Visualization models of technological heredity in mechanical engineering

Alexander Konoplin, Natalia Baurova* and Sergei Abrakov

Moscow Automobile and Road Construction State Technical University (MADI), 125319, Moscow, Leningradskii pr.64, Russia

*nbaurova@mail.ru

Abstract. By the example of machine-building products the model of visualization of their quality indicators at different stages of life cycle is offered. It is shown that to visualize the influence of technological heredity on the quality indices of the product it is most demonstrative to use the graph theory and the Liebich metaphorical barrel. The proposed approach allows to use the principle of cybernetics, according to which the product, at each stage of its life cycle, is presented in the form of a set of separate elements connected with each other in a single information network. The joint use of the graph theory and the Liebich metaphorical barrel allows evaluating the studied indices and visually displaying them in the complex. The main advantage of this approach is the ability to illustrate which of the set of quality indicators of a particular product is most significant.

1. Introduction

For the overwhelming majority of designs of machines the big influence of factors of technological heredity is characteristic, especially it is actual at use of polymeric composite materials (PCM).

Process of accumulation of damages is a dynamic system in which the future is unequivocally defined by the past. Small causes can have great consequences, which mathematicians called «sensitivity to the initial data», and technologists call this relationship technological heredity [1].

One of the first scientists who paid attention to the most important influence of factors of technological heredity, was Voltaire, who in the mid-XVIII century suggested that «the state of an object is determined not only by the forces that affect it at the moment, but also by the history of the influence of these forces in the past».

According to a number of authors [2-4], technological inheritance is the phenomenon of transferring the properties of objects from previous technological operations to subsequent ones, and preservation of these properties has received the name – technological heredity. Defects in manufactured parts arise as a result of their technological processing, but the reasons causing them may be even at earlier stages, for example, as a result of manufacturing of individual components. During the technological process the defects can undergo very significant changes.

To understand and describe the technological heredity, a systematic approach is used, according to which the system is a set of individual elements that are connected in a single information network [1-3]. The most important in the process of property transfer is hereditary information and its definition is one of the main and most complex problems of modern engineering. Traditionally, in mechanical engineering at performance of technological processes and the account of factors of technological
heredity, for object of researchs object of processing is accepted, and carriers of the inherited information is a material and all surfaces of a detail [5-7]. For example, at the production stage there may be the formation of structural defects in the used materials at the molecular level, for the diagnosis of which there are no standardized methods. It is these defects at the subsequent stages of the life cycle that will lead to the loss of quality. Thus, the properties of the manufactured part (product) are formed not at the last operation, but throughout the entire technological process, since the errors can not only persist, but also synergistically accumulate.

Technological process of production and repair of mechanical engineering products is commonly represented as a sequential arrangement of technological operations, for each of which there are different materials and technological modes [4]. A distinctive feature of repair technologies is a significantly higher dispersion of initial parameters of the objects under consideration, which is associated with the presence of damage to a variety of physical nature and large disparity in the degree of aging of structural materials. If we consider the whole complex of factors, even for one product, it is unambiguously impossible to reliably evaluate and visualize which of them have the most significant impact on its quality. This problem becomes even more complicated, if to consider a product at several stages of its life cycle, for example, manufacturing-use-repair.

At visualization of the factors influencing quality of a finished product, all set of indicators of quality of products of mechanical engineering is accepted conditionally to subdivid into five groups: mechanical, technological, physicochemical, structural and operational. All groups of quality indicators are interdependent, but it is not clear with what kind of mathematical apparatus can connect them all to each other and visualize them accordingly. The relationship between mechanical and structural properties is well known and analyzed by many specialists, who agree that with minimization of structural defects there is an increase in the whole complex of mechanical characteristics [5, 8-9]. Similar regularities are established between technological modes and structure, for example at manufacturing of products from PCM, porosity and residual pressure are consequence of non-optimal modes of formation [10-13]. It is possible to result set of examples when the authors who are engaged in creation of the most various materials and designs, define correlative dependences between thermophysical, mechanical and other properties. However, the mechanism of formation of regularities of influence of some quality parameters on others, for each specific object of research, requires its detailed analysis.

It's probably due to two major factors:
- selectivity (the subjectivity of each individual researcher can hardly be overestimated);
- the high dimensionality of the task.

