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Relationship Between Complexity and Flexibility of Production Structures

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The aim of this paper is to contribute to the development of procedures for the design of effective production structures of an enterprise. In order to do this, the paper focuses on two main aspects. Firstly, the paper considers the possibilities of making production structures more manageable by means of lowering the degree of complexity of those structures. Secondly, the focus is on ways of enabling those structures to adapt to changes in the environment, i.e. on flexibility. Complexity of a production structure is a characteristic defined by the number of structural elements and their interdependence. Flexibility of production structures is observed through three components: technological component, capacity component and flexibility of flows.

Odnos između složenosti i fleksibilnosti proizvodnih struktura

Izvornoznanstveni članak

Cilj članka je prilog razvoju postupaka za dizajniranje efektivnih proizvodnih struktura poduzeća. U tom smislu člnak se fokusira na dva bitna aspekta: prvi je razmatranje mogućnosti uspostavljanja proizvodnih struktura visoke pogodnosti upravljanja putem sniženja stupnja njihove složenosti, a drugi je dizajniranje proizvodnih struktura osposobljenih za prilagođavanje promjenama u okolini, odnosno za potrebnu i dovoljnu fleksibilnost. Složenost proizvodnih struktura se definiše putem broja elemenata strukture i njihovom međusobnom uslovljenošću, dok se fleksibilnost proizvodnih struktura razmatra u svjetlu tri komponente: tehnološke komponente, kapacitivne komponente i fleksibilnosti proizvodnih tokova.

1. Introduction

Enterprise-environment relations and disorders in the work process, bearing in mind their accidental character, have lead to a situation in which industrial system structures - enterprises develop in the following conditions:

- uncertainty of the environment and lack of knowledge about the characteristics of enterprise-environment relation
- frequent changes in the development of technologies and in the behaviour of the employees
- changes in the approach to organization, from mechanistic -based on the principle of division of labour and management suitable in cases of specified work conditions, to organic-based on the principle of functioning of the living beings and on management based on feedback, which is suitable when work conditions are not specified.

The relations in the production programme of enterprises [72] determine the basic types of production structures which are presented as Types I-IV in Figure 1.

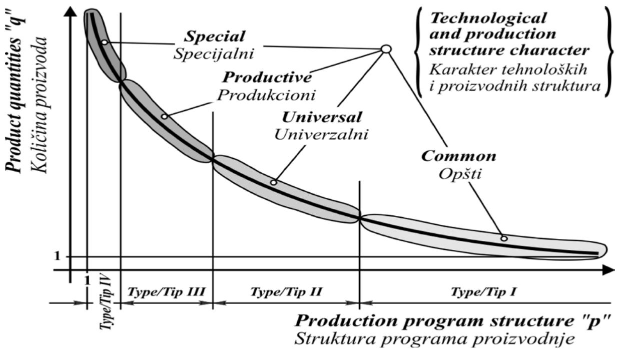


Figure 1. The relations in the production programme of an enterprise

Slika 1. Odnosi u programu proizvodnje preduzeća

They have the following characteristics:

- Type I: The field of slow technologies and technological and production structures of *common character*
- Type II: The field of technological and production structures of *universal character*
- Type III: The field of technological and production structures of *productive character*

Symbols/Oznake

p	- production program structure - struktura programa proizvodnje	f_T	- degree of technological flexibility - stupanj tehnološke fleksibilnosti
q	- product quantuty, komada - količina proizvoda, pieces	f_k	- degree of capacity flexibility - stupanj kapacitivne fleksibilnosti
i	- production phase - faza (operacija) procesa	f_p	- degree of flows flexibility - stupanj fleksibilnosti tokova
m	- number of production phases (operations) - broj faza (operacija) procesa	R_i	- average capacity reserve - prosječna rezerva kapaciteta
j	- observed structure's element - posmatrani elemenat proizvodne strukture	x_g	- work object parameter - upper limit, mm - karakteristika predmeta rada - gornja granica
WU	- working unit - radna jedinica	x_d	- work object parameter - lower limit, mm - karakteristika predmeta rada - donja granica
κ	- degree of complexity of production structure - stupanj složenosti proizvodne strukture	P_g	- probability on the upper limit of the object parameter - verovatnoća na gornjoj granici parametra strukture
η	- loading (utilization) degree - stupanj iskorišćenja	P_d	- probability on the lower limit of the object parameter - verovatnoća na gornjoj granici parametra strukture
k	- structure parameter (characteristic) - parametar (karakteristika) strukture	μ	- expected value of the work object parameter, mm - očekivana vrijednost karakteristike predmeta rada
K_e	- capacity of the structure's element - kapacitet elementa proizvodne strukture	σ	- standard deviation of the work object parameter, mm - standardna devijacija karakteristike predmeta rada

- Type IV: The field of fast technologies and technological and production structures of *purposeful character*

The presented relations and tendencies in the development of production, organizational and management structures of enterprises increase the requirements concerning the characteristics of those structures. These requirements are presented in Fig. 2 and are reflected in:

- the need to achieve a high degree of integration of material, energy and information flows on the one hand, and of the functions of an enterprise on the other, for the purpose of developing the most suitable procedures of production, organization and management
- the tendency of constant increase in the complexity of elements and structures of an enterprise, expressed in the function of the characteristics of production programmes; changes in the work process
- the requirements to free the potential of employees by enriching the content of work and removing people from work that is mentally and physically strenuous and dangerous -automatization of the work process [65, 72, 74].

In the earlier researches on production structures [65-66, 72-73], the basis for the development of effective enterprises was formed. The idea of this basis (Figure 2) is: change of the flow and structure designing approach - from *process* to *product*. The result of the mentioned changes in the approach is the creation of the Working Unit, the basic module of an effective enterprise - designated as ***WU*** in Figure 2. Working Unit is defined as part of the production structure of an enterprise capable to carry out a certain task which is part of the work programme, should conditions of adequate space, equipment and the required structure of employees be met.

Working Unit has the following characteristics:

- it is independent of the other parts of the system's structure concerning the human resources and technical capacity,
- it is responsible for completion of programme part, concerning the amount, quality and deadlines and
- it is suitable for process automation.

Specific researches have indicated the importance of one basic characteristic of production structures - *flexibility*, the value of which should be on the satisfactory level.

2. Enterprises Complexity and Flexibility: A brief literature review

2.1. A Complexity

Earlier researches into complexity of production systems are characterized by different ways of looking at complexity and can be divided into four groups:

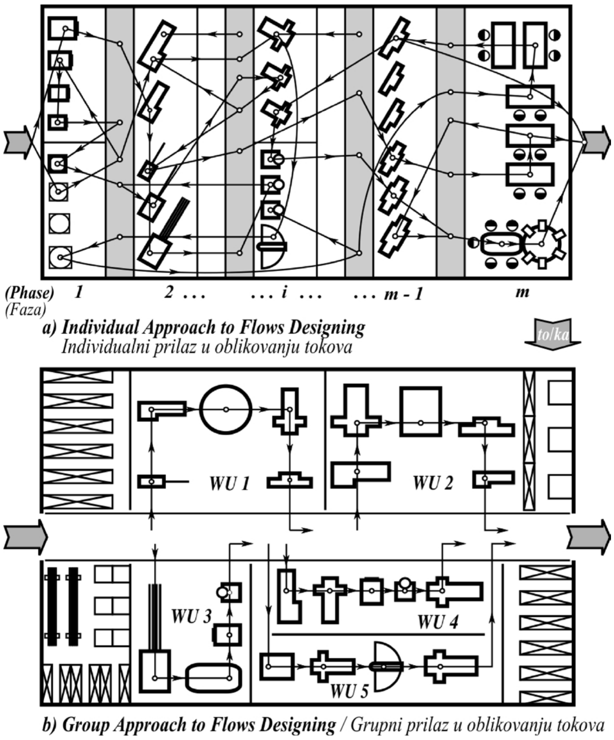


Figure 2. The basic changes in approaches to production structures designing

Slika 2. Promene prilaza u oblikovanju proizvodnih struktura

1. Theoretical views of production systems complexity

The most recent theoretical views on the complexity of production structures are primarily based on the general principles of the systems theory and mathematical modelling of a system's structure in general sense.

Methods of non-linear dynamics and simulation techniques are used in order to answer the questions of the amount and quality of data required for the analysis of a system's structure [1]. There have also been attempts to reduce the chaos and miscellany that cause dynamic changes and behaviours in a system to the simple model of a production system that enables its stability [2]. Finally, complexity of a production system's structure is a key characteristics in the approaches which introduce the concepts of knowledge management and organizational learning [3].

2. Measuring the complexity of production systems

Theoretical models have already pointed to the need to measure the complexity of production systems.

Such a need is particularly significant in practical approaches which use the complexity of production systems in designing and managing their processes.

There is a connection between the complexity of a system and the system's performances, and in the measuring methods, the following criteria are used most frequently: the number of elements in a structure, costs, manageability [4]. The systems of designating structural components lead to the concept of structural complexity. This concept introduces into the way of its measuring the interdependence between components and a variety of information that they exchange between one another [5-6]. There is also an interesting aspect that considers the so-called management complexity [7], but only in the case of industrial co-operation of systems from different lines of business, i.e. on the level of complex socio-technical systems.

3. Decreasing the complexity of production systems

The need for decreasing the complexity of production systems has been widely acknowledged. Hypothetical lean models are not applicable.

A practical approach is being sought that would enable the transition from highly complex production systems to small scale systems (lean factory). Case studies have mostly used analysis models based on frameworks [8]. The need for decreasing the complexity of a production structure is particularly evident when solving problems of planning and work distribution in the systems with a high product variety. In most of the case studies this problem has not been adequately solved [9].

4. The effect of complexity on effectiveness

Lately, complexity has been observed as a key characteristic that determines the quality of production systems. There have been investigations into the effect of complexity of production systems on the character of production flows, organization of an enterprise, management actions, information support and total effectiveness of business.

Apart from technical-technological components, social components such as the role in organizing, personal motives, experience and identity are also taken into consideration. These additionally increase the complexity of the process of establishing an effective organization [10]. Conceptual approaches concerning the complexity of production systems are directed to the level of determining the complexity of the organization-enterprise as a whole [11]. Special attention is given to case studies which include: the structure of the so-called virtual enterprises and managing an enterprise which is not based on hierarchical organizational structure [12]. The complexity of management procedures and appropriate management methods (ERP, MRP, JIT...) are also related to the complexity of the object that is being managed - the production system and its performances [13], [14], [60].

2.2. Flexibility

1. Theoretical considerations of flexibility

In recent literature, the theoretical views of flexibility of production systems deal with defining the term flexibility in a broad sense, and with the ideas of measuring flexibility. There is a whole variety of approaches and opinions of various authors, depending on the fact whether flexibility as a characteristic of a system is observed from technical, economic, managerial or some other point of view.

