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Analysis of the Lifecycle of Mechanical Engineering Products

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Abstract. Principal phases of the lifecycle of mechanical engineering products are analyzed in the paper. The authors have developed methods and procedures to improve designing, manufacturing, operating and recycling of the machine. It has been revealed that economic lifecycle of the product is a base for appropriate organization of mechanical engineering production. This lifecycle is calculated as a minimal sum total of consumer and producer costs. The machine construction and its manufacturing technology are interrelated through a maximal possible company profit. The products are to be recycled by their producer. Recycling should be considered as a feedback phase, necessary to make the whole lifecycle of the product a constantly functioning self-organizing system. The principles, outlined in this paper can be used as fundamentals to develop an automated PLM-system.

1. Introduction
“Product lifecycle” is a complex index of product lifetime that has been introduced recently and is thought of as its lifetime on the whole, including engineering design, manufacture, service and disposal of manufactured products. It is considered that a global automated information system entirely covering this cycle and abbreviated to PLM (Products Lifecycle Management) is to be developed urgently [1,2]. Prior to the development of PLM-system it is necessary to carry out a comprehensive analysis of the entire process of mechanical engineering product life cycle control [3].

2. Results and Discussion
In terms of PLM concept a product appears primarily in the head of the developer as a general idea of the structure. Then this guiding idea is implemented in the set of needed engineering design documents. While engineering design planning the first problem of optimal design is resolved, as well as its criteria and aims of optimization are set on the ground of requirements for both manufacture and service of the product. [3-6]

The next phase of product development involves a great number of human and material recourses, as the result the phase of machine manufacture is implemented as a certain serial production. Hence, the second problem of optimization arises, which generally focuses on overall reducing of production costs and on timely transition to manufacturing a completely new product.

After the product is sold at the market the consumer starts its service. This phase requires for consideration of the third optimization problem concerning the consumer’s interests. Among them are minimization of operational costs and determination of an optimal term of maintenance, followed by product replacement by a new one and its disposal [7].

The disposal of the machine is a final phase of product life cycle. An open cycle is usually under consideration so it is assumed that a product subsequently getting through the phases of marketing investigations, engineering design, manufacture, maintenance and disposal completes its lifetime, therefore, meets some private or public requirements. At the same time we know that such open function chains viewed from the standpoint of the theory of automated regulation and control are not efficient. The system is to be closed to improve its controllability and stability through introduction of a feedback. It is suggested to use the phase of disposal as such a feedback [8,9].

Fig. 1 shows a variant of closed PLM-system functioning for purposes of mechanical engineering enterprise. The entire control is concentrated in the block of marketing. Alongside with investigation and analysis of the market it has other tasks. The main focus of the marketing phase is on development of feasibility analysis and preliminary specifications (TDA) for product design. At the same time its functions are to be as follows: determination of economically substantiated lifetime of the machine T_E, obsolescence period of this machine structure T_M, optimal program of product manufacture $N_{\max}$, estimated product price K_P, limits of current expenses and capital investments in manufacture, optimal cycle time of product manufacture, estimated profit of the enterprise and a number of other macroeconomic indexes. T_E, determined at this phase, is to be a guideline for optimal machine engineering design according to the criterion of reliability margin and a reference for the user in the technical certificate of the product maintenance. The price of the product and its changes caused by the current situation based on the principles of fair price for both producer and consumer is given on the market and constantly monitored via a feedback. The block of marketing is also responsible for strategic planning of manufacture phase determining the time of transition to manufacture of a new product structure through the obsolescence period. This block obtains timely information from the structure dealing with disposal to estimate current expenses on product maintenance, this information is used for T_E and K_P assessment [5,10].

