TECHNICAL UNIVERSITY IN KOŠICE
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FLEXIBLE AND MODULAR PRODUCTION SYSTEMS

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The monograph aims to acquaint the professional public and the members of academic community with the modular structure of production technology in the field of Mechanical Engineering, focusing on Manufacturing Technology. The monograph presents the results of the research into modular construction of production technology, which uses its intrinsic understanding of the construction of the patented Universal Rotary Module - URM. The monograph draws on the results of the authors' own research activities within the framework of the grant project VEGA 1/0437/17 Research and development of rotary module with an unlimited degree freedom of rotation. This work was supported by the Slovak Research and Development Agency under the Contract no. APVV-18-0413.

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PREFACE

We prepared the present scientific monograph in order to acquaint the professional public, but also students majoring in Mechanical Engineering, with selected results of research into flexible production systems focusing on modular production systems in Manufacturing Technology and the related fields and also with building such systems. Our unique contribution to the field is the patented Universal Rotary Module URM.

Moreover, it is the ambition of the monograph to contribute to the field of modular structures by summarizing and unifying widely used concepts employed by various branches of mechanical engineering from their respective points of view and to precisely define individual structures from a single perspective.

Most of the terms also include an example from practice, or at least an idea for the future composition and execution of the structure.

The publication draws on the results of the authors' own research activity conducted under the grant project "VEGA 1/0437/17 Research and development of rotary module with unlimited degree of rotation" to be applied in construction of production machines and robots and from previous grant research projects, the partial results of which have been published in the works listed in the bibliography. The branch of engineering focusing on Production Machines and Equipment has developed and validated methodologies for virtual identification of modular production structures' workspaces. They can be applied to industrial practice of the existing, or potential producers of the structures in question.

This work was supported by the Slovak Research and Development Agency under the Contract no. APVV-18-0413.

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At this point, we would also like to thank our families for their humble support and unlimited tolerance they have afforded us so that we could work on the publication.

Košice December 16, 2019

Authors

Devoted to our dear wives, children and grandchildren

LIST OF ABBREVIATIONS

Ab0	A transformation matrix describing the position and rotation of the 0^{th} coordinate system pair in the D-H principle
AM_i	Unified modular unit (functional node, modular block, ...).
A_S	Machine system
A_Z	Machine
AVS	Automated production system
ARIZ	Algorithm of Solutions of Inventional Tasks. A tactical approach that supports the search for solutions that can be obtained within the FNA section. It shows how to find a solution
b_{ij}	i, j^{th} motion matrix member
CAI	Expert computer system for inventing the thinking of the designer, or a designer known under the commercial name of Tech Optimizer
D-H	"Denavit - Hartenberg" advantageous principle of arrangement and designation of coordinate systems of kinematic pair
DFX	Design For X
DOF	Degrees of Freedom
E	Element, the basic building element of a unified modular unit
EMF	Electromagnetic Fields
FM_i	Functional model of “i“ module
FNA	Functional Cost Analysis - solution strategy and identification of an improvement–suitable element
FMEA	Analysis of the possibility of defects and their consequences
GCS	Global Coordinate System
HPC	High Performance Cutting
ICNIRP	International Commission on Non-Ionizing Radiation Protection
Kaizen	Japanese for "Improvement" - philosophy focused on continuous improvement
Kanban	Workshop production management system using cards.
LCS	Local Coordinate System
LiPol	Lithium - Polymer battery
M_E	Existential matrix, expressing possibilities of module connection
M_P	Motion matrix, expressing motion possibilities of module connection
MC	Machining Centre
MEMS	Micro-electrical-mechanical systems
MPC	Multiprofessional Production Centre
MPRC	Multiprofessional Production Robotic Centre
MS	Modular system
MTS_s	Matrix of the system’s technical structure
MTS_f	Matrix of technical structure functionality
MTS_{pb}	Mobility matrix of technical structure
MTS	Modular technical system
MTS_{ψ}	Modular technical system arranged in the ψ system structure
NC	Numerical Control
PEH	Relative Effective Value - ratio of utility value and labor (cost)
PR	Industrial Robots
PRaM	Industrial Robots and Manipulators
PP	Working Area