There are classifications of different terms that are connected with flexibility in production, the development of appropriate structural divisions and schemes, as well as efforts to determine the measure of different types of flexibility [15-16, 34-39, 58]. Different aspects of flexibility have created a gap between theoretical ideas and the possibilities of their application.

This gap causes the need for integration of the theoretical and practical views of production systems flexibility, especially concerning the advantages of measuring flexibility [17-19, 40-50].

2. Considerations of flexibility in terms of capacity

Both in theoretical and practical considerations, flexibility is most commonly observed from the angle of capacity of parts of a system's structure and system as a whole, i.e. their ability to adapt to changes in the requirements of the market concerning the amount of product and services.

The criteria used to measure flexibility in the sense of capacity are : the duration of the stages of a process, the degree of utilization of a workplace or machines, and the capacity of storage facilities of the production system. The duration of stages is seen as the criterion of the minimum, the degree of utilization of a workplace or machines as a limiting criterion, and the capacity of storage facilities as necessary ballast. The influences of the degree of utilization of the capacity and capacity reserves are also included so that the requirements of the market could be accepted in the set deadlines [20-21].

From the angle of the capacity of the elements of a system and the system as a whole, special attention is given to the procedures of designing production systems. The problem with determining the size of production capacities is ever more based on the estimates of future needs rather than on the simple calculations determined by an exact project task. This view pushes the simple criterion of load (as well as utilization) in the background and puts the future requirements of customers in the foreground. Efforts are being made to develop and apply simulation procedures, with the aim of designing an optimum flexibility value concerning capacity [22-24].

3. Considerations of technological flexibility of production systems and "flexible automatization"

Technological aspect of flexibility is probably the most exploited one in production. Numerous solutions connected to this aspect of flexibility are more the result of engineering solutions to practical problems which concern designing elements of production structures according to the exact task, and less the result of observing this aspect of flexibility on the level of production function of an enterprise.

Individual case studies and solutions that provide a satisfactory level of flexibility of a certain machine, production cell and their elements are the subject of special analysis that focuses on the problems of designing and automatization of production processes. Efforts to design flexible parts of a system can be thus seen as a necessary condition for providing flexibility of a production system as a whole. However, the problems of planning and terminating the work process of production systems have lead to integrative solutions such as flexible manufacturing systems (FMS).

Those solutions are based on a high flexibility degree of parts of the system, but also of the support systems such as systems of material management, systems of tools provision and systems of information-control support [25-26].

In the end, the technical aspect of flexibility of a production system is nowadays observed as integrating material flows and control procedures [27, 51-54].

4. Considerations of the flexibility of flows of production systems

Flexibility has a much greater scope than just observing the capacity reserves and technical possibilities of parts of the structure of a production system. It includes observing the interdependence between elements of the structure which is mainly influenced by the flows of materials in a system. What is more, the relations between the production system and the market also have to be included, in the light of the dynamics of changes in the requirements of the consumers.

Production flexibility is seen as a key strategy whose task is improving sensitivity in the conditions of uncertain future requirements for products. The developed flexibility principles are being applied in the process of designing production flows and structures of production systems [28], and models for the lay-out of workplaces in the production system on the basis of flexibility [29], [30].

2.3. Complexity and flexibility relationship

The earlier researches into the characteristics of complexity and flexibility of production systems were carried out separately, as it can be seen in the available literature.

Although there are efforts on part of a large number of experts to explore these characteristics both theoretically and practically, the situations in which these are directly connected are rare. Experience in designing, organizing and managing production systems and enterprises as wholes shows, however, that such a connection between complexity and flexibility exists [60-64]. This paper also shows [59, 78] the existence of a direct connection between complexity and flexibility and this connection is inversely proportional.

In literature, there are certain hints that suggest the existence of this connection but they are mentioned only indirectly. That is how concepts such as complexity of technologies and complexity of enterprise-environment relation are introduced into the basic framework of the theory of flexibility and models of analysis [31, 55–56].

Apart from flexibility, the key to success of an enterprise is the need to pay attention to the robustness, agility and adaptability during the whole life cycle of a system which at the same time affects its complexity. The mentioned characteristics are, in the conditions of frequent changes in the environment, used as criteria in designing the basic architecture of a production system with an appropriate degree of complexity [32-33, 55-57].

3. Production Structures Complexity

3.1. A Definition

The measure of complexity of the structure of industrial systems - enterprises, defined as the degree of complexity, or variety, is extremely important.

In accordance with the principle of the minimum necessary in the development procedures of production, organizational and management structures of a system, the complexity of the observed part of the structure represents: the measure of interdependence between the observed part of the structure and its other parts, the ground for the elements simplification, a connection between elements and the structure as a whole, and the ground for comparison with structures of similar characteristics. Complexity is also a measure of quality of the design of an enterprise's structures [58].

The degree of complexity of industrial system structures is determined by the characteristics and the number of structural elements, the position of elements in the structure and the relations between the elements of the structure. Therefore, it is one of the basic general characteristics of industrial systems - enterprises.

In accordance with the character of flows in a system (material, energy and information) and of the structures of a system (production, organizational, management), complexity, as a general characteristic of an enterprise, can be measured by the degree of complexity of production structures, the degree of complexity of organizational structures and the degree of complexity of management structures of an enterprise [76].

The project of production structures of an industrial system basically defines the static structure. Production function is only made possible as the result of harmony between other functions of an enterprise (determined by the project of organizational structures) to which control procedures (determined by the project of control structures) are applied. The project is used to determine the characteristics and the number of elements of a structure (based on the elaboration of work procedures and calculations), to determine the position of elements in a structure upon the chosen approaches to flows designing, and to establish relationships between elements of a structure by designing of system's lay-out, i.e. to determine the causes of complexity of production structures. That way the degree of complexity of production structures is determined by the quality of project of material flows and system's lay-out. The degree of complexity is a measure of quality of a project whereby the lower degree of complexity means a better quality of a product and vice versa.

Bearing in mind the need for flows simplification in a system, whose variety generates limitations to the effective work process, the degree of complexity of production structures is determined by conditionality of flows in a system, as a relation between the total number of connections between elements and the number of structural elements, as shown in Figure 3 [75-76].

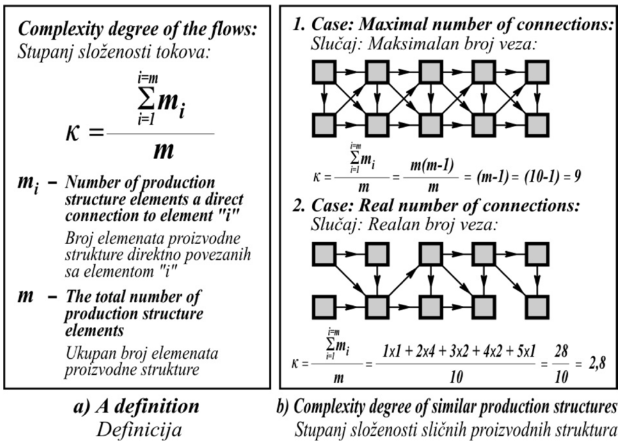


Figure 3. Complexity Degree of the Production Flows

Slika 3. Stupanj složenosti proizvodnih tokova

When the degree of complexity of production structures is considered, in accordance with the definition in Figure 3, elements of a structure are the basic parts of a system-workplaces, and their interrelations are observed.

A more detailed analysis of the presented relation has shown [75, 77] the existence of a connection between the degree of complexity (variety of production structures shown on Figure 1) and characteristics of certain types of material flows. The relation between the degree of complexity and conditionality of flows, shown in Figure 4, is determined upon:

- the total number of structural elements
- the total number of connections between elements.

This relation enables qualitative analysis of material flows types and the development of criteria for selection of the most favourable variant.

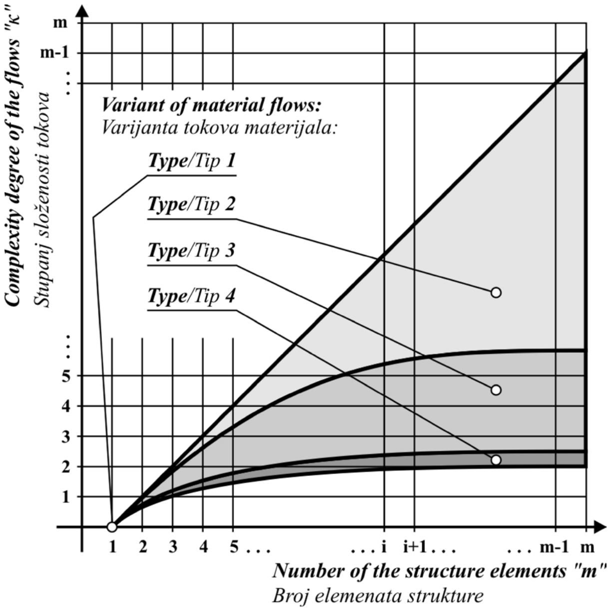


Figure 4. Analysis of production structures complexity degree

Slika 4. Analiza stupnja složenosti proizvodnih struktura

3.2. Results of the research into production structures complexity

Research into the degree of complexity of production structures was conducted in more than thirty different cases-enterprises with different production programmes, and gave results which are presented in the text that follows, on the example of analysis of an enterprise that produces machine tools [67, 76].

The analysis of complexity was performed in a way that took these into consideration:

- structures in state - production structures based on individual approach to material flows designing and process approach to production structures designing
- a certain number of newly projected possible variants of production structures in which, in accordance with the principles in Fig. 5, there was a switch to group approach to material flows designing and product approach to structure designing.

The data presented about a structure in state are:

- the number of different work objects: 123
- the number of elements (workplaces): 30
- values that characterize the state of production structure - a list of workplaces (Table 1) and load/capacity ratio (Figure 5).

Table 1. Data About Production Structure - State

Tablica 1. Podaci o proizvodnoj strukturi - Stanje

Workplace/ Radno mesto, Code/ Oznaka	Load/ Opterećenje, min/year	Capacity/ Kapacitet, min/year	No/ Broj	Loading degree / Iskorišćenje, η_{ii}
0120	255368	180000	2	0.71
0150	46885	180000	1	0.26
0160	94205	180000	1	0.52
0170	75305	180000	1	0.42
0180	57695	180000	1	0.32
0230	152228	180000	1	0.85
0240	176997	180000	1	0.98
0250	112528	180000	1	0.63
0260	1282187	180000	8	0.89
0320	257512	180000	2	0.72
0330	170409	180000	1	0.95
0340	25268	180000	1	0.14
0350	150817	180000	1	0.84
0390	194658	180000	1	1.08
0420	123111	180000	1	0.68
0430	1233318	180000	7	0.98
0490	347685	180000	2	0.97
0710	69215	180000	1	0.38
0810	31660	180000	1	0.18
0820	155020	180000	1	0.86
0840	548328	180000	3	1.02
0850	509912	180000	3	0.94
0870	170685	180000	1	0.95
0920	185380	180000	1	1.03
1010	585035	180000	4	0.81
2510	64600	180000	1	0.36
2520	336610	180000	2	0.93
2530	113861	180000	1	0.63
6010	180	180000	1	0.01
6020	180	180000	1	0.01

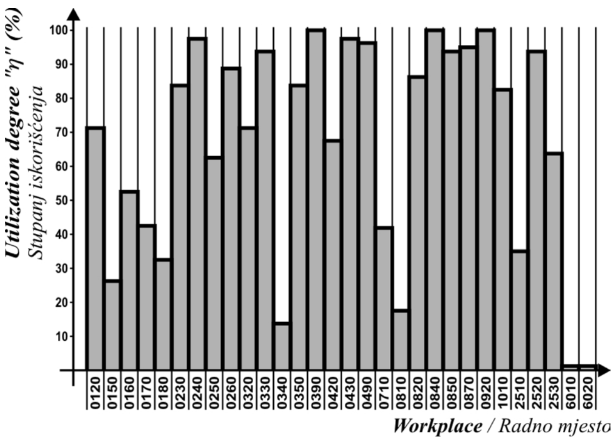


Figure 5. Loading degree for the example of state of production structure

Slika 5. Stupanj iskorišćenja za primer stanja proizvodne strukture

By revitalization procedure two variants of production structure were designed.

