ISSN 1068-798X, Russian Engineering Research, 2016, Vol. 36, No. 3, pp. 223–228. © Allerton Press, Inc., 2016.
Original Russian Text © V.V. Bushuev, A.P. Kuznetsov, V.V. Molodtsov, 2015, published in STIN, 2015, No. 8, pp. 7–12.

Contemporary Equipment Design

V. V. Bushuev, A. P. Kuznetsov, and V. V. Molodtsov
Stankin Moscow State Technical University, Moscow, Russia
e-mail: stankin-okm@yandex.ru

Abstract—Trends in the development of industrial machines and corresponding design methods are considered. The problems to be solved in the design of traditional and innovative machine tools are discussed. Approaches to meeting the operational requirements on industrial machines are outlined.

Keywords: industrial equipment, metal-cutting machines, design approaches, quality assessment, design concepts, industrial development

DOI: 10.3103/S1068798X16030035

The development of manufacturing is associated with continuous improvements in equipment design. Even before work on one generation of industrial machines is complete, principles are formulated for the next generation. We now consider some aspects of industrial development [1, 2].

The *life cycle* of a machine includes four stages: development, manufacture, operation, and disposal. In operation (Fig. 1a), the key consideration is the ratio between the operating costs *2* and the outcome *1* [2, 3]. When the operating time exceeds T_{cr}, further use is inadvisable.

The *variation in demand* for a machine is shown in Fig. 1b.

In engineering, *progressive evolution* involves transition to a new design with the following most probable cycle of design exhaustion:

(a) with constant structure and operating principles, the parameters of the design are improved until they are close to optimal;

(b) after the exhaustion of the potential of the original design, a better structure is adopted, and the cycle of optimization begins anew;

(c) after the exhaustion of the potential of this design, a third approach is adopted.

The development of a machine by this means, which corresponds to a sigmoid curve (Fig. 1c), proceeds until the limit is reached (line *1*) [4, 9].

At times T_A and T_B, a new machine with the same operating principle appears. The scope for development is determined by the distance from line *1* to *A* and *B*. Obviously, improvement in machine *B* is senseless; a different approach is required.

At certain stages of development, conditions are created for evolutionary leaps, associated with the accumulation of technical potential in society. Examples in the history of metal-cutting machines include the appearance of numerically controlled machines (in the 1950s) and modular design on the basis of mechatronic systems (today).

The appearance of numerically controlled machines was associated with the development of new tool materials and relatively efficient components, such as control systems, sensors, and feedback-equipped sensors.

The distinguishing feature of the current stage (the second evolutionary leap) is the transition to modular design on the basis of mechatronic components [1, 6, 13, 14].

Traditional kinematic chains in machine tools are being replaced by mechatronic systems, which are generally combined with executive elements of the machine tool.

In mechatronic systems, energy, information, and control components are combined, as a rule, into a single compact mechanism. That offers the basis for fundamentally new design solutions. In particular,

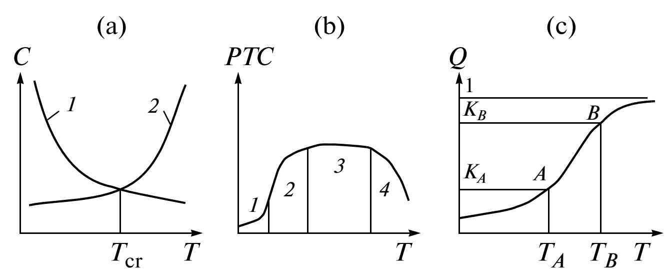

Fig. 1. (a) Life cycle of a machine tool: (*1*) profit; (*2*) operating and maintenance costs; *C*, monetary amounts; (b) evolution of demand: (*1*) initial development; (*2*) growth; (*3*) maturity; (*4*) decline; DTS, development of technological system; (c) development of a machine tool with a constant operating principle: *Q*, parameters, properties, characteristics; *T*, time.