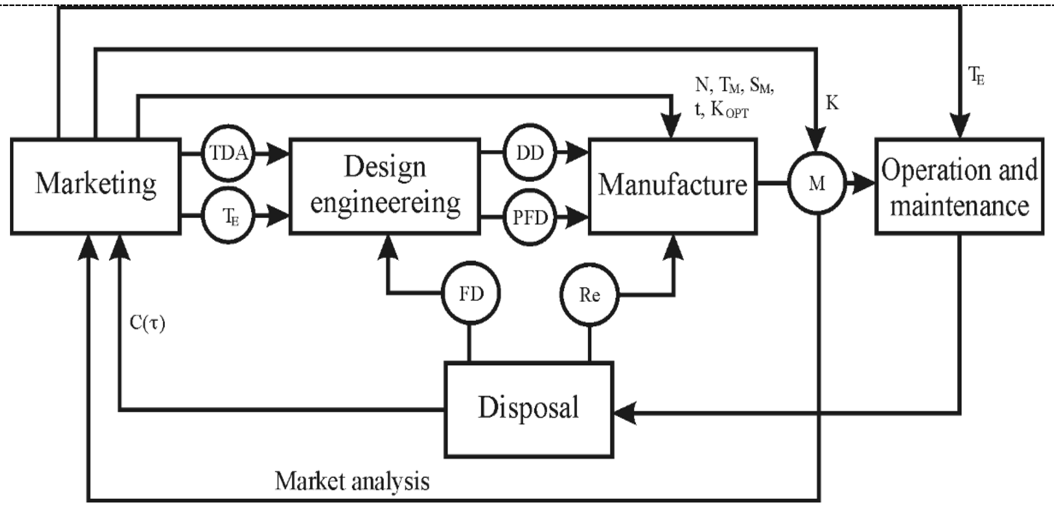

Figure 1. Closed product life cycle:
TDA – preliminary specifications; DD – design documents;PFD – process control documents; M – market; FD – fault detection; Re – renovation.

The product is utilized in order to reduce the burden on the environment and to optimize the life cycle of the product, moreover, to close the cycle according to a positive feedback. Here two problems of this phase are to be distinguished, fault detection of the depreciated machine and renovation of its parts [3,7].

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Fault detection of the depreciated machine is aimed mainly at obtaining of source information on performance deterioration of the product as the whole and its components, aggregates, units, and couplings followed by statistic processing the results of such monitoring. As these data significantly interest designer and manufacturer of the product a special service responsible for put-back and disposal of over-aging machine is to be established at mechanical engineering enterprises.

Faults are to be controlled according to specially developed methods involving a wide range of up to date flaw detection facilities. This control is to be attended by sorting machine components aimed at their further renovation and re-use in new products or at recycling to source material [5,6].

For efficient implementation of the phase under consideration the structure of any machine is to be improved to provide a complete diagnosis of its current and final condition. First of all, it is to be equipped with microchips providing information on the intensity of machine maintenance, concerning both the period of service and modes of its operation. It is the data that make it possible to precise the regularities of physical depreciation of the product, therefore, determine the economically estimated lifetime, and a planned price of the product.

A number of over-aging assemblies and components of the machine might be of quite high quality after fault detection is completed. Among them are, as a rule, base and frame components of the product designed with a significant safety factor and service life because their faults often cause untimely failure of the whole machine. Generally speaking, the more components like those mentioned above are in the structure of the machine the less optimal this structure is. At the same time these components of the machine can be reconstructed and applied either for assembling similar machines unless they are still produced or as repair parts in technical support service. A great number of repair mechanical engineering technologies has been recently developed, which enable complete restoring of the product lifetime [10].

Three mentioned above issues of product lifetime optimization are interconnected, moreover, inequivalent. This is because of the so-called consumer dictate typical for the most market relations involving the manufacturer of the product and the consumer of it. The consumer determines the reasonability of purchasing any product following his needs and financial resources. On the other hand, producer dictate is also possible, especially in monopolistic economy, where the consumer has no choice when purchasing a product. As the biggest economies of the world have antimonopoly laws the latter is rather rare and not typical for well-developed market relations. Therefore, the third problem of optimization (optimization of service phase) is the main one and determines development of optimal industrial economy; the first two problems are inferior ones [10].

When servicing the product the consumer gets a positive effect from its use, on one hand, on the other hand, has input and current operational costs. Input costs of the consumer include value of the product and costs arising from assembling and start-up of the product. They are of the same importance as capital investments at the phase of manufacture. Current costs depend on the purpose and structure of the product and can embrace costs on electricity, fuel, technical service, repair components and so on. Their purpose is similar to the cost price in manufacturing process. The following formula is recommended to apply for calculation of product servicing [5,10]:

$$C = C_K \cdot \tau + \frac{K_P}{\tau + 1}, \qquad (1)$$

where C_K is a coefficient with the dimension (standard unit of value)/(standard unit of time)^2; τ - current term of product maintenance, standard unit of time; K_P - product price, standard unit of value.

