Journal of Engineering Science | Vol. XXX, no. 1 (2023), pp. 8 - 21
Fascicle | Industrial Engineering | ISSN 2587-3474
Topic | Applied Engineering Sciences and Management | eISSN 2587-3482

https://doi.org/10.52326/jes.utm.2023.30(1).01
UDC 621.9:519.8

IMPROVING THE DESIGNING OF MECHANICAL TECHNOLOGIES THROUGH OPTIMIZED DIMENSIONAL STRUCTURES

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Received: 01. 12. 2023
Accepted: 03. 09. 2023

Abstract. Modern trends in technological development related to the use of numerical control machine tools are manifested by minimizing the number of technological operations, installations, operation elements. One of the most effective ways to improve the design of mechanical processing technologies is to create optimal technological dimensional structures. In the paper, optimality requirements are formulated in relation to the elementary dimensional structures and the entire structure. It is shown that a technological dimensional structure is optimal if it is similar to the constructive dimensional structure. Real constructive dimensional structures are very complex and varied, so that the optimality of some sequences of the structure excludes ensuring the optimality of other sequences. Reciprocal structural adaptations are required, which can be done by constructively resizing the equivalent part. As a criterion for the resizing, the non-admission of the increase in the tolerance of the machining allowance is manifested.

Keywords: *mechanical technologies designing, optimal dimensional structure, dimensional analysis, technological dimensional chain, machining allowance.*

Rezumat. Tendințele moderne în dezvoltarea tehnologică legate de utilizarea mașinilor-unelte cu comandă numerică se manifesta prin minimizarea numărului de operații tehnologice, de instalări, de faze tehnologice. Una dintre cele mai eficiente modalități de îmbunătățire a proiectării tehnologiilor de prelucrare mecanică este crearea structurilor dimensionale tehnologice optimale. In lucrare sunt formulate cerințe de optimalitate în raport cu structurile dimensionale elementare şi cu structura întreagă. Se arata ca o structură dimensională tehnologică este optimală daca este asemănătoare cu structura dimensională constructivă. Structurile dimensionale constructive reale sunt foarte complexe și variate, astfel încât optimitatea unor secvențe ale structurii exclude asigurarea optimității altor secvențe. Sunt necesare adaptări structurale reciproce, care se pot face prin redimensionarea constructivă echivalenta a piesei. În calitate de criteriu al redimensionării se manifesta neadmiterea creşterii toleranţei adaosurilor de prelucrare.

Cuvinte cheie: *proiectare tehnologii de prelucrare mecanică, structură dimensională optimală, analiză dimensională, lanț dimensional tehnologic, adaos de prelucrare.*

1. Introduction

One of the important tasks of mechanical engineering is to obtain competitive products in the sense of minimizing the total costs at the stages of the entire life cycle of the product. This is especially true for the stages of design, development of technological processes and production with the requirement of minimal cost, high quality workmanship while maintaining high productivity.

A characteristic feature of most technological problems is multi-variance. This is due to the possibility of manufacturing a product using a variety of equipment and tools with different structures of operations and their sequence in the technological process. And since there are several possible solutions, there are better and worse options, there is one best option.

Therefore, an important problem is the synthesis of the optimal dimensional structure of the technological process of machining, which allows, at the stage of preparation of production, to obtain an optimal technological process that ensures the achievement of the specified quality and precision of the part, with high productivity of their manufacture, taking into account specific production conditions [1]. The modern solution of such problems is carried out within the framework of the concept of concurrent engineering, developing mutually acceptable and mutually coordinated designs of parts and their manufacturing technologies.

The search for a technology option that ensures the quality and cost-effectiveness of manufacturing parts based on the optimization of dimensional-precision relationships requires finding the optimal technological parameters [2]. At this stage, the main issue is solved the technological support of the technical conditions for the manufacture of the part.

In chronological order, the process of enhancing the design of mechanical technologies was synchronized with the process of technical support of these technologies.

