads directly to a reduction in the system's productivity. If the existing system is not capable of producing 500 parts a day, it is expanded by adding another (new) machine tool at an appropriate location in the production line (a bottleneck). The main goal of this study was to find answers to the following questions.*

- 1) *How will the system be expanded (how many machine tools will be added in what locations) for each of the analyzed structures as the reliability of the machine tools decreases?*
- 2) *What level of reliability will the system achieve (for each structure) as it is scaled to the required productivity level?*

These questions need to be answered to identify the structures of the RMS under design that allow to maintain the assumed level of productivity while the level of reliability of machine tools decreases and new machines are added to the system.

### 4. Methods and results

As previous analyses and research findings for the analyzed RMS (see [15, 22]) show, the required productivity level of 500 parts a day can be achieved (assuming that all machine tools are 100% reliable) using one of the eight structures shown in Fig. 4. Because the production process must be carried out using at least two workholding fixtures (one for the execution of operation No. 10 and at least one for operations No. 20–50), we analyzed structures with from two (where operations No. 20–50 are executed using one type of multi-task ma-

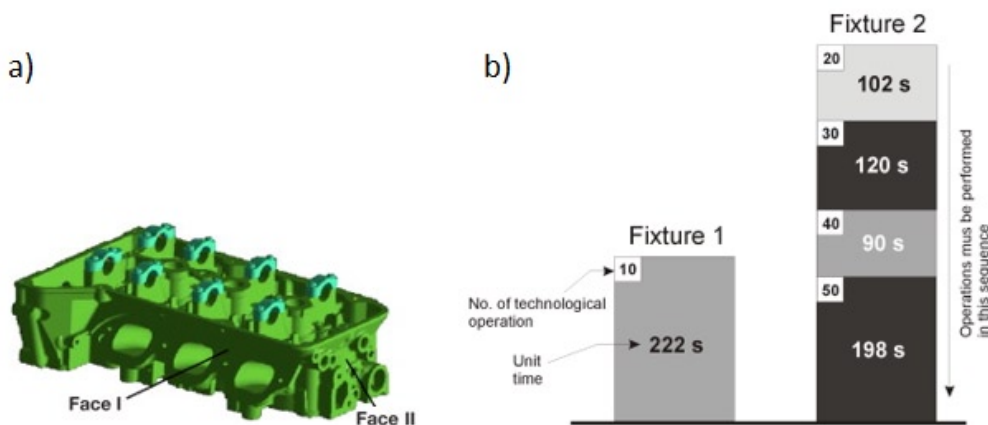


Fig. 3. Body-type part : a) general schematic view of the product, b) structure of the product's technological process