Figure2 provides the calculation of the dependence (1) for various values K_P, $C_K = 200$ is constant.

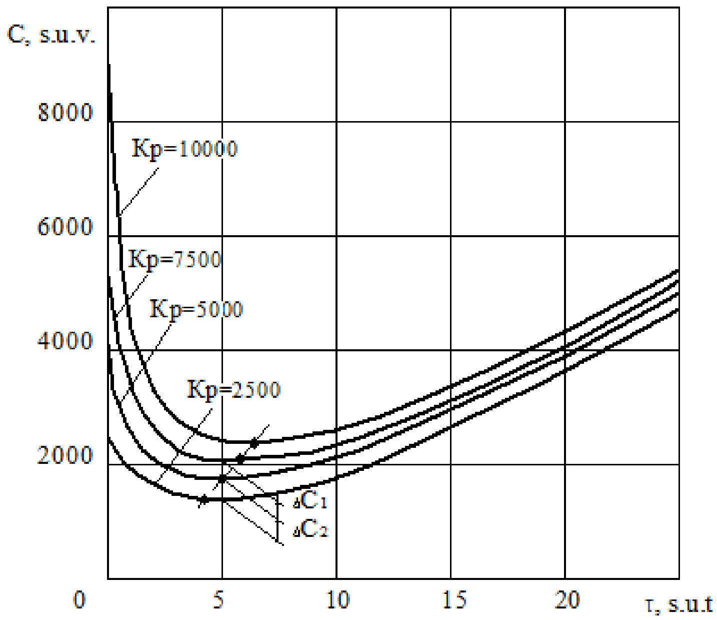

Figure 2. The dependences of current reduced expenditure on maintenance on various prices of its selling.

Figure demonstrates that all curves have a global minimum of specific reduced expenditure of the consumer for a certain period of product servicing. Let us denote the duration of the lifetime as T_E and call it an "economically substantiated lifetime", which is further thought of as a period of product maintenance and after its completion the specific reduced expenditure of the consumer are the minimum ones. Further maintenance of the product is unprofitable; the product is to be replaced by a more up to date one.

The value of an "economically substantiated lifetime" can be calculated from the equation (1), by taking a derivative with respect to the time τ and equating it to zero:

$$T_E = \sqrt{K_P / C_K}\ , \quad (2)$$

In terms of (2) the value of "economically substantiated lifetime" doesn't depend on the absolute values of input costs of product K_P purchasing and on the level of specific current costs of its maintenance C_K , but on their correlation. The higher the correlation of price to the current costs is the higher the optimal term of its maintenance is to be and vice versa. It is drawn attention to the fact that reducing price of the product causes reduction of its "economically substantiated lifetime" (see the dashed line in Fig.1), that is, a cheap product is to have shorter optimal lifetime. However, the fact of a rigid functional relation between the price of the product and its "economically substantiated lifetime" is a more important conclusion drawn from mentioned above dependences[11,12].

It makes itself evident in the following way: for known values C_K and T_E the price of the product K_P can't be determined at random, but it must have a quite determined optimal value (fair price). We analyze this fact in more details on the examples.

Let us take as a basis the curve corresponding with the input expenditure on purchasing a product K_P=5000 standard units of value. The coordinates of optimal point A for this correlation are as follows (see Fig.2): T_E=5 standard units of time; $C_{\min}$=1833 standard units of value. We consider two variants of rough setting the price of the product, agreeing with K_P=7500 standard units of value and K_P=2500 standard units of value. In the first variant we have a cooperative financial advantage of product manufacturer and seller at the rate ΔC_1= 417 standard unit of value (see Fig.1), and in the second one – the advantage of the consumer at the rate ΔC_2=416 standard units of value. In other words, the first variant agrees with the dictate of the manufacturer, and the second one – with the dictate of the consumer of the product. To meet the requirements of both sides when purchasing and selling the price of the product is to agree with its optimal value, calculated according to the equation below:

$$K_P = C_K \cdot T_E^2 . \tag{3}$$

Therefore, only planned and fact specific current expenditure on product maintenance matching exactly cause a balance of economic interests of both manufacturer and consumer and provide an optimal result for them [10].