They had the following characteristics:

Variant 1:

- number of working units: 2
- number of different work objects: WU 1: 85; WU 2: 38
- number of workplaces: WU 1: 19; WU 2: 20
- characteristics of Variant 1 of the production structure:

1. for WU 1: specification of the workplaces (Table 2) and load/capacity ratio (Figure 6)
2. for WU 2: specification of the workplaces (Table 3) and load/capacity ratio (Figure 7).

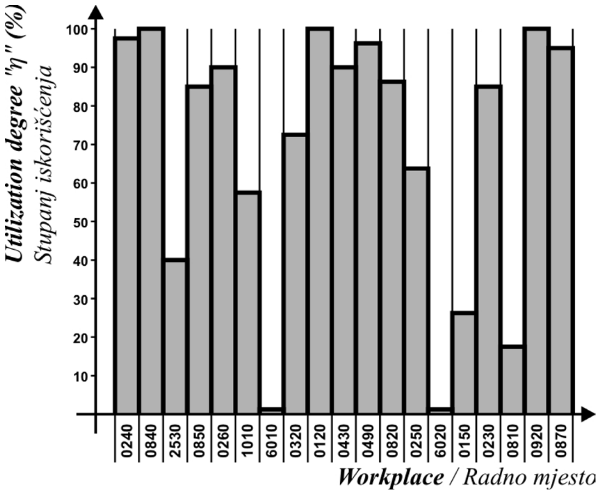


Figure 6. Loading degree for the example of WU 1 in Variant 1

Slika 6. Stupanj iskorišćenja za primer RJ 1 u Varijanti 1

Table 2. Data About Production Structure - Variant 1, WU 1

Tablica 2. Podaci o proizvodnoj strukturi - Varijanta 1, RJ 1

Workplace/ Radno mesto Code/ Oznaka	Load/ Opterećenje min/year	Capacity/ Kapacitet min/year	No / Broj	Loading degree / Iskorišćenje, η_{ii}
0240	176997	180000	1	0.98
0840	196473	180000	1	1.09
2530	70106	180000	1	0.39
0850	461634	180000	3	0.85
0260	1137697	180000	7	0.90
1010	208258	180000	2	0.58
6010	180	180000	1	0.01
0320	257512	180000	2	0.72
0120	181427	180000	1	1.01
0430	325110	180000	2	0.90
0490	347685	180000	2	0.97
0820	155020	180000	1	0.86
0250	112528	180000	1	0.63
6020	180	180000	1	0.01
0150	46885	180000	1	0.26
0230	152228	180000	1	0.85
0810	31660	180000	1	0.18
0920	185380	180000	1	1.03
0870	170685	180000	1	0.95

Variant 2:

- number of working units: 4
- number of different work objects: WU 1: 62; WU 2: 23, WU 3: 26; WU 4: 12
- number of workplaces: WU 1: 16; WU 2: 18, WU 3: 11; WU 4: 16
- characteristics of Variant 2:

1. for WU 1: specification of the workplaces (Table 4) and load/capacity ratio (Figure 8)
2. for WU 2: specification of the workplaces (Table 5) and load/capacity ratio (Figure 9)
3. for WU 3: specification of the workplaces (Table 6) and load/capacity ratio (Figure 10)
4. for WU 4: specification of the workplaces (Table 7) and load/capacity ratio (Figure 11).

Table 3. Data About Production Structure - Variant 1, WU 2

Tablica 3. Podaci o proizvodnoj strukturi - Varijanta 1, RJ 2

Workplace/ Radno mesto Code/ Oznaka	Load/ Opterećenje min/year	Capacity/ Kapacitet min/year	No/ Broj	Loading degree/ Iskorišćenje η_{ii}
0120	73942	180000	1	0.41
0430	908208	180000	5	1.01
1010	376778	180000	2	1.05
0330	170409	180000	1	0.95
6020	180	180000	1	0.01
0840	351891	180000	2	0.98
2530	43755	180000	1	0.24
0420	123111	180000	1	0.68
6010	180	180000	1	0.01
0260	144490	180000	1	0.80
0710	69215	180000	1	0.38

0170	75305	180000	1	0.42
0160	94205	180000	1	0.52
2510	64600	180000	1	0.36
0180	57695	180000	1	0.32
2520	336610	180000	2	0.93
0850	44278	180000	1	0.25
0390	194658	180000	1	1.08
0350	150817	180000	1	0.84
0340	25268	180000	1	0.14

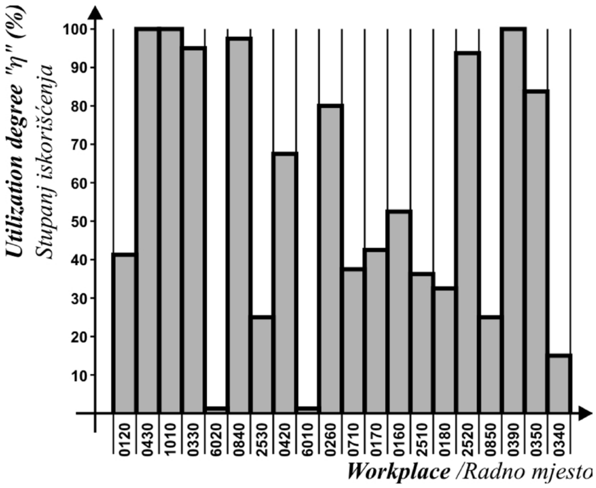


Figure 7. Loading degree for the example of WU 2 in Variant 1
Slika 7. Stupanj iskorišćenja za primer RJ 2 u Varijanti 1

Table 4. Data About Production Structure - Variant 2, WU 1
Tablica 4. Podaci o proizvodnoj strukturi - Varijanta 2, RJ 1

Workplace/ Radno mesto (Code/ Oznaka)	Load/ Opterećenje [min/year]	Capacity/ Kapacitet [min/year]	No/ Broj	Loading degree/ Iskorišćenje η_{ii}
0240	155822	180000	1	0.87
0840	170545	180000	1	0.95
2530	58091	180000	1	0.32
0850	108903	180000	1	0.61
0260	547025	180000	3	1.01
1010	163513	180000	1	0.91
6010	180	180000	1	0.01
0320	195022	180000	1	1.08
0120	92981	180000	1	0.52
0430	237805	180000	2	0.67
0490	321940	180000	2	0.89
0820	45185	180000	1	0.25
0150	46885	180000	1	0.26
0250	73625	180000	1	0.41
0230	37315	180000	1	0.21
0870	8265	180000	1	0.05

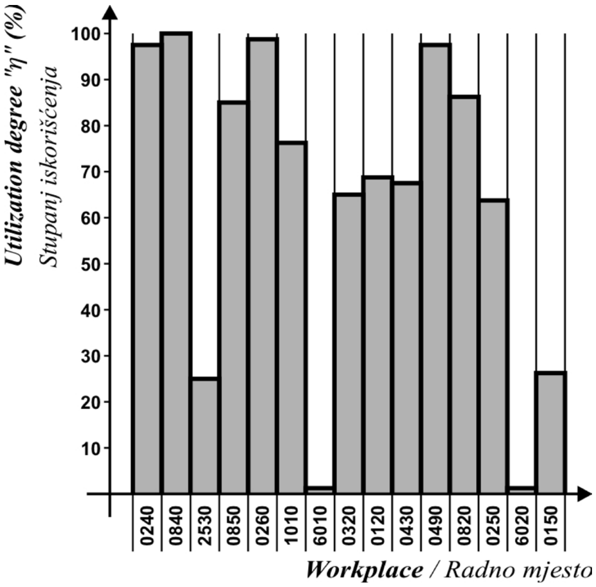


Figure 8. Loading degree for the example of WU 1 in Variant 2
Slika 8. Stupanj iskorišćenja za primer RJ 1 u Varijanti 2

Table 5. Data About Production Structure - Variant 2, WU 2
Tablica 5. Podaci o proizvodnoj strukturi - Varijanta 2, RJ 2

Workplace/ Radno mesto (Code/ Oznaka)	Load/ Opterećenje [min/year]	Capacity/ Kapacitet [min/year]	No/ Broj	Loading degree/ Iskorišćenje η_{ii}
0120	88446	180000	1	0.49
0250	38903	180000	1	0.22
6020	180	180000	1	0.01
0320	62490	180000	1	0.35
6010	180	180000	1	0.01
0820	109835	180000	1	0.61
0840	25892	180000	1	0.14
0850	352742	180000	2	0.99
0260	590672	180000	4	0.82
2530	12015	180000	1	0.07
0240	21175	180000	1	0.12
0430	87305	180000	1	0.49
1010	44745	180000	1	0.25
0490	25745	180000	1	0.14
0230	114913	180000	1	0.64
0810	31660	180000	1	0.18
0920	185380	180000	1	1.03
0870	162420	180000	1	0.90

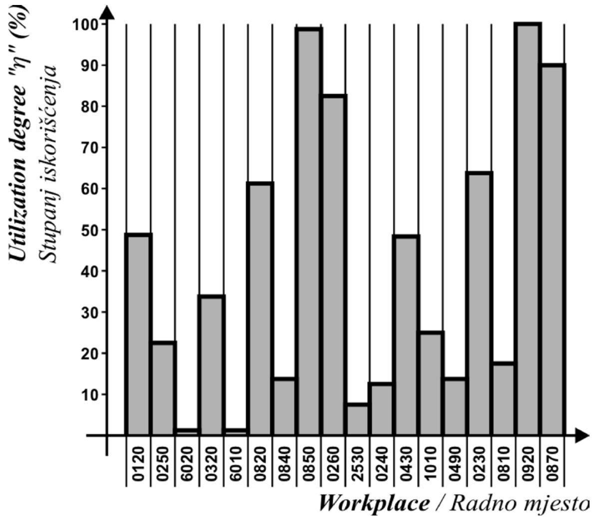


Figure 9. Loading degree for the example of WU 2 in Variant 2

Slika 9. Stupanj iskorišćenja za primer RJ 2 u Varijanti 2

Table 6. Data About Production Structure - Variant 2, WU 3

Tablica 6. Podaci o proizvodnoj strukturi - Varijanta 2, RJ 3

Workplace/ Radno mesto (Code/ Oznaka)	Load/ Opterećenje [min/year]	Capacity/ Kapacitet [min/year]	No/ Broj	Loading degree/ Iskorišćenje η_{ii}
0120	73942	180000	1	0.41
0430	642288	180000	4	0.87
1010	254458	180000	2	0.71
0330	103950	180000	1	0.58
6020	180	180000	1	0.01
0840	243405	180000	2	0.68
2530	43755	180000	1	0.24
0420	14330	180000	1	0.08
6010	180	180000	1	0.01
0260	8670	180000	1	0.05
0710	54135	180000	1	0.30