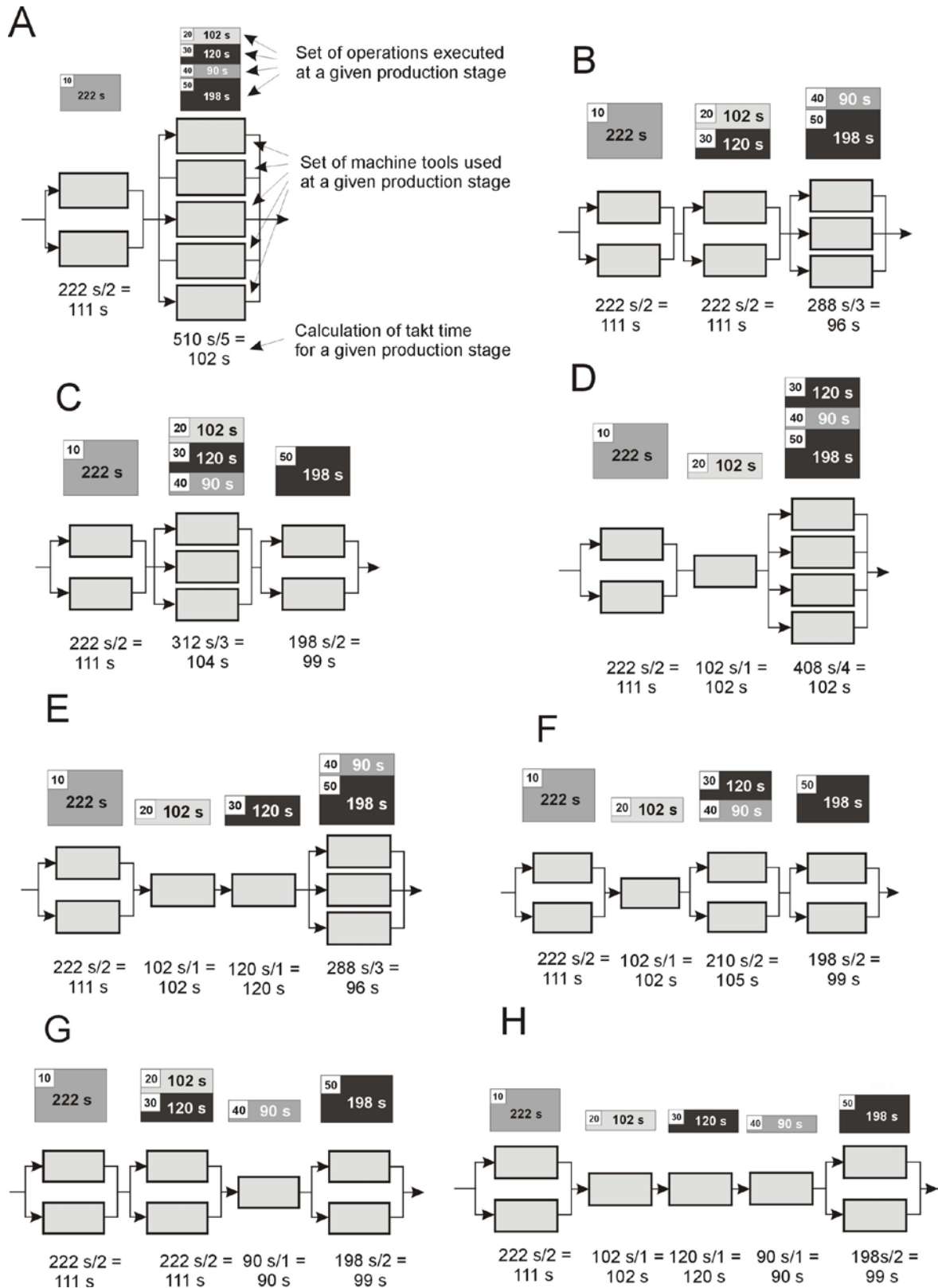


Fig. 4. RMS structures analyzed in this study

chines) to five stages (where each operation is performed on a different machine tool in the sequential stages of the process).

To answer the questions formulated in point 3, we carried out studies in which we:

- identified bottlenecks in the individual systems to find locations for system expansion in the event the reliability of the individual machine tools should decrease preventing the system from achieving the required productivity level;

- calculated the system's reliability level for each structure, taking into account the necessity of expanding the system to meet the existing production demand.

#### 4.1. Analysis of the scalability of selected RMS structures as related to a decrease in system reliability

The scalability of an RMS, apart from allowing to dynamically adjust the system's structure to the existing production demand, also

plays an important role as a “safety buffer” against wear and aging of the system’s machines. Operation of any technical system is associated with a decrease in reliability, which translates into a reduction in its efficiency and productivity. In systems such as RMS, which ensure a short time-to-market and lower system expansion costs, the missing production capacity can be offset by adding new machines that will allow to execute the required production tasks. Obviously, excessive expansion of a system entails additional costs associated with purchasing machines and expanding the in-plant transport system as well as the need to find additional production space. This factor must be taken into account when selecting an appropriate system structure at the stage of designing an RMS.

We analyzed how a decline in the reliability of machine tools affected the expansion of the machine tool subsystem of the designed RMS for each of the eight structures shown in Fig. 4. To determine the impact of the decrease in reliability on the system’s scalability, we assumed that the reliability of each machine tool was reduced by 1% in each observation period (this value was assumed to be sufficient to reliably interpret the results). Computer simulations were run to assess the impact of the decrease in reliability on the system’s productivity. A Tecnomatix Plant Simulation model of the RMS was created for each of the eight structures, and a simulation of system operation was run, which covered a 1000-minute production period at a predefined level of reliability of the machine tools used in the production subsystem. An example of a model of the RMS developed for structure C (reliability level of 95%) is shown in Fig. 5.

In the context of the design requirements defined earlier, the overriding goal is to maintain the system’s production capacity at the level of minimum 500 parts per working day. When such a production volume cannot be obtained, it is necessary to identify the bottleneck (i.e. the production stage in which the machine tools have lost the ability to produce the specific number of products) and to eliminate it by “supplying” an additional machine tool that will provide reserve production capacity for the system’s remaining service life. In this present study, it was assumed that each time the RMS’s reliability is reduced, a new machine (with a 100% reliability level) with a functionality identical to that of the other machines at a particular stage of the system’s struc-