QFD	Quality Function Deployment - method of quality planning, or a tool to transform customer requirements into product technical parameters
RMS	Reconfigurable Manufacturing System
STS	Structural Technical System
Lean layout	Manufacturing system with the structure focused on max. effectiveness
$\mathbf{U_i}$	Interface (compatibility of ij module $\mathbf{U_i}$ to $\mathbf{U_j}$)
URM	Unlimited Rotational Module
URM 01	Unlimited Rotational Module, variant 01
$\mathbf{X_i}$	Module input parameters (given requirements)
$\mathbf{X_{ij}}$	i,j^{th} member of the existential matrix
$\mathbf{Y_i}$	Module output parameters (features, operating functions), "**a**" active, "**p**" passive
TPM	Total Productive Maintenance
TQM	Total Quality Management
Trimming	Cleaning of the system from insignificant ties
TRIZ	Methodology of creative work by creating and solving innovative tasks
VS	Production machine
ψ	System structure

INTRODUCTION

Globalization has resulted in many changes on the market, also affecting industrial engineering. Characteristic features of this trend are a never-increasing competition on the world market, narrowed (in terms of time, finance) space for taking advantage of market opportunities and frequent changes (demand turbulence) in the demand for products. These trends (features) bring considerable risks to manufacturers, but also great opportunities. In order to take advantage of these opportunities, the mechanical engineering sector must deliver production systems capable of producing a wider range of products within the relevant product group and category. For these reasons, the technology of flexible manufacturing systems is becoming more widespread.

Flexible manufacturing systems have a well-established application in a rapidly changing manufacturing environment, characterized by sophisticated competition in ~~a~~ global context and by progressive changes in process technologies and their structure according to market requirements. Such systems necessitate rapid and factual integration of new technologies and new functions into both system and process relationships.

The outlined trends and their conditions and requirements call for a flexible approach to production to ensure:

- Operational adaptation of the production capacity of manufacturing systems to market requirements, i.e. achieving rapidly viable new products;
- Quick integration of modern process technologies and new features into the existing manufacturing systems capable of easily adaptation to dynamically changing batches of individual products.

Lean production as a concept that originated in the 1990s in the US. Its philosophy has also successfully taken root in Slovakia [1, 2]. Lean production is based on the idea of shortening time between customer and supplier. It eliminates waste in the chain that links them. Lean production focuses on increasing the value defined by customer requirements.

The current state of affairs confirms that manufacturers who operate according to the principles of lean manufacturing have their own concept, including a set of tools, techniques and methods they use to work within this concept. The set of tools, methods and techniques is in many cases very similar, Fig. 1. [1]

Proper use of lean manufacturing tools to eliminate the basic types of waste is important. The decisive point of the concept of such production is how its production systems are organized.

Fig. 1 Lean Manufacturing Tools

Flexible Manufacturing Systems – **FMS** enable flexible production of a product group on a single production system. Flexible cell manufacturing, which is a fundamental concept of flexible manufacturing systems, has recently become one of the most important production organizing systems. These arrangements are (include several types) theoretically and methodically based on the search for a mathematically modelled component-manufacturing cell relationship that would guarantee the production of different types of parts with a small number of pieces in a batch. The cell structure of the production systems facilitates interconnection between machines, saving on-going production time and space requirements. The operation of the machines is synchronized, and the material flow is fast (parts move between machines at an optimal distance). Production cells combine, assume and apply many benefits of other types of production structures, Tab. 1. Although this is a significant shift, these systems have not yet been widely utilized in production practice [3].