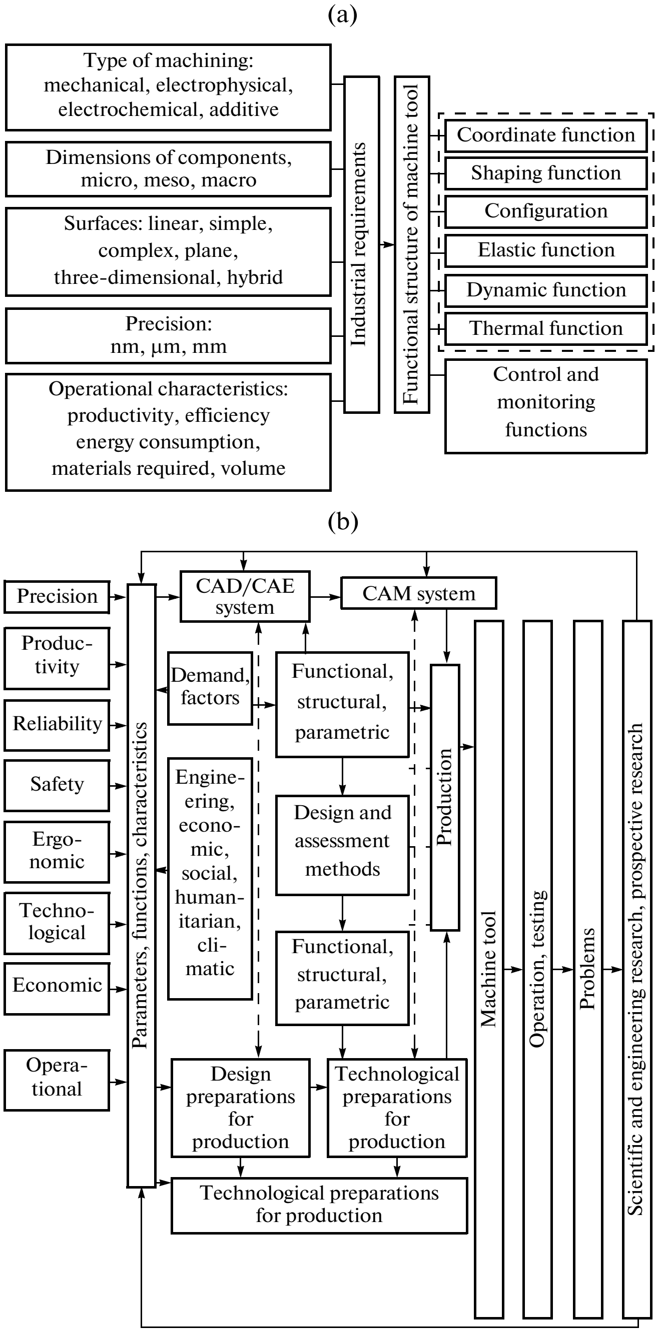

Fig. 2. Relation between industrial (consumer) requirements, the structure, and the function of machine tools (a); and the development of machine tools and equipment (b).

machine tools based on very different design principles may be created: for example machines, with parallel kinematics (drives, hexapods, etc.).

Progressive evolution may be illustrated by the development of metal-cutting machines. Along with the development of metal-cutting machines, a corresponding classification has evolved. Thus, machines in which different machining processes are performed simultaneously or successively by tools moving linearly and/or rotating independently (for example, milling lathes or milling and grinding machines) are categorized as multifunctional machine tools [5]. In addition, systems that employ not only the cutting process but other physical processes (such as laser machining) are customarily classified as multitask machine tools However, it might be better to refer to them as machine tools for hybrid technologies, since all machine tools have a single task, which is to machine parts with the required quality and productivity.

Therefore, it is expedient to classify equipment in terms not only of the machining method (turning, drilling, etc.) but primarily of the physical principle of the machining process performed (mechanical, electrophysical, electrochemical, hydroabrasive, laser, electromagnetic, and other processes).