On the basis of carried out analysis the following principle of any mechanical engineering product maintenance can be stated: to minimize the cooperative costs of consumer and manufacturer a product with certain structure and of certain quality is to be utilized within its economically substantiated lifetime, the latter depends on the values of input expenditure on purchasing and current costs on service of this product.

On the other hand, if optimal lifetime of the product is set and specific maintenance costs are determined, to minimize the overall expenditure of the manufacturer and consumer price of the product is to be rather certain, its excess or reducing cause the losses of either consumer or manufacturer of the product. This price is optimal (fair) both for the phase of manufacturing and maintenance of the product and must be a guideline for the manufacturer and a seller. That is why, in contrast to the notorious market uncertainty, determining the price of the product on the basis of competition, pricing in terms of economically substantiated lifetime adds a planned nature to the activity of a mechanical engineering company both when starting manufacture of a new product and in resolving other industrial problems [11,12].

For the foregoing reasons the phase of engineering design of a mechanical engineering product is to focus primarily on providing its economically substantiated lifetime and needed current expenditure on maintenance. Here, the methods of machine design are to foresee obtaining equal operating life for all its components. A structure is thought of as an optimal one which is designed on the basis of uniform strength, wear and other particular objective functions providing a uniform distribution of service properties (uniform inflexibility, resistance to corrosion etc.). When developing an engineering design of the machine it is necessary to search for the most optimal form of the components, units and the machine as the whole, as well as for optimal distribution of physical and mechanical properties of the construction material. A perfect product can be designed by simultaneous optimizing form and material only [3]. These principles of design enable forced restriction of product lifetime by the value of economically substantiated lifetime. Then, a consumer will face a problem of purchasing a new, more up to date machine, and a manufacturer will be able to plan volumes and development outlooks of the manufacture through constant relations with the users.

The problem of an optimal design project of the product viewed generally is to have the following solution sequence [5].

1. Calculation of an optimal operational life of the component on the basis of economically substantiated lifetime of the machine.
2. In terms of the uniform strength criterion calculation of the range of optimal forms of the product from certain material, subjected to either concentrated or distributed force and thermal loads.
3. According to the principle of uniform strength determination of the optimal structure of material for a particular form of the product.
4. Synthesis of the range of optimal solutions for form and variants of projects with optimal distribution of physical and mechanical properties of product material according to uniform strength. This phase is to be performed by the method of successive approximations, that is, after the first solution of full-strength form is made, a complying with it distribution of elasticity modulus of the component material is studied, afterwards, an optimal profile in terms of the changed VAT is

developed by a numerical method, and so forth. It is calculated till the form of the product matches the structure of its material with a set degree of approximation.

5. Calculation of optimal projects range of rubbing surfaces form of the product, manufactured from a certain material in accordance with the uniform wear.

6. Determination of tribological properties optimal distribution on product rubbing surfaces and development of projects of selective structured wear resistant coating.

7. Synthesis of optimal projects in terms of form and intensity of rubbing surfaces wearing providing a mode of uniform wear.

8. Optimization and synthesis of product projects with uniformly distributed properties in terms of other criteria of optimization (uniform inflexibility of the structure, equal corrosion resistance etc.).

9. Synthesis of the range of full-strength and uniformly wearing forms of the product with optimized structure of its material.

The final phase of optimal design consists in selecting from all technically and technologically possible variants the most economical one through comparing the term of its service life with the economic stability, determined in section 2. This methodology results in obtaining an optimal project of a perfect product with needed strength, wear resistance and efficiency for given conditions [11-15].

For stable functioning of the main production corresponding facilities of auxiliary production are necessary, the key purpose of the latter includes design and manufacture technological facilities required for new machine production. This industry has a single-piece and small-scale manufacture, so the principles of flexible technology and equipment with numerical control are required. This tool-making and experimental production is to be the third basis of the contemporary mechanical engineering enterprise and guarantee it a high efficiency.

Summary

- An economically substantiated lifetime of the product conforming to the minimal overall expenditure of the manufacturer and consumer of the machine is the basis of optimal organization of mechanical engineering production.
- The structure of the machine and its manufacturing technology are economically interrelated through the maximum profit of the enterprise.
- Disposal of the products is to be implemented by the enterprise-manufacturer and play a part of a feedback link to make the complete lifetime of the product a stable functioning self-organizing system.
- Principles stated in this paper can be used as the basis of automated PLM-system development.

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