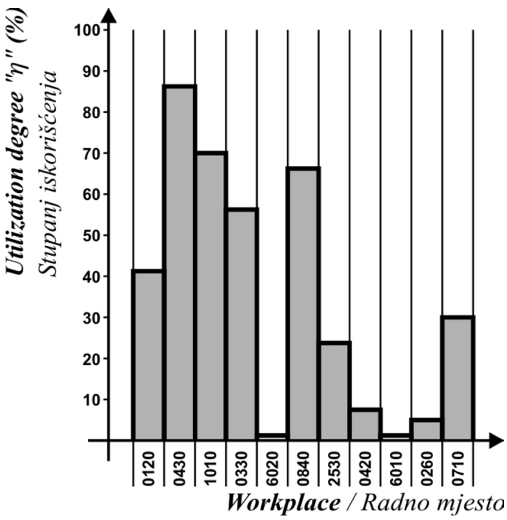


Table 7. Data About Production Structure - Variant 2, WU 4

Tablica 7. Podaci o proizvodnoj strukturi - Varijanta 2, RJ 4

Workplace/ Radno mesto (Code/ Oznaka)	Load/ Opterećenje [min/year]	Capacity/ Kapacitet [min/year]	No/ Broj	Loading degree/ Iskorišćenje η_{ii}
0170	75305	180000	1	0.42
0160	94205	180000	1	0.52
2510	64600	180000	1	0.36
0180	57695	180000	1	0.32
0330	66459	180000	1	0.37
0430	283920	180000	2	0.79
2520	336610	180000	2	0.93
0420	108781	180000	1	0.60
0710	15080	180000	1	0.08
0840	108486	180000	1	0.60
1010	122320	180000	1	0.68
0260	135820	180000	1	0.75
0850	44278	180000	1	0.25
0390	194658	180000	1	1.08
0350	150817	180000	1	0.84
0340	25268	180000	1	0.14

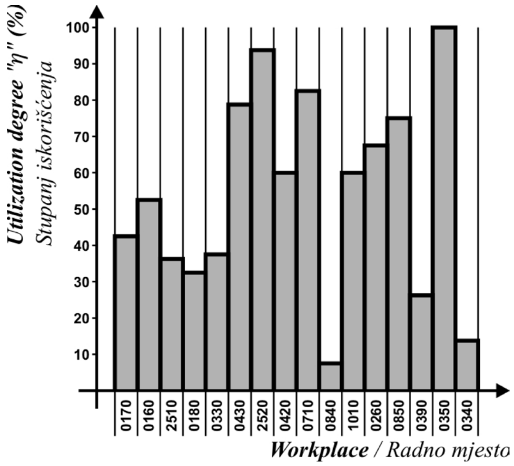


Figure 11. Loading degree for the example of WU 4 in Variant 2

Slika 11. Stupanj iskorišćenja za primer RJ 4 u Varijanti 2

What follows for the observed example are the results of the analysis of complexity degree for all the considered variants of production structures.

*The existing variant of production structure (**state**)*

The observed variant of production structure was designed according to process principle which generated relations between the elements and the degree of complexity presented in Figure 12.

Figure 10. Loading degree for the example of WU 3 in Variant 2

Slika 10. Stupanj iskorišćenja za primer RJ 3 u Varijanti 2

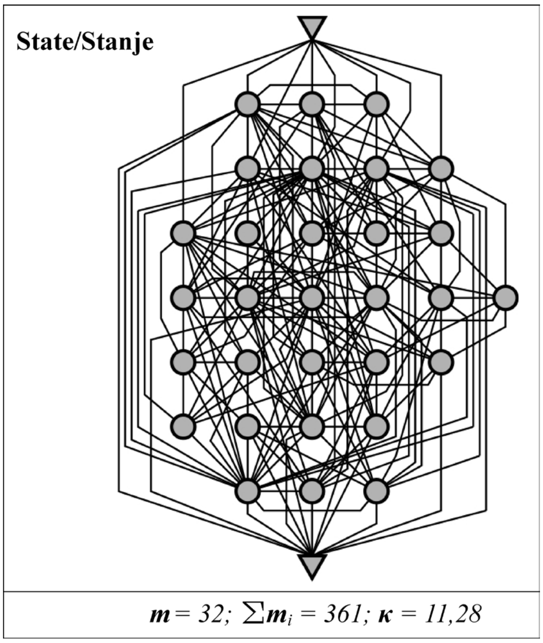


Figure 12. Complexity degree - state of production structure
Slika 12. Stupanj složenosti - stanja proizvodne strukture

*Project - **Variant 1** of the production structure*

The observed variant of production structures was designed according to product principle with two WUs which generated relations between the elements and the degree of complexity presented in Figure 13.

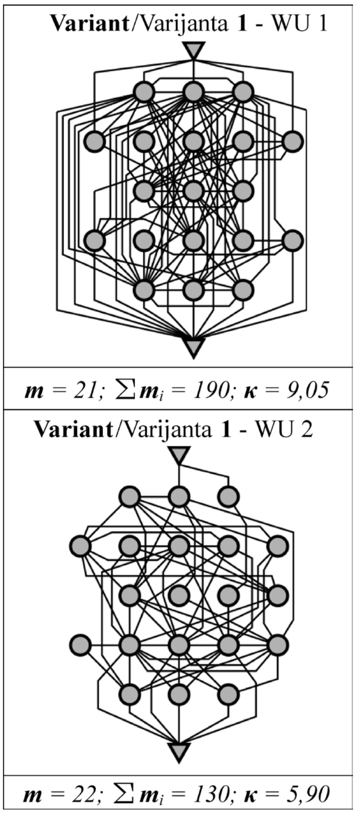


Figure 13. Complexity degree for Variant 1 - project
Slika 13. Stupanj složenosti Varijante 1 - projekt

*Project - **Variant 2** of production structure*

The observed variant of production structure was designed upon the product principle with four WUs which generated relations between the elements and the degree of complexity presented in Figure 14.

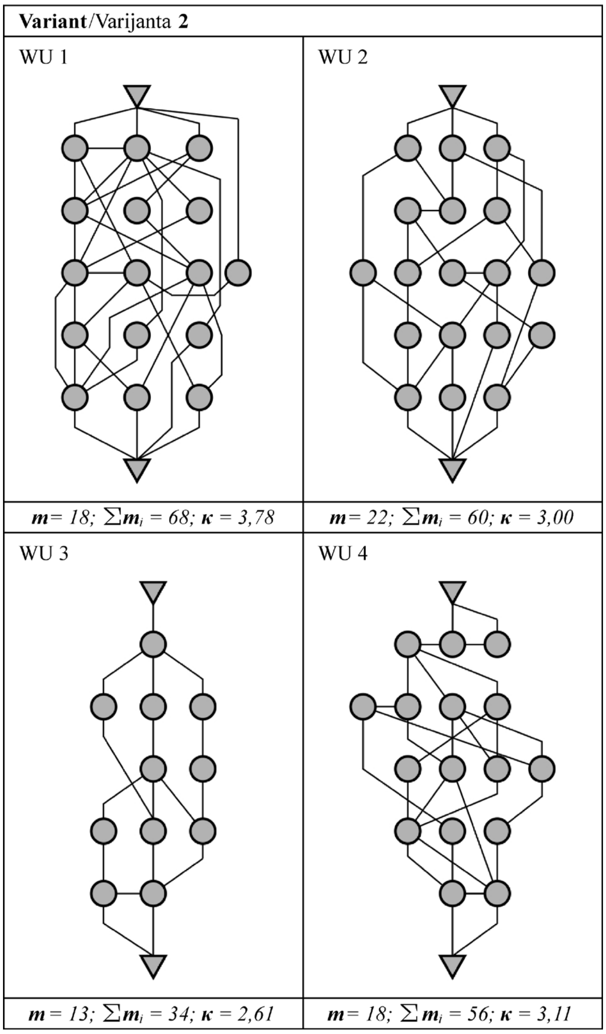


Figure 14. Complexity degree for Variant 2 - project
Slika 14. Stupanj složenosti Varijante 2 - projekt

The analysis of the values in Figure 13, 14 and 15 and dependency (***m-κ***) in Figure 15 for the observed example of production structure shows that:

- by projecting production structures of an enterprise on the basis of group approach in flows designing, transformation from process to product flows designing is made possible,
- by designing more variants of production structures, their degree of complexity can be significantly managed and
- the degree of complexity of a certain variant of production structure is determined by the quality of project of working units (WU) concerning their structure and size.

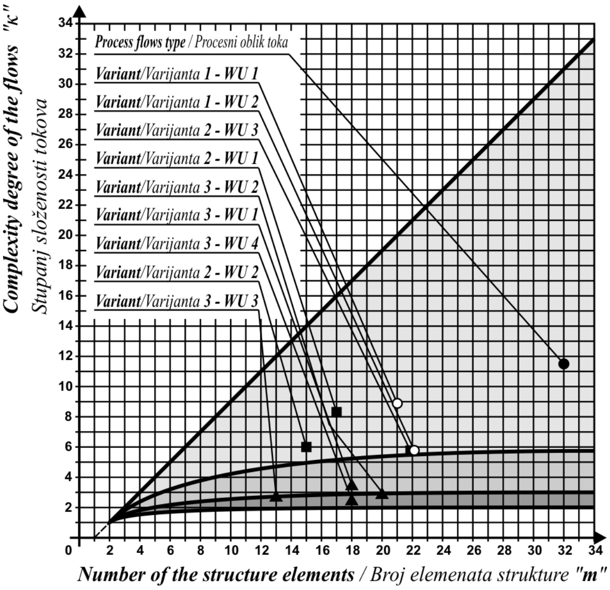


Figure 15. Complexity degree for all the observed structure variants

Slika 15. Stupanj složenosti svih posmatranih varijanti proizvodne strukture

3.3. The possibilities of designing production structures of lower complexity

Experience in development of production structures with WU as the core has shown that this approach enables the transformation from the most widespread process flow design into the more effective product flow design [69, 76]. The dependency (***m-κ***) which was analyzed in real enterprises shows that additional analysis is needed towards the selection of the most adequate variant of production structure, in the sense of moving towards the lower limit of the degree of complexity of flows (possibilities are shown in Figure 16).