Tab. 1 Overview of production systems structures

Type of production	Structure definitions and objectives
Production line	The line is designed for the production of a specific (one) product, using the technology of gradual pro-duction with given tools and a fixed level of automation. The economic objective of production lines is to cost-effectively produce one particular type of product in large quantities and the required quality.
Flexible manufacturing system (**FMS**)	Structure of production system with fixed hardware and programmable software for realization of changes to production assortment according to current orders, changes to production plans with tools for several types of products. The economic objective of **FMS** is to ensure an efficient production of several types of products, which can change over time with shorter time of corresponding changes to the same production system, while maintaining the requirements for scale and prescribed quality of production.
Reconfigurable Manufacturing System (**RMS**)	Structure of a production system that can be created by multiple groupings of basic process configurations of changeable modules (hardware and software) of the system. Reconfiguration allows for the addition or removal of specific process characteristics, controls, control software, or machine structure to adapt the system's production capacity to changes in market demand, or to the necessary and related technological changes. This system structure ensures the flexibility of the system for a particular product group, while the system is technically ready for change so that it can be further improved, upgraded and reconfigured, and not just replaced. [4] The goal of RMS is to provide the functionality and capacity that is needed at any given time. In terms of system composition, the RMS configuration can be reserved or flexible or changeable between these two properties as needed. RMS economically exceeds FMS goals, allowing for: • shortening of the innovative systems implementation time and reconfiguration of the existing systems; • immediate production adjustment and rapid inte-gration of new technologies, new functions into the existing manufacturing systems.

The view of cell production can be characterized in terms of their advantages and disadvantages, as seen by current manufacturing practice under complex conditions and relationships of real production processes. [3]

The main problem for current FMS users is a high risk of rapid obsolescence. Dynamic development in the field of computers, information science, data processing, control and control systems, optical systems, drives and materials, which takes place in short cycles, significantly influences the growth rate (obsolescence) of the technical level of these systems. An efficient production system can become inefficient in a short time. In addition, the current customer and environment-oriented market brings about faster launch of new products. Adaptability of the existing production systems to new products does not have sufficient technical availability No sufficient technical availability exists to support the adaptability of the existing production systems to new products and the introduction of new technically available systems may take too long a time from the point of view of production availability (machine tools approximately two years).

For these reasons, it is necessary to pay constant attention to flexible, modular and reconfigurable production systems and consequently to improve them systematically and technically and adapt them to the needs of current production processes or to the needs of current engineering production. [4, 9]

The application of modern system structures and modern technologies in engineering production is a prerequisite for successful operation of its implementers (producers) on the current global market. The relationships and competitive categorization of production system models in this context is illustrated in Fig. 2. [5, 6]