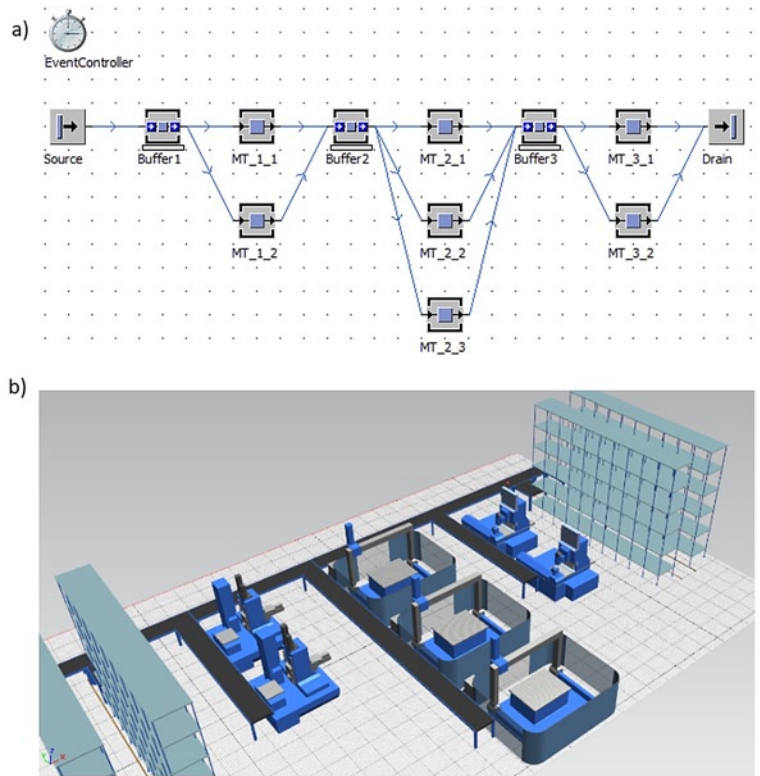


Fig. 5. A Tecnomatix Plant Simulation model for structure C: a) two-dimensional model of the machine tool subsystem, b) 3D visualization of the RMS

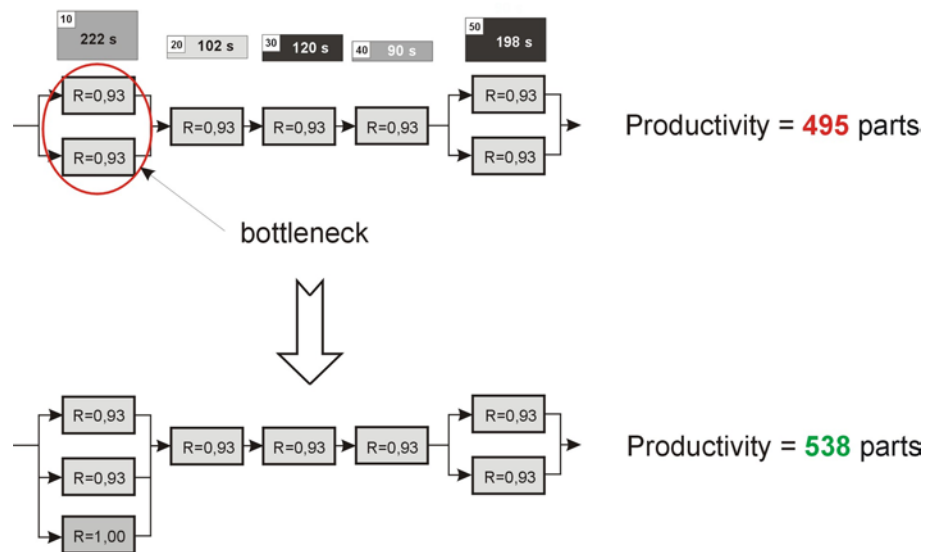


Fig. 6. Process of expanding the production structure of the RMS

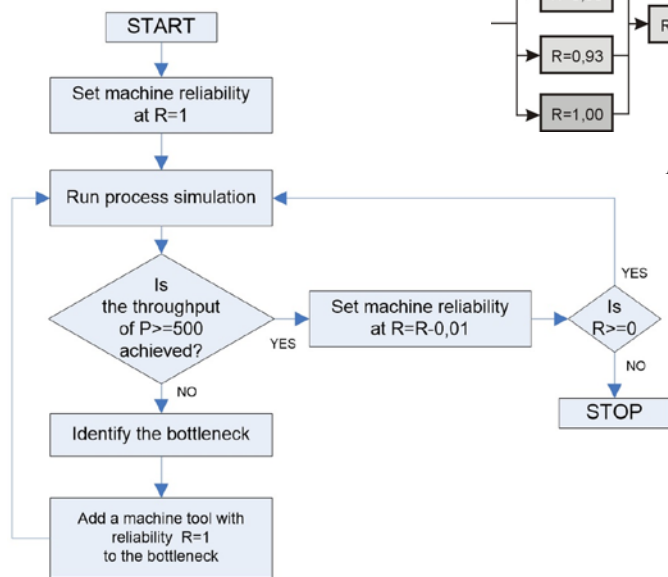


Fig. 7. Algorithm for scaling RMS in the event of reduction in machine tool reliability

ture is added to the system. For example, in the case of structure H, a drop in reliability of the base machines (machines that were originally in the system) to 93% makes it impossible to achieve a throughput of 500 parts (the system’s productivity at this level of machine reliability is 495 pcs.). To compensate for this reduction, a new machine tool has to be added to stage I of the process, which is the bottleneck (Fig. 6). A general algorithm for the assessment of the impact of the decrease in machine reliability on system expansion is shown in Fig. 7.