Information regarding the size (characteristic geometric parameter), shape, and properties of a product permit the determination of its manufacturing technology. A characteristic geometric dimension no greater than 10^{-7}–10^{-9} m corresponds to nanotechnology; 10^{-7}–10^{-4} m to microtechnology; and $>10^{-4}$ m to traditional technologies. For cutting, the associated physical phenomena are determined by the type of destruction and the volume of material removed [6]. They determine the type of machining and the requirements on the machining equipment.

The principle of correspondence between the function and structure of the equipment means that there are no extraneous subsystems and the elimination of any element will impair some characteristic or property. The principle of dimensional correlation between parameters arises because many design parameters in machine tools depend on a basic dimension. For example, in lathes, the dimension of the spindle's front end depends on the maximum diameter of the workpiece. Therefore, three basic methods are used to reduce the range of objects:

(1) the creation of dimensional series for machines, with rationally selected intervals between them;

(2) the creation of more universal machines – that is, expansion of each machine's range of functions;

(3) the introduction of additional potential in the design, which may be used in modernization.

The development of dimensional series is based on similarity laws (such as geometric, temporal, mechanical, and temperature similarity) and geometric series of normal numbers. The dimensional series are mainly based on geometric progressions.

To satisfy industrial requirements on machine tools, they must be systematized, in terms of their structure and capabilities (Fig. 2a). This permits the identification of a correspondence between the structure of the equipment and its functions.

In practice, metal-cutting machines employ only a small number of machining methods. However, the machines play a key role in industrial revolutions.

Table 1

Machine-tool components and systems	Knowledge domain (KD)					(KD), (RD), (SD)
	mechanics	continuum mechanics	solidstate physics	information science	mathematics	
Immobile		+	+		+	Solution domain (SD)
Mobile	+	+	+	+	+	
Functional	+			+	+	
	Requirement domain (RD)					

Much of the engineering knowledge and knowhow gathered in working with machine tools may be applied in other fields. The use of a large number of new machine tools is an important competitive advantage for any national industry. The creation of innovative machine tools must not only meet structural requirements (rigidity, machining space, etc.) and functional requirements (shaping, control, monitoring, etc.) but also permit the rapid introduction of new technologies, materials, and components and the development of new machine-tool designs. Machine tools draw on findings in electronics, mechatronics, engineering design, measurement theory, technological design, information science, and so on. The implementation of new knowledge and solutions (Table 1) permits satisfaction of the requirements on industrial machine tools (Fig. 2a).

The knowledge domain contains and determines the methods of describing the behavior, state, structure, and properties of the process in the object being designed. For industrial equipment (including metal-cutting machines), we may categorize its structural components as immobile, mobile, or functional [7].

The requirement domain contains the parameters, characteristics, and properties of the object being designed (and its structural components) such that the industrial requirements are met (Fig. 2a).

The solution domain contains and determines the actually attained or potentially attainable parameters, characteristics, and properties of the object being designed (and its structural components) during the development process.

The designer must determine the best of the possible parameters, characteristics, and properties of the object being designed. Its structural components and their relations constitute a system with specified functions and behavior.

The creation of machine tools and other new equipment (Fig. 2b) may be described by the following sequence: requirements, function of the equipment, conception, design, production, operation, testing, problems, research, technological breakthroughs, requirements, function of the equipment, and so on.

The arrows in Fig. 2b indicate the initial data for the design and production of machine tools; the dashed lines denote relations due to the constraints on the design process. The two alternative fluxes of information transformation (in the creation and subsequent operation of the machine tool) correspond to the available design tools: the lower flux corresponds to traditional methods; and the upper flux to automated methods based on computer systems. Obviously, the methods of information processing will be different for these fluxes. That calls for the creation of design methods corresponding to the design tools employed.

Components of the design process such as structural and parametric analysis and the creation of drawings (Fig. 2b) may be largely automated by means of CAD/CAE/CAM software.