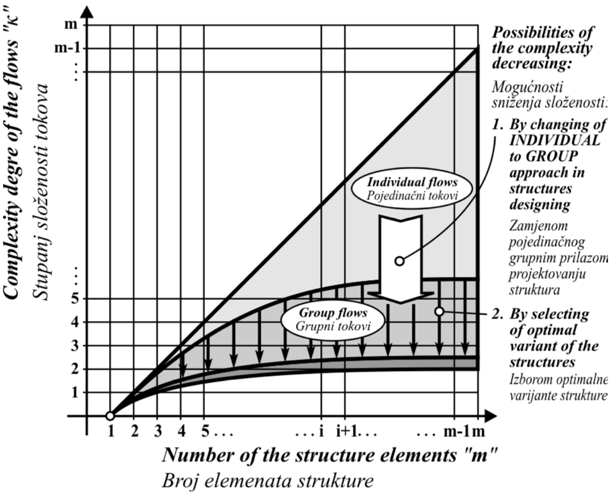


Figure 16. The possibilities of lowering the complexity degree of production structures

Slika 16. Mogućnosti sniženja stupnja složenosti proizvodnih struktura

4. Production Structures Flexibility

4.1. A Definition

The ability of enterprises to adapt to changes in the surroundings and to the disorders in the work process is their extremely important characteristic called *flexibility* [32-33, 58]. Considering the characteristics of enterprise structures and the character of changes, three components of flexibility [67, 71] can be defined:

- characteristics of elements - *technological flexibility*,
- capacity of system elements - *capacity flexibility*,
- dependability of system flows - *flexibility of flows*.

Technological Flexibility

Technological flexibility is determined by the parameters of technological system elements and by the characteristics of the work objects.

The measure of technological flexibility of a system's structures [15, 68, 73] (Figure 17) is represented by the likelihood with which the given element of a structure, within the certain installed parameters, will accept a group of work objects on which part of the work should be done in accordance with the projected technological procedures.

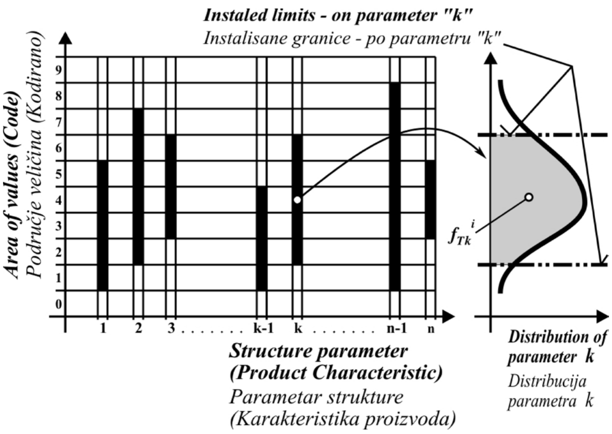


Figure 17. Technological Flexibility

Slika 17. Tehnološka fleksibilnost

Capacity Flexibility

Capacity flexibility is determined by the ability of elements, parts of the structure and the entire system to do that amount of work that is necessary for manufacturing the projected amount of the work object.

The measure of capacity flexibility [22, 70, 72] is determined by (non-) existence of capacity reserve as represented by next relation (Figure 18):

$$f_k^{\,i} = \frac{K_{eu}^{\;i} - K_{ep}^{\;i}}{K_{eu}^{\;i}} = 1 - \frac{K_{ep}^{\;i}}{K_{eu}^{\;i}}, \qquad (1)$$

where $\boldsymbol{f_k^i}$ is the degree of capacity of flexibility of a workplace *"i"* in the system *(i =1,2...m)*, $\boldsymbol{K}_{eu}^{\;i}$ - installed and $\boldsymbol{K}_{ep}^{\;i}$ - required capacity of that workplace.

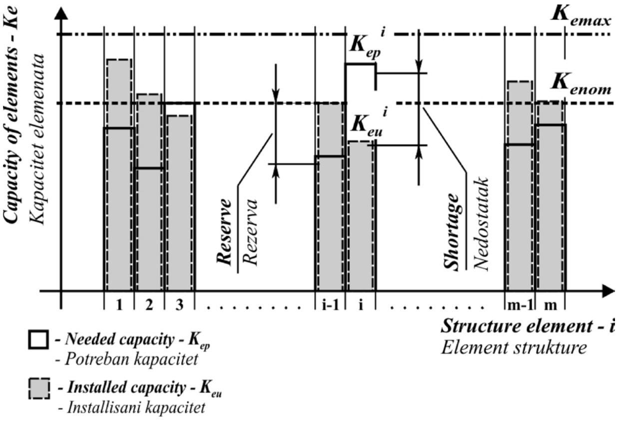


Figure 18. Capacity Flexibility

Slika 18. Kapacitivna fleksibilnost

Flexibility of Flows

Flows flexibility is determined by flows capacity (Figure 19), the relation between structure complexity degree (κ_p) and maximum complexity degree of the structure with a determined number of elements (κ_m):

$$f_p = \frac{\kappa_p}{\kappa_m}. \qquad (2)$$

Considerations of production structures flexibility indicate the existence of a close relationship between some components of flexibility in a way that:

- parameters of structure elements, i.e. the value of technological flexibility degree and
- the value of the existing and the reserve of the capacity, i.e. the value of capacity flexibility degree,

in the sense of compatibility between the technological and capacity flexibility in sections of flow, enable relationships between them, i.e. flows flexibility value.

$$f_p = f(f_t^{(i)}; f_k^{\,i}). \qquad (3)$$

4.2. Results of production structures flexibility research

Technological component of production structures flexibility

Research into the value of the technological component of a system's structure points to significant possibilities of maintaining certain characteristics on the desired level. The main result of the research was the following [67, 72, 76]:

- Using the sample of 30 production programmes of real industrial systems, the technological component of flexibility was determined in the conditions: *state - individual approach* to flow designing and *process approach* to structure designing, and *project - group approach* to flow designing and *product approach* to structure designing. More than 10,000 work objects and 100 technological systems were analysed;
- In accordance with the presented definition (Figure 17), basic dimensions of parts were analysed and technological component of flexibility determined (for the same enterprise- example from part 3.2), taking into consideration the possibility of accepting the work object, as shown in Figure 20a and 20b.

Capacity component of production structures flexibility

For the same enterprise and production structures variants from part 3.2, the research gave information about the degree of capacity flexibility, i.e. the average utilization degree (■) and average capacity reserve (■), shown in Figure 21a, 21b and 21c.

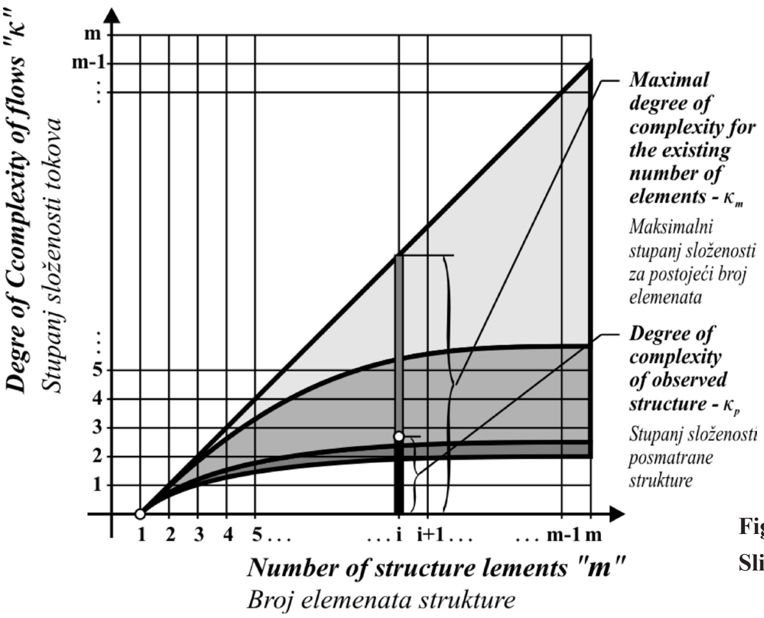


Figure 19. Flexibility of flows

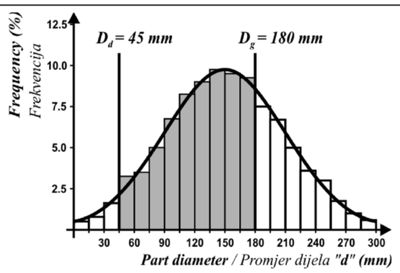
Slika 19. Fleksibilnost tokova

Technological system: 0250 Universal lathe
Tehnološki sistem: Univerzalni tokarski stroj
Characteristic: DIAMETER OF PARTS
Karakteristika: PROMJER PREDMETA RADA

BEFORE DESIGNING / PRIJE PROJEKTOVANJA

Size of sample: Veličina uzorka	120	Distribution: NORMAL Distribucija: NORMALNA □$_x$(d) = 150.000 □$_x$(d) = 70.863
Interval beginning: Početak intervala	0	
Interval end: Kraj intervala	300	
Interval width: Širina intervala	15	

DISTRIBUTION DIAGRAM / DIJAGRAM RASPODJELE



ACCOUNTING OF FLEXIBILITY
PRORAČUN FLEKSIBILNOSTI

$x_g(d) = 180$ $x_d(d) = 45$	$P_g(d) = 0.6628$ $P_d(d) = 0.0694$	$f_{T,d}$ = **0.5934**

Figure 20a. An example of the results of technological flexibility research - before designing

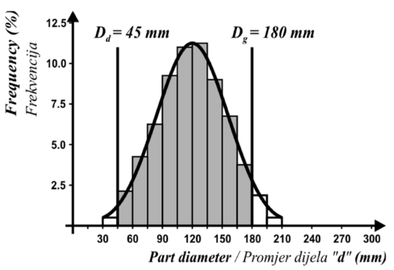
Slika 20a. Primjer rezultata istraživanja tehnološke fleksibilnosti - prije projektovanja

Technological system: 0250 Universal lathe
Tehnološki sistem: Univerzalni tokarski stroj
Characteristic: DIAMETER OF PARTS
Karakteristika: PROMJER PREDMETA RADA

AFTER DESIGNING / POSLIJE PROJEKTOVANJA

Size of sample: Veličina uzorka	75	Distribution: NORMAL Distribucija: NORMALNA □$_x$(d) = 120.000 □$_x$(d) = 28.336
Interval beginning: Početak intervala	30	
Interval end: Kraj intervala	210	
Interval width: Širina intervala	15	

DISTRIBUTION DIAGRAM / DIJAGRAM RASPODJELE



ACCOUNTING OF FLEXIBILITY
PRORAČUN FLEKSIBILNOSTI

$x_g(d) = 180$ $x_d(d) = 45$	$P_g(d) = 0.9830$ $P_d(d) = 0.0040$	$f_{T,d}$ = **0.9790**