Selectivity leads to the absence of an overall development strategy, because each researcher, depending on his or her own priorities, chooses a limited number of quality parameters, which are further considered in a narrow subject area and visualized by appropriate algorithms [9, 14-15]. Absence of common methods, as well as the great speed with which new software systems are introduced into the practice of scientific works, has led to the fact that mathematical models gradually began to replace the physical ones, which is associated with their much lower cost. As a result, the number of parameters on which the quality of engineering products (and the materials from which they are made) is assessed is steadily growing, but this does not contribute to the creation of common patterns.

A complex system cannot be described in detail, and none of the existing theories can claim to provide a correct description of the process of information inheritance at each technological transition. It is connected by that such difficult problem, as inheritance of quality of products of mechanical engineering, has set of aspects as considered objects are so various on appointment, accuracy and complexity that simply to speak about process of transfer of the inherited sign would be rough simplification.

The purpose of the given work is the generalized visualization of factors of technological heredity at an estimation of quality of products of mechanical engineering at all stages of their life cycle.
2. Results and discussion

When describing the behavior of a complex hierarchical system, it is first necessary to determine what to choose as the main idea. If the emphasis is on process physics, you can use the simplest models. If the primary goal is to take into account numerous factors, then it is necessary to use complex models.

Quite often, when researchers face such a dilemma, the solution is found in the use of graph theory [16]. The simplest purpose of the graph is an illustration. Accordingly, the theory of graphs allows to visualize connections between considered objects (visually to present complex process) and to consider set of the most various factors (including mutually exclusive).

The use of graphs in the description of technological heredity, despite the abstract approach, allows to highlight the most significant features of real technological systems. At the same time, all the results obtained depend on the choice of abstraction level, and this choice depends entirely on the preferences of the researcher. Traditionally, the object of study is presented in the form of a black box, for which the input and output parameters are known, and not always there is an adequate mathematical apparatus describing the mechanism of «input» and «output» connection. A distinctive feature of the graph theory, as applied to the task of describing technological heredity, is the task of the «input-output» relationship in an implicit form. In this case it is very convenient to ascribe a certain significance (weight) to the edges of the graph, which allows to make the graph in the real scale of significance of each of the edges [16].

An example of such a graph is shown in figure 1(a), where X3, X9 and X10 edges are smaller than all other edges of this graph. For example, a part is produced by powder metallurgy from two metal powders and with this technology the properties of the original components A1 and A2 have the same value. Vertex A4 (which, as well as A3, initially has no connection with vertices A1 and A2) denote any parameter of the technological equipment used, such as the accuracy of providing a given temperature in the chamber. Let us denote conditions at the production site where the mixture is prepared and sintering, e.g. humidity, with the A3 vertex. The X3 edge is almost two times smaller than the X4 edge, which indicates a smaller contribution of humidity to the value of the inherited error in comparison with the temperature. It is possible to designate in the same way all subsequent technological operations: for example, with the vertex A5 we designate quality of preliminary mixing of components, with the vertex A7 — quality of a mix after the end of mixing process, accuracy of other used technological equipment we designate with the vertices A6, A8, A9.

![Figure 1](image_url)

**Figure 1.** Example of a related oriented (a) and weakly related (b) graph.
If the vertex $A_8$ denotes the thermal operation, such property as hardness will not change further, as shown by the vertex $A_{11}$, which is not associated with any other vertices of the graph (figure 1, b). Other properties of a detail, for example roughness $A_9$ or accuracy $A_{10}$, as a result of the subsequent mechanical operations will change.

For the graphs we distinguish strong and weak components, which are evaluated by the degree of connectivity. An example of a weakly connected graph is shown in figure 1 (b), where the vertex $A_{11}$ is not connected with any other vertices except $A_8$. This approach is convenient to use in case it is necessary to show a stop of transmission of an inherited feature. Depending on the task at hand, such a stopping can be both useful and harmful. For example, if we are talking about gradual accumulation of residual stresses, then stopping or at least slowing down this process leads to positive consequences. In the case of an increase in residual deformation, this inherited characteristic is negative and will lead to negative consequences, practically irrespective of the object and the task being solved.