The operating time of any automated design system performing a single complete cycle in accordance with its function consists of the time t associated with manual labor (preparation of the initial data, coding, etc.) and the time t_{ap} required for automated design procedures. Thus, the sum of these times (or their financial equivalents) is the total time for a single design process. The degree of automation of the system depends on their ratio. If t is large, the system is inefficient and unsuited to practical use; its level of automation is low. With decrease in t, it becomes more efficient and more useful; its level of automation increases. Therefore, we may assess its level of automation U_c from the formula

$$U_c = \frac{t_{ap}}{t_{ap} + t}. \quad (1)$$

It follows from Eq. (1) that decrease in t is associated with increase in U_c and in the system's level of automation. As $t \to 0$, U_c tends to one, and the system will be automatic; the whole design process is completed without human intervention. (However, this is not feasible without artificial intelligence.)

We now determine the integral level of design automation U_{in}, characterized by the ratio of the total time (or its financial equivalent) required for automated design to the total time required for the corresponding nonautomated design process

$$U_{in} = t_{ap} + t/t_a + t_n, \quad (2)$$

Table 2

Characteristic	Formula	Range	Description
Coverage of automated design	$U_{co} = \frac{N_a}{N}$	0–1	Proportion of automated procedures N_a in the total number of design procedures N
Level of automation of design	$U_{ad} = \sum_{i=1}^{N_a} t_i \Big/ \sum_{i=1}^{N_a} t_i$	0–1	The time saving in automated design relative to nonautomated design
Level of automation of the system	$U_c = \frac{t_{ap}}{t_{ap} + t}$	0–1	The time consumed by manual operations in automated design. When $U_c = 1$, the system is fully automated
Efficiency of automated design procedures	$U_a = \frac{t_{ap}}{t_a}$	0–1	Reduction in the time required for the same design procedures on automation
Efficiency of design automation	$U_{ae} = \frac{t_{ap}}{t_a + t_n} = U_{ad}U_a$	0–1	Time for automated procedures with respect to the total time for unautomated design
Integral level of design automation	$U_{in} = U_{ad}\,U_a/U_c$	0–1	Total automated design time with respect to the total time for unautomated design
Integral CAD efficiency	$U_e = U_c U_{ad}/U_a$	1–∞	Reduction in the total design cycle thanks to CAD

where t_a and t_n are the times required in nonautomated design for the procedures that, respectively, are and are not automated in the automated design process.

Dividing the numerator and denominator by $t_{ap}t_a$, we obtain

$$U_{in} = \frac{(t_{ap} + t)(t_{ap}t_a)}{(t_a + t_n)(t_{ap}t_a)} = \frac{[(t_{ap} + t)/t_{ap}]t_a^{-1}}{[(t_a + t_n)/t_a]t_{ap}^{-1}} = \frac{[(t_{ap} + t)/t_{ap}][t_{ap}/t_a]}{[(t_a + t_n)/t_a]} \quad (3)$$

or

$$U_{in} = U_{ad}U_a/U_c.$$

Here $U_a = t_{ap}/t_a$ characterizes the ratio of the time required for the same design procedures with and without CAD procedures.

Thus, for objective assessment of the CAD system in terms of its level of automation, we need to use several characteristics, corresponding both to the design properties of the system and its operational properties. Table 2 presents generalized characteristics of the CAD system, methods for their assessment, their limits of variation, and a brief description.

In manufacturing, 80–85% of the expenses are determined by the decisions made in the design and development of the technology. The importance of improving the design process is illustrated by the following data: labor productivity rose by 1500% in the twentieth century, while the productivity in design increased by only 40–50%; the complexity of industrial systems (in terms of their number of components) doubles every 15 years; the expenditure of time in creating new products falls by half every 25 years; and the number of classes of engineering systems doubles every decade.

The current stage in the development of machine tools and manufacturing as a whole is characterized by the transition to computer design, which offers greatly expanded design capabilities. In these circumstances, the success of a design largely depends on the designer's ability to make full of the potential of CAD systems.

CAD systems sharply reduce the number of designers required for a particular project; reduce errors, on account of the greater clarity of the design process and expanded monitoring capabilities (the ability to inspect the design from different perspectives, virtual motion of the components in the working space and the detection of their collisions, determination of the working zone, etc.); and increase the responsibility of each designer for the outcome.