Figure 20b. An example of the results of technological flexibility research - after designing

Slika 20b. Primjer rezultata istraživanja tehnološke fleksibilnosti - poslije projektovanja

State: Process type of production structure
Stanje: Procesni oblik proizvodne strukture

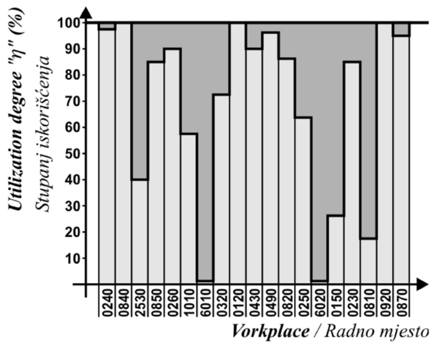
Average utilization degree: Prosječni stupanj iskorišćenja: η_{ii} = 0.67	Average capacity reserve: Prosječna rezerva u kapacitetu: R_i = 0.33

Figure 21a. An example of the results of capacity flexibility research (State)

Slika 21a. Primjer rezultata istraživanja kapacitivne fleksibilnosti (Stanje)

Project: Variant 1 (two working units)
Projekat: Varijanta 1 (dvije radne jedinice)

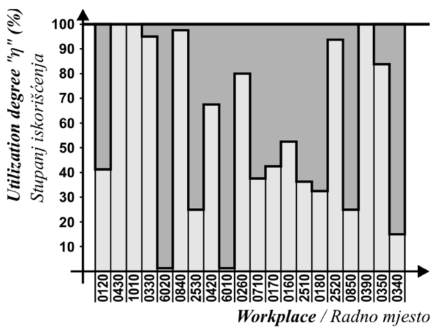
Working unit / Radna jedinica: WU 1



Average utilization degree: Prosječan stupanj iskorišćenja: η_{ii} = 0.64

Average capacity reserve: Prosječna rezerva kapaciteta: R_i = 0.36

Working unit / Radna jedinica: WU 2



Average utilization degree: Prosječan stupanj iskorišćenja: η_{ii} = 0.56

Average capacity reserve: Prosječna rezerva kapaciteta: R_i = 0.44

Figure 21b. An example of the results of capacity flexibility research (Variant 1)

Slika 21b. Primjer rezultata istraživanja kapacitivne fleksibilnosti (Varijanta 1)

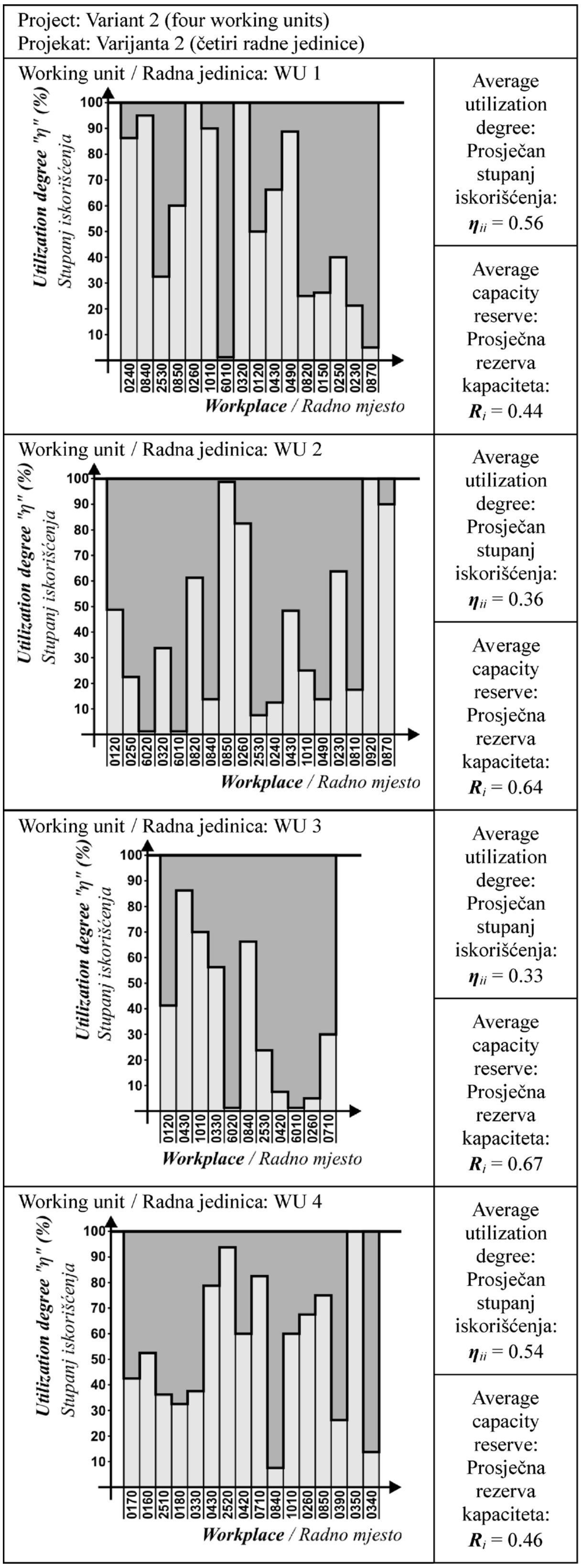


Figure 21c. An example of the results of capacity flexibility research (Variant 2)

Slika 21c. Primjer rezultata istraživanja kapacitivne fleksibilnosti (Varijanta 2)

Flexibility of flows of production structures

For the same enterprise and variants of production structure from part 3.2, the degree of flexibility of flows is presented in Table 8.

Table 8. Flexibility of Flows of Production Structures

Tablica 8. Fleksibilnost tokova proizvodnih struktura

Structure variant /Varijanta strukture		m	$\sum m_i^{(p)}$	$\kappa_p=\sum m_i/m$	$\kappa_m=m$-1	$f_p=\kappa_p/\kappa_m$
State/Stanje		32	361	11.28	31	0.36
Variant / Varijanta 1	WU 1	21	190	9.05	20	0.45
	WU 2	22	130	5.90	21	0.28
Variant / Varijanta 2	WU 1	18	68	3.78	17	0.22
	WU 2	20	60	3.00	19	0.16
	WU 3	13	34	2.61	12	0.22
	WU 4	18	56	3.11	17	0.18

The investigation into the flexibility of flows of production structures was carried out in more than thirty real programmes. The results show that the flexibility component is significantly higher in the process approach than in the product approach to flows designing.

The presented relations are logical, bearing in mind the definition of the flexibility of flows and the fact that the process approach enables the maximum number of connections between structural elements, i.e. it enables a higher level of flexibility of flows than any other. Thus, the relation:

$$\kappa_p^{(procesflowtype)} \rightarrow \kappa_m,\ i.e.\ f_p^{(p)} = \frac{\kappa_p^{(p)}}{\kappa_m} \rightarrow 1. \qquad (4)$$

The results of the analyses in the above described real production programme show that:

- the flexibility of flows is directly connected to the degree of complexity of production structures and
- efforts should be made towards finding the most favourable solutions by comparing the quality of the variants in terms of the degree of flexibility of flows, instead of providing the maximum flexibility of flows for the conditions that are generated by the characteristics of production programme.

4.3. The possibilities of designing flexible production structures

Research on the flexibility of production structures [59, 67] has shown that when group approach is used in designing flows and product approach in designing production structures - the division of the system's structure into *working units* [64, 69], as a result of the narrowing of the area of work object characteristics divergence in the working unit, variants of structure can be formed in the case of technological flexibility (Figure 22) in which the technological component does not decrease in relation to state. On the contrary, elements of structure - technological systems with an increased reserve for accepting and manufacturing the work object - occur in the greatest number of the observed cases.

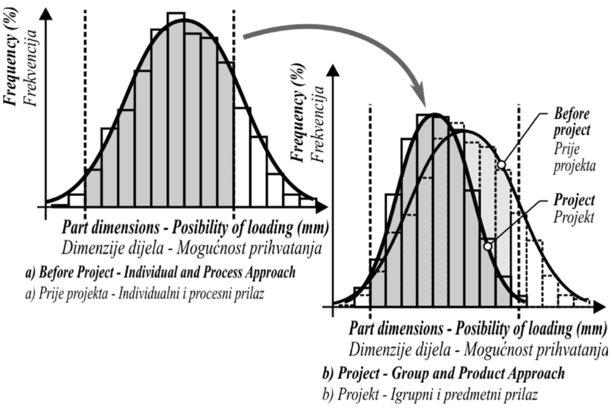


Figure 22. Increase of the technological flexibility

Slika 22. Povišenje tehnološke fleksibilnosti

Research into the capacity flexibility of production structures has shown that the division of the system's structure into working units, and for the purpose of their independency, leads to the design of parallel workplaces in which load/capacity relation provides a higher level of capacity flexibility and a lower degree of complexity of a structure, but also a lower degree of utilization in comparison with the process flow design (Figure 23).