Simulation experiments were carried out for each of the structures, in which the level of reliability of the base machines was reduced to from 99% to 1%. The results regarding the number of machine tools in each structure and the level of system productivity obtained are shown in Table 1 (to increase the transparency of the data, the tables show experimental and calculation results for every 5% decrease in reliability).

Table 1. System productivity and number of machine tools required to achieve the desired production target (with a division into production stages)

R	Configuration							
	A	B	C	D	E	F	G	H
1.00	2+5	2+2+3	2+3+2	2+4+1	2+1+2+3	2+1+2+2	2+2+1+2	2+1+2+1+2
	534	534	534	534	534	534	534	534
0.95	2+5	2+2+3	2+3+2	2+1+4	2+1+2+3	2+1+2+2	2+2+1+2	2+1+2+1+2
	509	508	509	506	508	508	506	506
0.90	3+5	3+3+3	3+3+2	3+1+4	3+1+2+3	3+1+2+2	3+3+1+2	3+1+2+1+2
	525	561	514	523	522	509	544	518
0.85	3+6	3+3+3	3+4+2	3+2+5	3+2+2+3	3+2+3+2	3+3+1+2	3+2+2+1+2
	616	531	514	646	531	514	514	514
0.80	3+6	3+3+4	3+4+3	3+2+5	3+2+2+4	3+2+3+3	3+3+1+3	3+2+2+1+3
	581	656	635	607	654	660	533	533
0.75	3+6	3+3+4	3+4+3	3+2+5	3+2+2+4	3+2+3+3	3+3+2+3	3+2+2+2+3
	545	614	600	572	615	619	621	617
0.70	3+6	3+3+4	3+4+3	3+2+5	3+2+2+4	3+2+3+3	3+3+2+3	3+2+2+2+3
	508	565	555	530	561	574	578	564
0.65	3+7	3+3+4	3+4+3	3+2+6	3+2+2+4	3+2+3+3	3+3+2+3	3+2+2+2+3
	540	533	522	541	526	531	532	521
0.60	4+7	4+3+4	4+5+3	4+2+6	4+2+2+4	4+2+3+3	4+4+2+3	4+2+2+2+3
	546	502	98	601	541	541	598	588
0.55	4+7	4+4+5	4+5+3	4+2+6	4+2+2+5	4+2+2+3	4+4+2+3	4+2+2+2+3
	504	697	553	552	549	503	553	540
0.50	4+8	4+4+5	4+5+3	4+2+6	4+2+3+5	4+2+4+3	4+4+2+3	4+2+3+2+4
	574	647	508	512	633	508	508	641
0.45	4+8	4+4+5	4+5+4	4+2+7	4+2+3+5	4+2+4+4	4+4+2+4	4+2+3+2+4
	527	594	526	600	574	601	599	578
0.40	4+9	4+4+5	4+6+4	4+2+7	4+2+3+5	4+2+4+4	4+4+2+4	4+2+3+2+4
	553	541	555	533	533	543	541	520
0.35	5+9	5+4+6	5+6+4	5+3+7	5+3+3+6	5+3+4+4	5+5+2+4	5+3+3+2+4
	546	501	607	506	697	563	626	624
0.30	5+10	5+5+6	5+6+4	5+3+8	5+3+3+6	5+3+4+4	5+5+2+4	5+3+3+2+4
	609	642	547	597	642	505	560	559
0.25	5+10	5+5+6	5+7+4	5+3+8	5+3+3+6	5+3+5+4	5+5+3+4	5+3+3+3+4
	551	582	510	536	577	513	510	507
0.20	5+11	5+5+6	5+7+5	5+3+9	5+3+3+6	5+3+5+5	5+5+3+5	5+3+3+3+5
	561	511	563	564	511	563	559	533
0.15	6+11	6+5+7	6+7+5	6+3+9	6+4+4+7	6+3+5+5	6+6+4+5	6+3+4+3+5
	544	504	537	560	661	577	663	655
0.10	6+12	6+6+7	6+8+5	6+3+10	6+4+4+7	6+3+5+5	6+6+4+5	6+3+4+3+5
	592	575	590	620	586	506	585	573
0.05	6+12	6+6+7	6+8+5	6+3+10	6+4+4+7	6+3+6+5	6+6+4+5	6+3+4+3+6
	527	503	516	538	514	510	511	519

Legend:

2+2+3	- system configuration (number of machine tools in each stage of the process)
508	- system productivity (number of products manufactured in 1000 minutes)

An analysis of the data given in Figure 8 shows that the largest number of machine tools had to be added to structures with the largest number of stages (configurations E, F, G, and H) to ensure the required production capacity level. Regardless of the level of decrease

in machine reliability, in all cases, the smallest number of machine tools were added to the system with the smallest number of stages (structure A).