The theory of graphs allows to make only qualitative estimation and in order to find the answer to the question about the quantitative relation, it is suggested to display this relation through the coefficient $k$, which is called the coefficient of change of some property [4, 16]:

$$k = \frac{\delta_i}{\delta_{i+1}},$$

where $i$ – is the number of the current technological operation; $\delta$ – a specific property that changes during the transition from a given technological operation to the next one.

If it is necessary to determine the coefficient of variation of accuracy or roughness, it is quite easy to do, because it requires knowledge of the size tolerance (or roughness value) at $i$ and $i+1$ transition. The property variation factor can also be determined relatively easily for hardness or waviness. However, direct property measurement methods are not available for all quality parameters [14]. For example, it is quite difficult to determine this index for the value of residual stresses and to characterize the purity of the surface (e.g. before bonding). At the same time, there are many quality indicators for which there are no standardized methods for determining them. To such indicators belong some characteristics (for example, forming properties) of fibrous fillers (glass, carbon, organic) used for manufacturing of details from PCM [11]. At the same time, the quality of laying such fabrics on the surface of double curvature rigging will depend on these parameters. Fabrics with poor forming properties are poorly deformed and at the laying can form folds which will lead to essential violations of the quality of the finished product.

Using $k$ coefficients, discrete technological heredity can be described. However, even for the simplest technological process consisting of ten operations and ten quality parameters, a rather complex system of equations is obtained. From the technical point of view its solution can be easily found, but in reality it is almost impossible to do. This is due to several problems:

1. Lack of all necessary information on $\delta_i$ and $\delta_{i+1}$ values.
2. All factors need to be ranked by their importance.

The first problem does not require complex control methods, but it does take time, which is not always economically feasible. To solve the second problem it is possible to use expert systems of estimation which allow to reveal essential and insignificant factors and to exclude the latter from consideration because of their small influence on object properties. However it also will demand the big time expenses.

Transfer of an inherited attribute is carried out not only throughout the whole route of manufacture of a product, but also throughout the entire production process. In this case the industrial environment is the carrier of the mechanism of change of properties of a product and, as a matter of fact, is the carrier of a prehistory of technological heredity, uniting influence of internal and external factors.

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For the account of influence of factors of the industrial environment many researchers suggest to use a functional which name the response [2-4]. It is believed that the inherited information passes through many barriers, on which it is filtered or even completely delayed [4].

A distinctive feature of most graphs (in relation to the description of technological heredity) is the hierarchical order. The most essential features of the hierarchical order are [16]:

- essential (by an order) differences in values characterizing elements of different levels;
- the choice of elements of each particular level depends on the mechanism of interaction characteristic of the given level.

Thus, in each of these two criteria there is uncertainty associated with very vague boundaries, which makes theoretical analysis impossible. However, the vast majority of researchers involved in technological heredity recognized the existence of hierarchical order at each scale level. Such orderliness was called vertical subordination [1, 16].

The principle of vertical subordination is typical for the vast majority of hierarchical systems. The main idea of such subordination is that the system is represented as a family of interrelated subsystems with feedback (figure 2). The activity of such hierarchical system is influenced by the nearest levels. If to assume that the algorithm of functioning of the system on each scale level is deterministic, it follows that until the system comes to its final form on the previous level, it can not go to the next one.

At each of these levels, an additional classification by level of abstraction and by level of complexity should be introduced. Such sublevels are commonly referred to as strata (these are abstraction levels that include a behavioral description of the system). The choice of strata is determined by the terminology used, and therefore each strategist should use his or her own set of concepts and principles of their construction.

![Figure 2. The structure of the hierarchical system with vertical subordination.](image)

However, quite often researchers are faced with a problem where there is no information to fully formalize the existing situation. In this case, it is advisable to identify all the many problems that have arisen, then identify all the many subproblems that have resulted in the existing problems and then try to find a solution to each of the existing subproblems in a consistent way. Thus, it is proposed to use one of the basic principles of hierarchical systems theory – the solution of the original problem will be found only if all the subproblems preceding it are solved. This system is called a hierarchy of decision-making layers.

At formalization of any technological system for which the problem of identification of inherited parameters is solved, researchers face the necessity to choose the «suitable» (in their opinion) level of abstraction. The higher the abstraction level, the more general will be the created model and, conversely, the lower it is, the more private will be all the conclusions made.