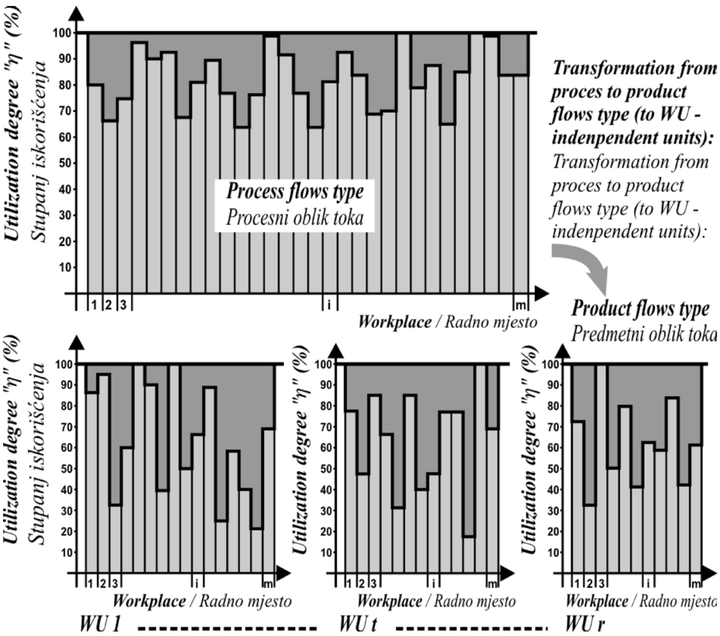


Figure 23. The change in the utilization degree

Slika 23. Promena stupnja iskorišćenja

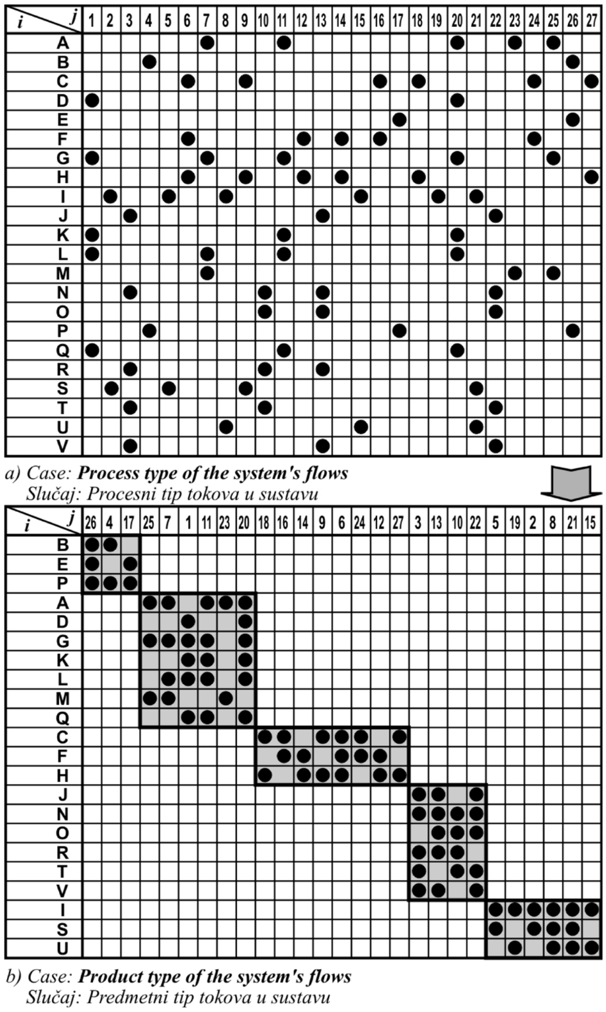


Figure 24. The explanation of the required and satisfactory degree of flexibility of flows

Slika 24. Objašnjenje potrebnog i dovoljnog stupnja fleksibilnosti tokova

This investigation, and those in [59-61] proved that in cases of production structures based on process flow design - which were always cases of state, flexibility of flows is not used enough and it is unnecessarily over-dimensioned. This way, one of the greatest limitations to achieving the desired effects has been installed into process organized production structures / the limitation of high complexity degree and low manageability.

The example of the analysis of flows [62-63] (Figure 24) presented as the matrix of interdependence between the work object in the production programme and elements of the production structure confirms this.

In Figure 24, the intersection of column *"j"* (work objects 1, 2, 3, etc.) and line *"i"* (structural elements A, B, C…) in the matrix of interdependence is designated as *"●"*, or it is not designated at all. The existence of this symbol in the field *"**i,j**"* denotes performing operation *"**i**"* on the work object *"**j**"*, whereas the absence of this symbol in the field *"**i,j**"* means the work object *"**j**"* does not undergo operation *"**i**"*. The general design of the observed matrix, which is of process type, is disorganized (Fig. 24a), but by swapping lines and columns, without changing the flows in the system, an organized matrix design, characteristic of product design, can be established. This shows that the necessary number of connections between elements of a production structure is technologically limited and much smaller than the number in the process structure. It can be concluded that there is a viable possibility of applying a structure with a lower degree of conditionality of flows - complexity, and at the same time a lower degree of flexibility of flows.

5. Conclusion

The contribution of this paper is the definitions and determination of the measures of the two most important characteristics of an enterprise's production structures - *complexity* and *flexibility*, and establishing their relationship.

Production structures complexity is defined by complexity degree. While in the great body of literature complexity is measured by size (number of structural elements), this paper observes the complexity degree as comprising a number of interrelationships between the elements of a structure, beside the number of elements. Complexity of production structures is thus identified as complexity of a network of flows in a system.

Flexibility of production structures consists of three interdependent components: technological component, capacity component and flexibility of flows. As these components are measured by different standards, no universal measure of flexibility can be given.

Analyses of complexity and flexibility of production structures performed on thirty different production programmes gave results which mostly coincide with the results presented in this text. Therefore, the following can be concluded:

1. Unlike in process flow designing, designing production structures of an enterprise on the principles of group and product approach, as independent working units, forms the basis for lowering the degree of complexity of structures;
2. Unlike in process flow designing, in designing production structures of an enterprise on the principles of group and product approach, as independent working units, conditions are provided for:
   - increasing the degree of technological flexibility of structures
   - increasing the capacity flexibility of structures
   - finding satisfactory solutions concerning the flexibility of flows which improve the total quality of structures.

Flexibility and complexity research results in defining and measuring the key performances which illustrate the quality of the structure of an enterprise. This way, through different analyses, the basis has been formed for quality evaluation as well as for comparison of real enterprises' structures.

However, flexibility and complexity characteristics of enterprises' structures, the way they are defined in this paper, could be used in future research as criteria for the analysis and choice of the optimum variant in the procedures of designing structures of enterprises.

REFERENCES

[1] WIENDAHLA, H. P.; SCHEFFCZYK, H.: *Simulation Based Analysis of Complex Production Systems with Methods of Nonlinear Dynamics*, CIRP Annals - Manufacturing Technology, vol. 48, no. 1, 357-360, 1999.

[2] KATZORKE, I.; PIKOVSKY, A.: *Chaos and complexity in a simple model of production dynamics*, Discrete Dynamics in Nature and Society, vol. 5, no. 3, 179-187, 2000.

[3] MCELROY, M. W.: *Integrating complexity theory, knowledge management and organizational learning*, Journal of Knowledge Management, vol. 4, No 3, 195-203, 2000.

[4] CAl INESCU, A.; EFSTATHIOU, J.; SCHIRN, J.; BERMEJO, J.: *Applying and assessing two methods for measuring complexity in manufacturing*, Journal of the Operations research Society, vol. 49, no. 7, 723-733, 1998.

[5] ELMARAGHY, H. A.; KUZGUNKAYA, O.; URBANIC, R. J.: *Manufacturing Systems Configuration Complexity*, CIRP Annals - Manufacturing Technology, vol. 54, no. 1, 445-450, 2005.

[6] KUZGUNKAYA, O.; ELMARAGHY, H. A.: *Assessing the structural complexity of manufacturing systems configuration*s, International Journal of Flexible Manufacturing Systems, vol. 18, no. 2, 145-171, 2006.

[7] . SCHUH, G; SAUER, A.; Doering, S.: *Managing complexity in industrial collaborations*, International Journal of Production Research, vol. 46, no. 9, 2485-2498, 2008.

[8] SHIELDS, T.; KILPATRICK, A.; POZSAR, M.; RAMIREZ-DE-ARELLANO, L. G.; REYNAL, V.; QUINT, M.; SCHOONMAKER, J.: *Lean Implementation Considerations in Factory Operations of Low Volume/High Complexity Production Systems*, Massachusetts Institute of Technology, 142, 1997.

[9] BRAUNER, N., CRAMA, Y., GRIGORIEV, A., VAN DE KLUNDERT, J.: *Multiplicity and complexity issues in contemporary production scheduling*, Statistica Neerlandica, vol. 61, no. 1, 75-91, 2007.

[10] ADERHOLD, J.; DUSCHEK, S.: *Organizing social complexity in production networks*, Journal of the Academy of Business and Economics, 2004.

[11] MIHNEA, C. M.; BAUER, R. M.: *On the relationship between organizational complexity and organizational structuration*, *Organization Science*, vol. 15, no. 1, 98-118, 2004.

[12] MARTINEZ, M. T.; FOULETIER, P.; PARK, K. H.; FAVREL, J.: *Virtual enterprise - organisation, evolution and control*, International Journal of Production Economics, vol. 74, no. 1-3, 225-238, 2001.

[13] MILTENBURG, J.: *Computational complexity of algorithms for MRP and JIT production planning problems in enterprise resource planning systems*, Production Planning and Control, vol. 12, no. 2, Taylor and Francis Ltd, 198-209, 2001.

[14] PERONA, M.; MIRAGLIOTTA, G.: *Complexity management and supply chain performance assessment. A field study and a conceptual framework*, International Journal of Production Economics, vol. 90, no. 1, 103-115, 2004.

[15] SCHEWCHUK, J. W.; MOODIE, C. L.: *Definition and Classification of Manufacturing Flexibility Types and Measures*, International Journal o Flexible Manufacturing Systems, No 10, Kluwer Academic Publishers, 325-349, 1988.

[16] GUPTA, Y. P.; GOyAl , S.: *Flexibility of Manufacturing Systems: Concepts and Measurement*s, European Journal of Operations Research, no. 2, 119-135, 1989.

[17] CARLSSON, B.: *Flexibility and the Theory of the Firm*, International Journal of Industrial Organization, No 7, 179–203, 1989.

[18] SETHI, A. K.; SETHI, S. P.: F*lexibility in Manufacturing: A Survey*, International Journal of Flexible Manufacturing Systems, vol. 2, no. 4, 289–328, 1990.

[19] D'SOUZA, D. E.; WIll IAMS, F. P.: *Toward a Taxonomy of Manufacturing Flexibility Dimensions*, Journal of Operations Management, no. 5, 577-593, 2000.

[20] yA O, D. D.; BUZACOTT, A.: *Modelling the performance of flexible manufacturing systems*, International Journal of Production Research, vol. 23, no. 5, 945 - 959, 1985.

[21] SONSINO, D.; MANDElb AUM, M.: Mandelbaum, *On Preference for Flexibility and Complexity Aversion: Experimental Evidence*, Theory and Decision, vol. 51, no. 2-4, Springer Netherlands, 197-216, 2001.

[22] BUITENHEK, R.; bAy NAT, B.; DALLERY, Y.: *Production Capacity of Flexible Manufacturing Systems with Fixed Production Ratios*, International Journal o Flexible Manufacturing Systems, no 14, Kluwer Academic Publishers, 203–225, 2002.

[23] PAGELL, M.; KRAUSE, D. R.: *Re-exploring the relationship between flexibility and the external environment*, Journal of Operations Managemen*t,* No 21, Elsevier B.V., 629–649, 2004.

[24] HAUSER, D. P.; DE WECK, O.: *Flexibility in component manufacturing systems: evaluation framework and case study*, Journal of Intelligent Manufacturing, 421-432, 2007.

[25] bASNET , C., MIZE, J. H.: *Scheduling and control of flexible manufacturing systems: a critical review*, International Journal of Computer Integrated Manufacturing, vol. 7, no. 6, 340-355, 1994.

[26] BORENSTEIN, D.: *Intelligent decision support system for flexible manufactu*ring system design, *Annals of Operations Research*, No 77, J.C. Baltzer AG, Science Publishers, 129-156, 1998.

[27] VOKURKA, R. J.; O'LEARY-KELLY, S.: *A Review of Empirical Research on Manufacturing Flexibility*, Journal of Operations Management, No. 4, 16-24, 2000.

[28] JORDAN, W. C.; GRAVES, S. C.: *Principles of the benefits of manufacturing process flexibility*, Management Science, no. 4, 577-594, 1995.