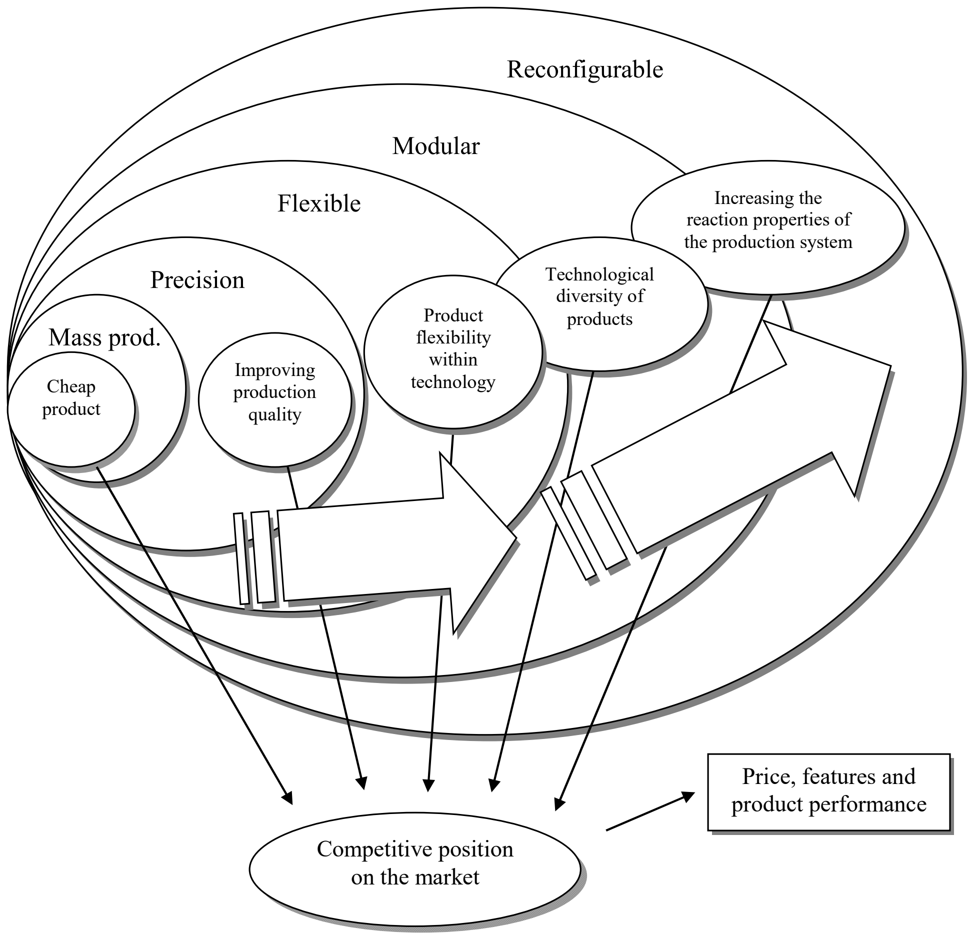

Fig. 2 Competitive categorization of production models

Trends in development of production technology

Forecasts focused on the position of modular technologies in the 21st century confirm the latter's important place in both fully automated manufacturing plants (engineering and non-engineering areas) and in non-manufacturing areas (service and maintenance activities).

An analysis of these trends transposed to manufacturing technology confirms that the research and development of these modular systems will focus mainly on:

- modularity of all construction nodes,
- increasing the accuracy, speed, quality and quantity of the activities performed;
- easy integration into production lines,
- full autonomy of individual modules,
- fully automated motion and position control
- developing innovative design approaches;
- development of microrobotic (or nano) handling equipment,
- module reconfiguration solution (change and rearrangement of components),
- use of modern CAx to solve module design problems and design modular

manufacturing systems.

Generally, the best-selling article (or an article with the highest investment value) of production technology are the CNC machine tools. Prof. Marek in [7] writes about the factors influencing development of machine tools, Fig. 3.

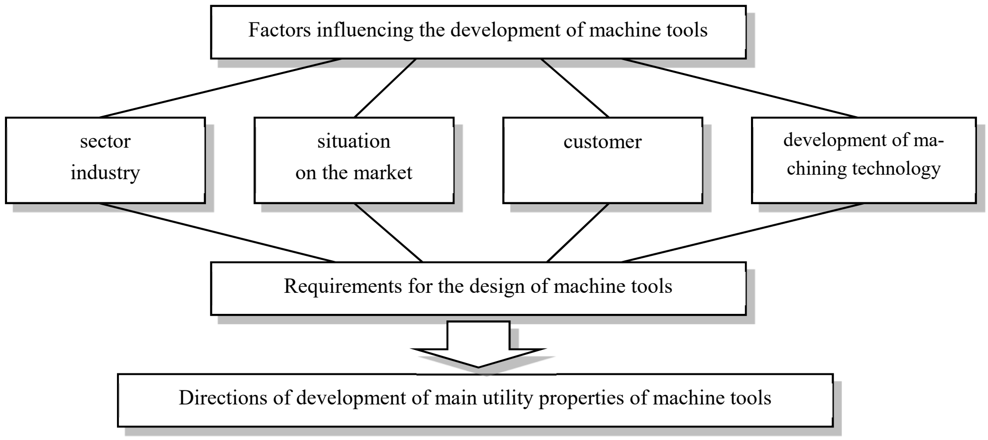

Fig. 3 Factors influencing development of machine tools

Utility (main and minor)	Type of industry					importance
	aerial	traffic	power generation	extraction (Petrochemical.)	manufacturing (General)	
Multifunctionality and versatility (in relation to process image)	■	■	■	■	■	low
	■	■	■	■	■	medium
	■		■			high
						extremely high
Reconfigurability (in relation to machine design)	■	■	■	■	■	low
		■			■	medium
					■	high
					■	extremely high
Cutting process adaptability (in relation to machine operation and operation)	■	■	■	■	■	low
	■					medium
	■					high
						extremely high

Tab. 2 Performance of machine tools in relation to the type of industry

The dictate of the aerospace industry of the direction of the CNC machine tool development still holds today. The use of new types of materials is specific to this industry, which in turn requires new technological processes, tools and machines. Other areas of industry, such as automotive, railway, energy, petrochemical and marine industries are also of great importance. Each of these industrial areas requires a specific machine tool design, ranging from heavy construction to precision and fast machine tools.