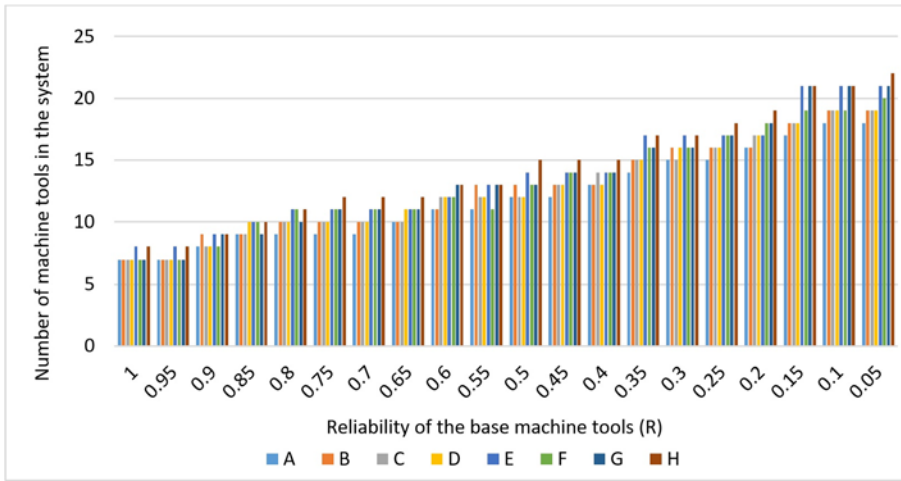


Fig. 8. Relationship between the number of machine tools in the system and reliability of the base machine tools

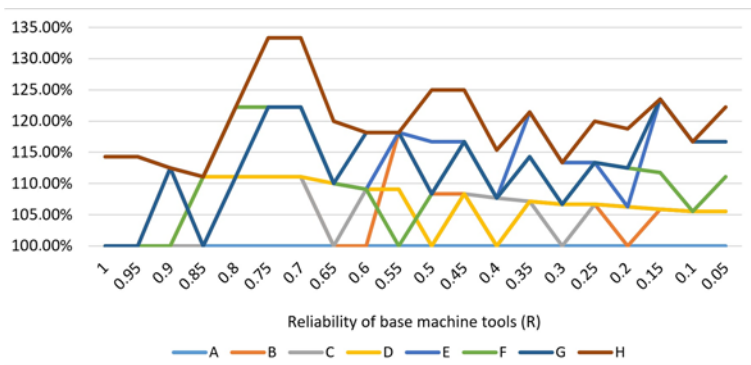


Fig. 9. A graph showing the percent increase in the number of machine tools in the individual RMS structures relative to structure A

The largest percent difference in the number of machine tools in relation to structure A was observed for structure H, which had the largest number of stages (Table 2, Fig. 9). The average percent increase in the number of machines relative to structure A ranged from 5.21% to 6.27% for the three-stage structures (B, C, and D), and from 5.35% to 12.32% for the four-stage structures (E, F and G). The system with structure H (a five-stage structure) used 19.82% more machine tools than the system with two stages (the largest difference of 33.33% was found for machine tool reliability level of 70–75% (Table 2).

An important factor that needs to be considered in assessing RMS structures is the impact of scalability of a system on its productivity. In the case under study, the system is expanded by adding a new machine tool at a location identified as a bottleneck when the decrease in machine reliability makes it impossible to achieve the productivity level of 500 items per 1000 min

(a day). Expansion of a system allows to maintain a required level of production capacity and, in many cases, also to build up production reserves as a buffer against a further decrease in productivity resulting from the aging of machines.

A system's scalability, in accordance with the principles of RMS, permits to dynamically adjust production capacity to the current production demand. To evaluate the impact of the investigated system's scalability on its productivity, simulation experiments were carried out for each structure in accordance with the algorithm presented in Fig. 5. The results are given in Figure 10

As shown in Figure 10, the system's productivity (production capacity) increases stepwise as new machine tools are added to the system. However, it increases slightly differently for each of the structures. When the increase in production capacity is

Table 2. Percent increase in the number of machine tools in the individual RMS structures relative to structure A