The overall impression of designs produced by digital technologies may be favorable, but errors are often present on account of the designer's inadequate training. Accordingly, the development of a general methodology plays a critical role in increasing the quality of the machines that are designed.

However, the knowledge and knowhow of experienced designers and engineers is essential in conceptual design, planning, prediction, and the assessment of development trends. Automation of these tasks is very difficult.

Therefore, we need to constantly systematize knowledge in machine-tool design and related fields (Table 1). That calls for considerable increase in the educational level of engineers and the development of their practical aptitude for developing innovative machine tools. On the one hand, this facilitates the development of machine-tool design; on the other, it permits the organization of the knowledge required for the education of new generations of designers.

Design work is an empirical and intuitive form of creative activity that has been little studied or systematized. The following design approaches are currently employed: multidimensional tables (Hertzsprung), the idea matrix (Hill), object-oriented design (Ross), the design structure matrix (Steward), robust design (Taguchi), and axiomatic design (Suh).

Specific design methods are always individualized. Therefore, it is very difficult to formalize design procedures [8]. The basic challenge in creative design is to fully comprehend the problem, in both design and technological terms. Therefore, systemic design is used at present. That involves an informed compromise between technological capabilities, the level of automation, modern design solutions, cost, production flexibility, productivity, and other factors.

The primary problem is to develop a conception (an idea of the machine), whose quality will largely determine the success of the design. We require only a minimum of constraints: for example, the manufacturing possibilities are not considered. In any creative enterprise, the most difficult task is to find the best option in the realm of possible solutions, which is so large that simplifications must be introduced.

The design process is represented either as a black box at whose output the solution appears or as a transparent box in which a logical and explicable process occurs. Likewise, design methods may be divided into algorithmic and heuristic methods.

Algorithmic methods employ logical algorithms written as a series of instructions. Such methods are most successful in developing the conception and in optimizing the design. The basic step is to break the problem down into individual parts, which may be solved in series or in parallel. In creating complex systems such as machine tools, which must meet many different requirements, it is usually impossible to break the problem into parts, and heuristic methods are employed.

Heuristic methods, which are based on the designer's experience and abilities, consist of ordered general rules and recommendations that assist in the solution of creative problems without preliminary assessment of the results. More than 30 heuristic methods are known: brainstorming; synectics; elementary questions; analogies; proceeding from the whole to the part; and guided operations [7–11].

In developing the conception, the principle of analogies draws on parallels with nature. For example, self-sharpening multilayer cutters resemble cat's teeth and claws, in which the hardness increases with depth; pipes resemble plant stems; and obviously honeycomb structures resemble bee hives.

The principle of adaptation is used to adjust known processes to specific conditions: for example, the adaptation of a water wheel to a hydraulic motor. The ability of porous materials to supply water may be used in wetting. The principle of multiplication involves increasing (or reducing) the dimensions and functions of a system without changing the operating principle. For example, a vertical lathe may be converted to a turret lathe with a machining diameter up to 25 m. The inversion principle involves seeing from the other side, so that, for example, a covered surface becomes a covering surface. In some turret lathes, the workpiece may be rotated, or the tool carrier may be rotated while the workpiece remains still. The integration principle involves combining functions. In a horizontal drilling machine with a drive spindle on hydrostatic bearings, there is no need to use a hollow spindle since the bearings permit both rotation of the spindle and its motion along the axis.

The differentiation principle involves distinguishing between the functions and components of a system: for example, the use of individual drives for each motion or the division of a machine tool into modules. Neology is the use of new processes, forms, or materials in the technology: for example, the use of the piezo effect in microscopic motors; or the use of a revolving lathe head analogous to the magazine of a gun.

The pulsation principle is employed by switching to discontinuous processes, such as ratchets or Maltese-cross transmissions. The dynamic principle supposes that the characteristics of the whole system or its components change in new operating conditions. It is used for devices which can only function when in motion: for example, the hydrodynamic effect in bearings and guides; or the introduction of tension in roller bearings as a function of the spindle speed.