[29] DANIEl S, R. L.; MAZZOLA, J. B.; SHI, D.: *Flow Shop Scheduling with Partial Resource Flexibility*, Management Science, vol. 50 Issue 5, 658-669, 2004.

[30] UPTON, D. M.: *The management of manufacturing flexibility*, California Management Review*,* 36(2), 72–89, 1994.

[31] DE GROOTE, X.: *The Flexibility of Production Processes: A General Framework*, Management Science, no. 7, 933-945, 1994.

[32] SCHULZ, A. P.; FRICKE, E.: *Incorporating flexibility, agility, robustness, and adaptability within the design of integrated systems-key to success?* 18th DASC, Gateway to the NewMillenium, IEEE, 1999.

[33] FRICKE, E.; SCHULZ, A. P.; WENZEL, S.; NEGEl E, H.: *Design for changeability of integrated systems within a hyper-competitive environment*, Conference "Systems Approach to Product Innovation and Development in Hyper-Competitive Environments", INCOSE, Colorado, 2000.

[34] BARAD, M.; SIPPER, D.: *Flexibility in Manufacturing Systems: Definitions and Petri Net Modeling*, InternationalJournal of Production Research, vol. 26, no. 2, 237-248, 1988.

[35] BENJAAFAR, S.: *Modeling and Analysis of Flexibility in Manufacturing Systems*, Ph.D. dissertation, School of Industrial Engineering, Purdue University, West Lafayette, 1992.

[36] BROWNE, J.; DUb OIS, D.; RATHMILL, K.; SETHI, S. P.; STECKE, K. E.: *Classification of Flexible Manufacturing Systems*, FMS Magazine, 114-117, 1984.

[37] GERWIN, D.: *An Agenda for Research on the Flexibility of Manufacturing Processes*, International Journal of Operations and Production Management, vol. 7, no. 1, 38-49, 1989.

[38] GERWIN, D.: *Manufacturing Flexibility: A Strategic Perspective*, Management Science, vol. 39, no. 4, 395-410, 1993.

[39 FRAZELLE, E. H.: *Flexibility: A Strategic Response in Changing Times*, Industrial Engineering, 17-20, 1986.

[40] GOLDHAR, J. D.; JEl INEK, M.: *Plan for Economies of Scope*, Harvard Business Review, vol. 61, 141-148, 1983.

[41] MANDElb AUM, M.: *Flexibility in Decision Making: An Exploration and Unification*, Ph.D. thesis, Department of Industrial Engineering, University of Toronto, Toronto, Canada, 1978.

[42] BRILL, P. H.; MANDElb AUM, M.: *On Measures of Flexibility in Manufacturing Systems*, International Journal of Production Research, vol. 27, no. 5, 747-756, 1989.

[43] CHANDRA, P.; TOMb AK, M. M.: *Models for the Evaluation of Routing and Machine Flexibility*, European Journal of Operational Research, vol. 60, 156-165, 1992.

[44] DOONER, M.; DE SIl VA, A.: *Conceptual Modeling to Evaluate the Flexibility Characteristics of Manufacturing Cell Designs*, Proceedings of the 28th Matador Conference, UMIST, Manchester, United Kingdom, 1990.

[45] CHRYSSOLOURIS, G.; lEE , M.: *An Assessment of Flexibility in Manufacturing Systems*, Manufacturing Review, vol. 5, no. 2, 105-116, 1992.

[46] PYOUN, Y. S.; CHOI, B. K.: *Quantifying the Flexibility Value in Automated Manufacturing Systems*, Journal of Manufacturing Systems, vol. 13, no. 2, 108-118, 1994.

[47] SON, Y. K.; PARK, C. S.: *Economic Measure of Productivity, Quality and Flexibility in Advanced Manufacturing Systems*, Journal of Manufacturing System*s*, vol. 6, no. 3, 193-207, 1987.

[48] YILMAZ, O. S.; DAVIS, R. P.: *Flexible Manufacturing Systems: Characteristics and Assessments*, Engineering Management International, vol. 4, no. 3, 209-212, 1987.

[49] CHUNG, C. H.; CHEN, I. J.: *A Systematic Assessment of the Value of Flexibility for an FMS*, Proceedings of the Third ORSA/TIMS Conference on Flexible Manufacturing Systems (Cambridge, MA), K.E. Stecke and R. Suri (Eds.), Elsevier Science Publishers, B.V., Amsterdam, The Netherlands, 27-34, August 1989.

[50] KUMAR, V.; KUMAR, U.: *Manufacturing Flexibility: A New Approach to Its Measurement*, IIE InternationalIndustrial Engineering Conference Proceedings, 469–475, 1987.

[51] BUZACOTT, J. A.: *The Fundamental Principles of Flexibility in Manufacturing Systems*, Flexible Manufacturing Systems, Proceedings of First International Conference, Amsterdam, The Netherlands, 23-30, October 1982.

[52] CARTER, M. F.: *Designing Flexibility into Automated Manufacturing System*s, Proceedings of the Second ORSA/TIMS Conference on Flexible Manufacturing Systems (Ann Arbor, MI), K.E. Stecke and R. Suri (Eds.), Elsevier Science Publishers, B.V., Amsterdam, The Netherlands, 107-118, August 1986.

[53] STEINHILPER, R.: *Recommendations for FMS Planning and Realization*, in *Flexible Manufacturing Systems*, H.J. Warnecke and R. Steinhilper (Eds.), Springer-Verlag, Berlin, 87-97, 1985.

[54] TAYMAZ, E.: *Types of Flexibility in Single-Machine Production System*, International Journal of Production Research, vol. 27, no. 11, 1891-1899, 1989.

[55] JONES, A. T.; MClEAN , C. R.: *A Proposed Hierarchical Control Model for Automated Manufacturing Systems*, Journal of Manufacturing Systems, vol. 5, no. 1, 15-25, 1986.

[56] GUPTA, D.; BUZACOTT, J. A.: *A Framework for Understanding Flexibility of Manufacturing Systems*, Journalof Manufacturing Systems, vol. 8, no. 2, 89-97, 1989.

[57] Sl ACK, N.: *The Flexibility of Manufacturing Systems*, International Journal of Operations and Production Management, vol. 7, no. 4, 35-45, 1987.

[58] ZELENOVIC, D.: *Flexibility - A condition for effective production systems*, International Journal of Production Research, vol. 20, no. 3, 319–337, 1982.

[59] ZELENOVIĆ, D.; ĆOSIĆ, I.; MAKSIMOVIĆ, R.: *Design and reengineering of production systems: Yugoslavian (IISE) approaches*, vol. I6 in Monograph *Group Technology and Cellular Manufacturing - State of-The-Art Synthesis of Research and Practice*, Kluwer Academic Publishers, Massachusetts, 517-537, 1998.

[60] BURBIDGE, J. L.: *The Principles of Production Control - Fourth Edition*, Macdonald and Evans ltd, Estover, Plymouth, 1978.

[61] BURBIDGE, J. L.: *The Introduction of Group Technology*, Heineman, London, 1978.

[62] BURBIDGE, J. L.: *Period batch control*, Oxford University Press, Clarendon Press, Oxford, 1996.

[63] BURBIDGE, J. L.; ZELENOVIĆ, D.: *Using P.F.A. to plan G.T. for a new Factory*, Material Flow, no. 1, 129-140, 1983.

[64] ZELENOVIĆ, D.; BURBIDGE, L. J.; ĆOSIĆ, I.; MAKSIMOVIĆ, R.: *The division of large complex production systems, into independent, autonomous units*, Proceedings of 13th International Conference of Production Research, Jerusalem, 213-215, 1995.

[65] ZELENOVIĆ, D.; ŠEŠl IJA, D.; ĆOSIĆ, I.; MAKSIMOVIĆ, R.: *On the Flexibility of Robotic Assembly*, Proceedings of 10th International Conference on Production Research, Nottingham, 552-553, 1989.

[66] ZELENOVIĆ, D.; TESIC, Z.: *Period batch control and group technology*, International Journal of Production Research, Vol 26, No 4, 539-552, 1988.

[67] MAKSIMOVIĆ, R.: *Complexity and flexibility of industrial system's structures*, Monograph, University of Novi Sad, Faculty of technical sciences, 2003, in serbian.

[68] PALČIČ, I.; BUCHMEISTER, B.; POLAJNAR, A.: *Model for production planning and control in make-to-order manufacturing*, Acta Mech. Slov., vol. 6,2, 175-180, 2004.

[69] VUJICA-HERZOG, N.; POLAJNAR, A.; TONCHIA, S.: *Development and validation of business process reengineering (BPR) variables: a survey research in Slovenian companies*, Int. Journal of Production Research, vol. 45, no. 24, 5811-5834, 2007.

[70] BUCHMEISTER, B.; KREMLJAK, Z.; PANDŽA, K.; POLAJNAR, A.: *Simulation study on the performance analysis of various sequencing rules*, International Journal of Simulation Modelling, vol. 3, no. 2-3, 80-89, 2004.

[71] TASIČ, T.; BUCHMEISTER, B.; AČKO, B.: *The development of advanced methods for scheduling production processes*, Journal of Mechanical Engineering, vol. 53, no. 12, 844-857, 2007.

[72] ZELENOVIĆ, D.; MAKSIMOVIĆ, R.: *Flexibility of effective enterprises*, International Journal of Industrial Systems, Institute of Industrial Systems Engineering, Novi Sad, vol. 1, no. 2, 33-38, 1999.

[73] MAKSIMOVIĆ, R.; LALIĆ, B.: *Flexibility and complexity of effective enterprises*, Journal of Mechanical Engineering vol. 54, no. 11, 768-782, 2008.

[74] POLI, M.; MITHIBORWALA, H.S.; MAKSIMOVIĆ, R.; LALIĆ, B.: *Project strategy: selecting the best project structure*, PICMET Conference 09, Portland International Center for Management of Engineering and Technology, Portland, 1276-1281, 2009.

[75] SCHMIGALA, H.: *Statische Systemgleichungen - Modelle zur Entscheidungsfindung über diskrete Produktionssysteme*, Wissenschaftliche der Friedrich-Schiler Universität, Jena, H.3, 445-453, 1989.

[76] ZELENOVIĆ, D.; ĆOSIĆ, I.; MAKSIMOVIĆ, R.: *Ein beitrag zur erforschung der bedingungen für die herabsetzung des komplexitätsgrads von produktionssystemstrukturen*, WT Werkstattstechnik, vol. 1, no. 11/91, 656-660, 1991.

[77] SCHMIGALA, H.: *Vom planwirtschaftlichen Betrieb zum marktwirtschaftlichen Unternehmen, von der Betriebsprojektierung zur Fabrikplanung*, Deutch - deutsches Symposium "Fabrikplanung", Jena, 3-41, 1990.

[78] MAKSIMOVIĆ, R.: *Investigation of production structure variant influence on degree of complexity and flexibility of industrial systems*, Ph.D. thesis, University of Novi Sad, Novi Sad, Serbia, 1999, in serbian.