R	B	C	D	E	F	G	H
1	0.00%	0.00%	0.00%	14.29%	0.00%	0.00%	14.29%
0.95	0.00%	0.00%	0.00%	14.29%	0.00%	0.00%	14.29%
0.9	12.50%	0.00%	0.00%	12.50%	0.00%	12.50%	12.50%
0.85	0.00%	0.00%	11.11%	11.11%	11.11%	0.00%	11.11%
0.8	11.11%	11.11%	11.11%	22.22%	22.22%	11.11%	22.22%
0.75	11.11%	11.11%	11.11%	22.22%	22.22%	22.22%	33.33%
0.7	11.11%	11.11%	11.11%	22.22%	22.22%	22.22%	33.33%
0.65	0.00%	0.00%	10.00%	10.00%	10.00%	10.00%	20.00%
0.6	0.00%	9.09%	9.09%	9.09%	9.09%	18.18%	18.18%
0.55	18.18%	9.09%	9.09%	18.18%	0.00%	18.18%	18.18%
0.5	8.33%	0.00%	0.00%	16.67%	8.33%	8.33%	25.00%
0.45	8.33%	8.33%	8.33%	16.67%	16.67%	16.67%	25.00%
0.4	0.00%	7.69%	0.00%	7.69%	7.69%	7.69%	15.38%
0.35	7.14%	7.14%	7.14%	21.43%	14.29%	14.29%	21.43%
0.3	6.67%	0.00%	6.67%	13.33%	6.67%	6.67%	13.33%
0.25	6.67%	6.67%	6.67%	13.33%	13.33%	13.33%	20.00%
0.2	0.00%	6.25%	6.25%	6.25%	12.50%	12.50%	18.75%
0.15	5.88%	5.88%	5.88%	23.53%	11.76%	23.53%	23.53%
0.1	5.56%	5.56%	5.56%	16.67%	5.56%	16.67%	16.67%
0.05	5.56%	5.56%	5.56%	16.67%	11.11%	16.67%	22.22%
Mean	5.93%	5.21%	6.27%	15.35%	10.19%	12.32%	19.82%

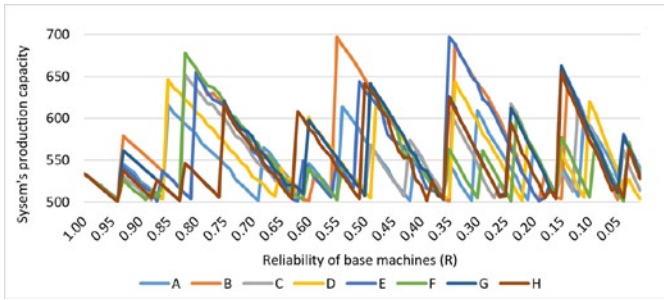


Fig. 10. Productivity of the RMS as a function of the reliability of the base machine tools (taking into account system scalability)

considered over the range from 100% ( $R = 1.00$ ) to 1% ( $R = 0.01$ ) machine reliability, the smallest “leaps” in production capacity are observed for structure A (from 502 to 616 pcs/1000 min of system operation). The largest spread is observed for structures B and E (from 501 to 697 pcs/1000 min.). The mean productivity values for the analyzed scenarios are as follows: structure A: 543 pcs/1000 min, Structure B: 568 pcs/1000 min, Structure C: 549 pcs/1000 min, Structure D: 552 pcs/1000 min, Structure E: 562 pcs/1000 min, Structure F: 555 pcs/1000 min, Structure G: 549 pcs. A graphic interpretation of the statistical analysis of the results is shown in Fig. 11.

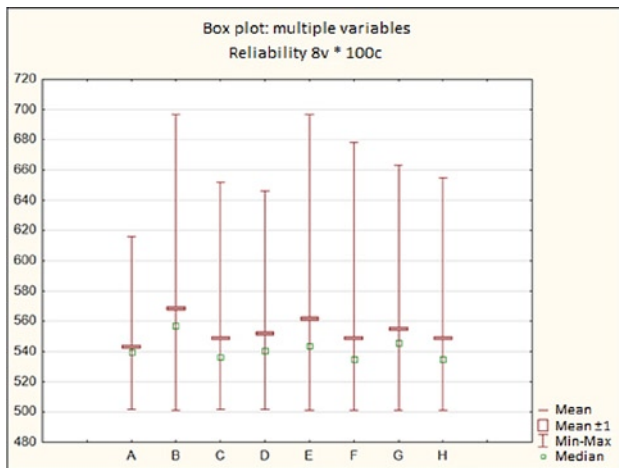


Fig. 11. Results of the statistical analysis of system productivity for the investigated RMS structures

The smallest spread between the minimum and the maximum increase in production capacity was observed for the two-stage structure (A). Taking into account the fact that smooth adjustment of production capacity to current demand is one of the key principles of RMS, structure A seems to be the most desirable. The largest “leaps” occurred in structures B and E. In practical terms, this means that these structures had excessive reserve capacity, which is not beneficial from the point of view of the economics of maintenance of technical equipment.

#### 4.2. Evaluation of RMS reliability

The scalability of a system has a direct impact on its level of reliability. In the case under study, on the one hand, reliability constantly decreases as a consequence of the decline in the reliability of the individual machines, and on the other hand, it increases as new, 100% reliable machine tools are added to the system’s structure. Considering that the total reliability of the system depends both on the reliability of all its components and the way they are arranged, the impact of expansion of the system on its reliability is an important factor that should be evaluated at the stage of selecting the appropriate functional structure of the designed RMS.