The many methods of finding the required design solution are associated with procedures such as the transformation of objects; the selection of options; the identification of compromises; the search for new relations between the components; the use of catalog design [11]; and various physical effects [12].

In creating any machines, there will be problems decisively affecting the attainment of the goal and the satisfaction of customer requirements. In machine-tool design, such problems include the selection of the shaping method, the kinematic system, the implementation of the selected shaping method, the configuration of the machine tool (which largely depends on the motion required), and the rational force distribution.

The design methodology is a process of assessment and decision making, as well as optimization or rationalization of the structure best satisfying the design goal. The optimal design is such that improvement in terms of one criterion (Fig. 2b) impairs the agreement in terms of another (Pareto optimization).

Thus, the improvement of design methods calls for better use of information technology to reduce the design time and improve the outcome; better understanding of the development of technology (including timely transition to a new generation of machines with a different operating principle); the full use of the available design methodologies (especially in developing the initial conception); and the development of new methods of knowledge expansion in the design process.

ACKNOWLEDGMENTS

Financial support was provided by the Ministry of Education and Science of the Russian Federation (project 9.1429.2014/K).

REFERENCES

1. Bushuev, V.V., *Praktika konstruirovaniya mashin: Spravochnik* (Practical Engineering of Machines: Handbook), Moscow: Mashinostroenie, 2006.
2. Skhirtladze, A.G. and Yarushin, S.G., *Proektirovanie nestandartnogo oborudovaniya: Uchebnik* (Design of Non-Standard Equipment: Manual), Moscow: Novoe Znanie, 2006.
3. Denkena, B., Harms, A., Jacobsen, J., Möhring, H.C., Lange, D. and Noske, H., Life cycle-oriented development of machine tools, in *Proc. 13th CIRP Int. Conf. on Life Cycle Engineering, Leuven, May 31st–June 2nd, 2006,* 2006, pp. 693–698.
4. Petrov, V.M., The pattern of function development. http://www.trizland.ru/ trizba/pdf-books/zrts-05-function.pdf
5. Moriwaki, T., Multi-functional machine tool, *CIRP Ann.,* 2008, vol. 57, pp. 736–749.
6. Kuznetsov, A.P., Structure of cutting processes and equipment. Part 1. Energy-information model of the structure of machining processes, *Russ. Eng. Res.,* 2015, vol. 35, no. 5, pp. 347–357.
7. Kuznetsov, A.P., *Teplovoe povedenie i tochnost' metallorezhushchikh stankov* (Thermal Behavior and Precision of Metal-Cutting Machines), Moscow: Yanus-K, 2011.
8. Kosov, M.G., Kuznetsov, A.P., Gurevich, Yu.E., et al., *Logika proektirovaniya. Metody i primenenie v tekhnike* (Logics of Engineering: Methods and Implementation), Moscow: Yanus-K, 2010.
9. Al'tshuller, G.S., *Algoritm izobreteniya* (Algorithm of Invention), Moscow: Moskovskii Rabochii, 1973.
10. Jones, J.C., *Design Methods,* New York: Wiley, 1970.
11. Roth, K., *Konstruieren mit Konstruktionskatalogen,* Berlin: Springer-Verlag, 1989.
12. *Fizicheskie effekty v machinostroenii: Spravochnik* (Physical Effects in Mechanical Engineering: Handbook), Moscow: Mashinostroenie, 1993.
13. Brecher, C. Esser, M., and Witt, S., Interaction of manufacturing process and machine tool, *CIRP Ann.,* 2009, no. 58, pp. 588–607.
14. Wang, Z.G., Cheng, X., Nakamoto, K., Kobayashi, S., and Yamazaki, K., Design and development of a precision machine tool using counter motion mechanisms, *Int. J. Mach. Tools Manuf.,* 2010, no. 50, pp. 357–365.

Translated by Bernard Gilbert