Prof. Marek [7] divides **Development of machine tools** into nine aspects:

- High Performance Cutting (HPC)
- Growth of feed and handling speeds
- High speed, dry and hard machining
- Increasing temperature, static and dynamic stability
- Increasing positioning and working accuracy
- Design of reliable nodes (reliable modules)
- Modularity and reconfigurability
- Diagnostics and active control
- User-friendliness

Table 2 shows selected relevant relationships between the main and secondary utility properties of machine tools to individual types of industry with regard to modifiability, flexibility and reconfigurability [7].

Thus, in terms of development directions, modularity and reconfigurability have the potential for further development in the future. Design of reliable modules or reliable building nodes is and will always be topical / of interest. This desired property can be achieved by drawing on experience, selection of suitable elements and of a reliable structure. In terms of reliability and reconfigurability, two areas can be focused on:

- Machine tool design (change in the machine so that it can manufacture another type of
- Production (change of technology to another type of workpiece)

The concept of flexibility is also related to reconfigurability and modularity. Flexibility can also be seen in terms of design and production, Fig. 4.

The possibilities and tools for increasing the performance of production machines in multifunction machines are associated with the developed ability to fully perform several types of machining. E.g. turning and milling at the same time, or milling and grinding etc.

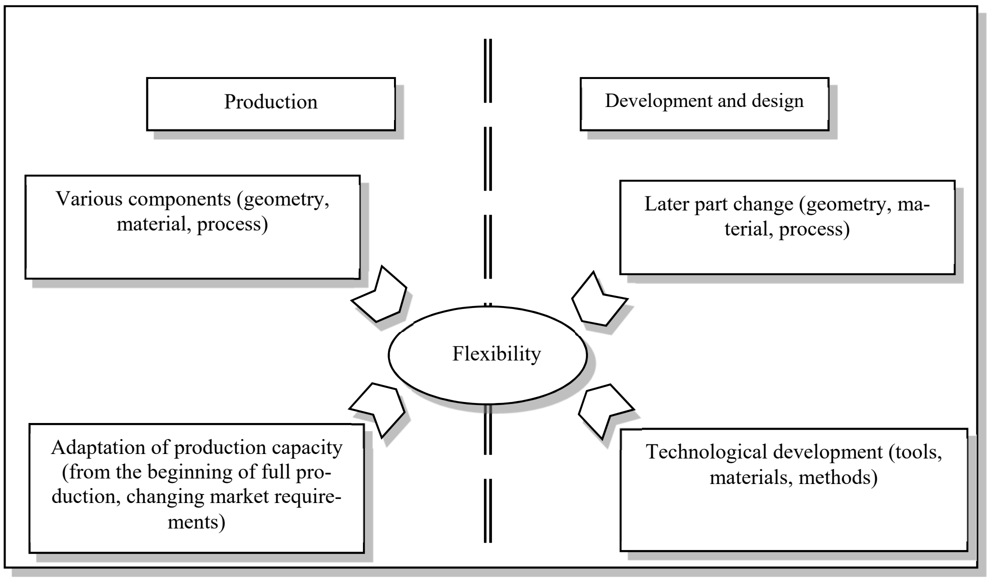

Fig. 4 An unconventional view of the term "flexibility"

Reducing the number of machine tools for the production of one component, less handling, shortening the lead times, minimizing the repetition of workpieces, maximizing the concurrence of operations, as well as the development of machine components and machine concepts for maximum machine multifunctionality contribute to:

- increased accuracy,
- increased production capacity,
- improved economy,
- reduced negative environmental impacts.

Unification of parts and components is carried out with the aim to minimize diversity of the components used while maintaining very good static and dynamic properties of the machines, while, at the same time:

- reliability is enhanced,
- and so is the economy.

Development of technical solutions for easy reconfigurability of machines based on customer requirements, where, e.g. one machine can be prepared as a primary turning machine and in the second case as a primary grinding machine leads to:

- increase in economy,
- reduced negative environmental impacts.

Machines with unconventional rearrangement of the carrier structure and motion axis drives lead to increased accuracy. [8]