The reliability of a system is a derivative of both the number of production stages and the number of machines used in each stage. If components are added serially, the system’s reliability is reduced. In a case like this, 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 components increases the overall reliability of the system. More components added in parallel (Fig. 12 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 system’s reliability is  $1-(1-R)^n$  [37]. All of the RMS structures analyzed in this example are hybrids that combine the characteristics of both parallel and serial structures.

Calculations of the system’s reliability for three selected structures are given in Table 3. To show precisely how the system’s reliability was calculated, structures with different numbers of stages and different levels of reliability of the individual machine tools were selected.

The system’s reliability level for each of the structures was calculated under the assumptions regarding the decrease in the reliability level of machine tools and system scalability presented in section 4.1 of this paper. The results of the calculations made for every 5% decrease in reliability are given in Table 4, and a graphic interpretation of the results is shown in Fig. 12.

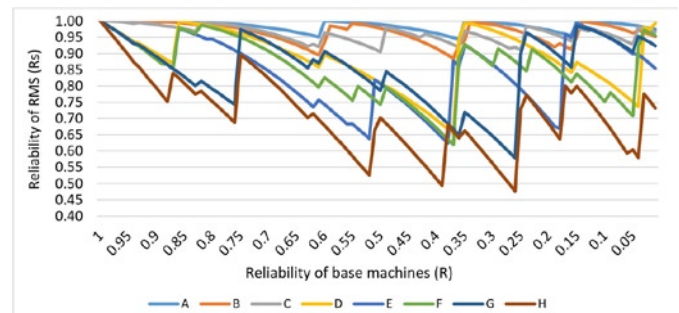


Fig. 12. Reliability of the scalable RMS ( $R_s$ ) as a function of the decrease in the reliability of its base machines ( $R$ )

The highest mean level of system reliability of nearly 98.92% was observed for the RMS with a two-stage structure (structure A). The poorest result was obtained for the five-stage structure (structure H), for which the mean level of system reliability was only 72.65%. It is worth emphasizing that it was only systems with two- or three-stage structures that had an over 90% reliability, and the system’s reliability decreased along with the increase in the number of processing stages (despite the fact that new machines characterized by 100% reliability were consistently added to the system).

The reliability curves for the analyzed period clearly show that the system with structure A had the highest and most stable level of reliability, while structures D, E, F, G and H were characterized by the largest leaps in reliability. This is confirmed by the summary\_results of statistical analysis shown in Figure 13.

A detailed analysis of the results clearly shows that the two-stage structure (structure A) has the best properties from the point of view of system reliability over the entire period analyzed. The scalability of the system with this structure, despite the decrease in the reliability of the individual machines (from 99% to 1%), allows to maintain system reliability at the level from 94.3824% to 99.9998%. In the case of the three-stage structures (B and C), the system’s reliability ranges from 88.5015% to 99.9999%, and for the remaining structures, it ranges from 47.6314% to 99.9799%. Considering the fact that the reliability of a system, in practice, translates into its flawless operation over the entire service life, this factor is key in selecting the appropriate system structure.



Table 3. Method of calculating the reliability level of the RMS under design

RMS structure	System reliability (R <sub>s</sub> )
<p>Structure H, reliability of base machines R = 0.94</p>	$R_s = [1 - (1 - 0.94)^2]^5 = 0.874091$
<p>Structure D, reliability of base machines R = 0.91</p>	$R_s = [1 - (1 - 0.91)^2]^2 * [1 - 0.98] * 0.91 * [1 - (1 - 0.94)^4] = 0.909793$
<p>Structure A, reliability of base machines R = 0.59</p>	$R_s = [1 - (1 - 0.59)^2]^2 * (1 - 0.66) * (1 - 0.99) * [1 - (1 - 0.59)^5 * (1 - 0.74) * (1 - 0.91)] = 0.999157$