In order to identify common patterns that are characteristic of products made from a variety of materials and operated in a variety of conditions, it is proposed to use the experience gained by representatives of various scientific disciplines in this paper.
Prominent German scientists, Justus von Liebig – one of the founders of modern organic chemistry and Karl Sprengel – renowned soil scientist and agronomist, are the authors of the «Minimum Theorem», which is better known as the «Law of the Limiting (or Limiting) Factor» [7]. They presented all the many factors influencing plant growth in the form of a barrel (which was called the Liebig barrel), and the water in it illustrated the system's performance (figure 3, a).

![Figure 3. Visualization of technological heredity using the Liebig metaphorical barrel: a – system without limiting factors and with admissible values of technological errors; b – system with inadmissible values of technological errors; c – system with the presence of limiting factor; d – unstable system at significant excess of one or several quality parameters.](image)

The components of the barrel are strips, each of which (according to the founders of the minimum theorem) represents a chemical element (or type of compound) on the content of which the growth of plants depends. This approach allowed them to create a balanced system of fertilisers, showing that the height of the lowest bar is decisive, while the height of all others is irrelevant. If water starts to flow over the smallest bar, it means that the growth of the object under study is stopped.
The application of this approach to the visualization of technological heredity in mechanical engineering allows to simplify the interpretation of many complex phenomena.

Let's represent a product of mechanical engineering in the form of a metaphorical barrel Liebich, where each bar represents a quality index (figure 3, a), and the distance between the bars illustrates technological errors (figure 3, b). This system clearly illustrates that even if all the quality parameters of the given values, the presence of technological errors in the transition from one technological operation to another leads to a loss of system performance.

The quality index, which is presented in the form of the lowest height bar (figure 3, c), will be the limiting index for this product, as it will cause the water to start pouring out of the barrel at this level. If one bar repeatedly exceeds all others (figure 3, d), such system becomes unstable, or, if to use terminology of the catastrophe theory – structurally unstable that leads to that the system leaves from a stationary mode and jumps to unstable at which there is a rigid loss of working capacity.

The Liebich barrel with one small (figure 3, c) and one large (figure 3, d) bar is, in fact, an illustration of two mechanisms of quality loss, which in the theory of catastrophes were called «soft» and «hard» loss of stability. The large bar is an illustration of a soft loss of stability, while the small bar is a hard loss of stability.

The main purpose of «soft» modeling is to reveal the general nature of the sudden change in the output parameter describing the properties of the system when the external conditions change smoothly. Also «soft» models are convenient to use when some generalized parameters (e.g. entropy) are used as a criterion of the output parameter [1-2]. However, the value of entropy itself does not characterize the process physics, which is the main reason for its limited use in evaluation models of engineering products.

Excessive fascination with «rigid» models leads to a consistent complication of the mathematical apparatus to such an extent that it becomes practically impossible (or very difficult) to use it for solving specific problems.

The use of the Liebich barrel in describing the dynamics of changes in the quality of the object at each specific stage of its life cycle, allows you to focus on the physics of the process and the visualization of relationships between its components. It allows to visualize a complex process taking into account many different factors, including mutually exclusive ones. Thus, the simplest appointment of the Liebich barrel at the decision of problems of an estimation of quality of products of mechanical engineering is a visual illustration.

3. Conclusions

Thus, to visualize the impact of technological heredity on the quality indicators of engineering products, the graph theory and the Liebich metaphorical barrel are most clearly used. In this case the principle of cybernetics is actually used, according to which the system is a set of separate elements connected into a single information network.

Graph theory is related to the theory of coordination, because on the basis of the latter are formulated strategies in the selection of coordinating signals. In the case of technological heredity, this coordination consists in harmonizing quality functions. The essence of this lies in the fact that the total (or global) optimal control influence of technological parameters is composed of optimal local solutions at each technological transition. The method of coordination is to determine how each specific element of the system interacts with other elements of its level. This task is solved by forecasting interactions. If we approach the evaluation of quality indicators from traditional positions, then each of the indicators is considered independently of the others, i.e. the superposition principle is used, which leads to a large number of errors. In the proposed approach, each particular indicator is an independent unit (the edge of the graph, the barrel metaphorical barrel), associated with neighboring independent units that generally characterize the state of the product at each stage of its life cycle.

The joint use of the theory of graphs and the Liebich metaphorical barrel allows evaluating the investigated indices in a complex and demonstrating them visually on the simplest schemes.
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