Table 4. System reliability level for each of the structures of the scalable RMS

R	A	B	C	D	E	F	G	H
1	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%	100.0000%
0.95	99.7500%	99.4882%	99.4882%	94.7619%	94.5138%	94.2893%	94.2893%	89.5748%
0.9	99.9690%	99.8401%	98.8713%	89.9640%	88.9842%	88.1825%	89.0465%	79.3643%
0.85	99.8200%	99.3040%	97.5675%	99.6703%	97.0989%	97.3619%	82.7887%	80.8286%
0.8	99.4784%	98.9627%	99.3448%	98.2784%	94.3548%	97.8933%	79.1068%	75.2708%
0.75	98.8653%	97.6863%	98.2578%	96.1184%	90.0758%	94.9574%	97.3349%	89.5211%
0.7	97.8943%	95.6439%	96.4277%	93.1161%	84.6097%	90.7285%	93.4441%	82.4031%
0.65	96.5670%	92.6579%	93.6670%	89.4721%	78.0068%	85.1405%	88.1195%	73.9058%
0.6	99.9795%	93.5076%	96.4467%	89.5713%	74.2614%	82.5733%	90.5954%	67.8813%
0.55	99.5436%	99.3086%	93.9766%	85.6135%	68.3080%	75.6173%	85.2320%	58.4092%
0.5	98.9172%	97.7842%	90.5059%	80.8523%	80.6762%	74.3454%	78.6073%	70.2166%
0.45	97.7812%	95.2754%	96.2272%	75.7465%	73.8451%	74.5410%	79.3085%	61.1457%
0.4	96.1827%	91.4958%	94.8327%	69.5560%	65.8819%	67.0279%	71.8052%	51.4000%
0.35	99.9782%	94.0611%	96.9576%	99.3216%	92.6218%	92.7751%	71.9428%	66.2636%
0.3	99.5370%	98.8758%	94.0071%	97.1635%	86.6447%	86.1818%	64.5615%	56.1794%
0.25	98.6472%	96.6963%	91.0543%	93.5488%	79.0229%	86.1307%	89.7804%	72.7402%
0.2	97.1968%	93.0106%	96.5654%	88.9814%	69.7254%	87.4975%	91.8359%	68.4206%
0.15	99.9875%	95.1974%	97.9106%	87.2665%	99.1206%	83.6950%	98.5187%	79.8808%
0.1	99.5791%	98.7923%	96.3801%	81.8705%	95.5585%	75.2534%	95.5665%	69.1655%
0.05	98.6743%	96.3186%	92.7535%	75.1184%	89.8394%	70.7615%	90.4742%	60.3720%
Mean	98.9174%	96.6953%	96.0621%	89.2996%	85.1575%	85.2477%	86.6179%	72.6472%

### 5. Conclusions and further research

In the process of designing a manufacturing system, it is necessary to consider aspects related to the system's entire service life. Particularly important in this respect is the problem of wear of machine tools

and other components of the system, which reduces its reliability and, consequently, also its efficiency and productivity. For that reason, reliability issues should be analyzed already at the stage of creating a technical design.

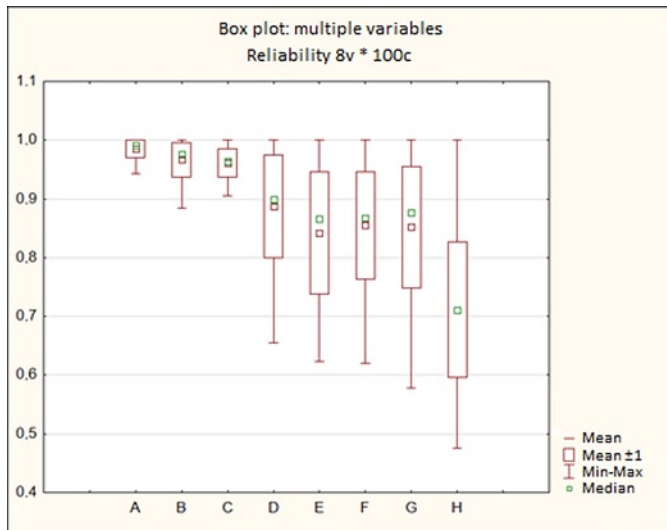


Fig. 13. Results of the statistical analysis of the reliability of the RMS for each of the analyzed structures

In the case of RMS, one of the key features of a structure being designed is scalability, which allows to adjust the system's production capacity to the existing market demand. This feature also permits to supplement a system's production capacity reduced by the decline in the reliability of the component machine tools, as discussed in the present study.

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As part of the present experiments, we analyzed eight structures of an RMS dedicated to the production of body-type parts. In particular, we wanted to find answers to the following questions: (1) How will the system be expanded, for each structure, in order to ensure the minimum required level of system productivity? (2) How will system expansion contribute to building up production reserves for the production subsystem? (3) How will the level of reliability change over the system's service life? Computer simulation methods were used to evaluate the system's productivity and to identify bottlenecks. The system's operation was modelled and simulated for each of the eight structures, assuming that machine reliability decreased in a linear manner over the system's service life.

The results clearly indicate that RMS structures that have the best properties are those with the smallest number of stages. Systems with this type of structures, when expanded, show small increments in production capacity (and thus a minimum redundancy of production reserves) and exhibit the highest levels of reliability. Unfortunately, in practice, the use of structures with fewer stages requires the deployment of multi-task machine tools, generating higher per-unit purchase costs. Given all this, in our future research, we plan to carry out a multicriteria analysis, in which, apart from the functional and efficiency-related features of the individual structures, we will look into the economic aspects of system construction, such as the price of machine tools, the methods and costs of organizing a system's transport and storage subsystems, as well as the use of elements for controlling the individual components of a system in accordance with the assumptions of Industry 4.0.

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