In the conditions of mass and large-scale production, the technological process was developed, and then tested and refined several times until a positive result was achieved. Due to the time and resources involved in production testing, the resulting successful technology was accepted without further optimization. This is also related to the fact that optimization requires a certain tactical behavior in the process of achieving the best result, when as a trial and error method it is based on experience and intuition.

The use of dimensional analysis has greatly simplified the task of designing mechanical technologies, eliminating the need for repeatable manufacturing tests. The latter were replaced by repetitive calculations, although such a synthesis of operating technologies is a rather complicated process due to the large number of parameters. The greatest difficulties arise in the development of schemes for setting technological sizes, the number of which, due to the many options for locating, is quite large. Analysis of all variants of schemes for setting technological sizes in order to find the optimal one requires a long time. Experience has shown that performing iterative dimensional analysis for multiple options leads not only to good solutions, but also to optimized technological structures.

2. Principles to improving the mechanical technologies designing

Changes in recent years, associated with a significant reduction in product series and the widespread use of CNC machines, **including machining centers, have led to the** need to develop technological processes with optimal dimensional structures in a limited time frame [3]. Thus, the dimensional analysis, which performs the function of checking technological sufficiency, turns into an element of guaranteed design of the optimized technological process of machining.

The marked trend also consists in a rather strong decrease in the number of technological operations. On machining centers, technological processes are not uncommon, including 2-3 operations, there are often single-operation technological processes.

If the developed mechanical processing technology contains many operations, then separate partial dimensional structures are formed from many locating datum. The dimensional structure of a part is formed by "assembling" or coordinating the partial dimensional structures into a single whole (Figure 1). Such an "assembly" is carried out with errors, so the reliability and quality of the developed technology are not easy to achieve. Compliance with the principle of the unity of bases can significantly improve the process of "assembling" the particular dimensional structures, however, the errors of repeated installations affect (Figure 2). Obviously, the larger the partial dimensional structures, the more accurate the dimensional structure of the machined part will be.

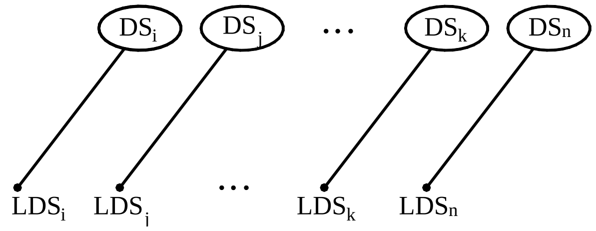

Figure 1. Formation of the part's dimensional structure by many reinstallations from various locating datum surfaces.

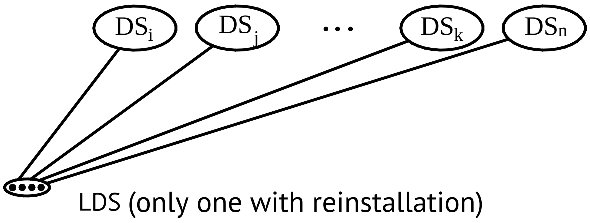

Figure 2. Formation of the part's dimensional structure by many reinstallations, but from only one locating datum surfaces.

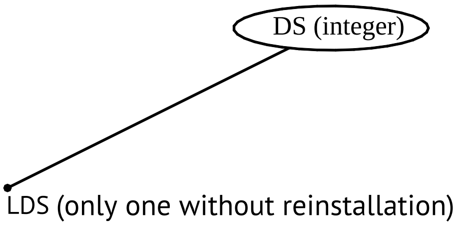

Figure 3. Formation of the part's dimensional structure through one installation.

For single-operation technologies, there is no need to assemble partial dimensional structures (Figure 3) and the dimensional structure of the part is completely determined by the dimensional structure of the technological system and by the measure of their consistency. The modern CNC machine-tools and machining centers provide significantly higher precision than classical ones, so dimensional precision can be achieved in fewer operatopnal elements. Thus, the first principle (direction) of designing optimization and, consequently, technological processes can be formulated as follows. *The number of technological operations, the number of installations and the number of operation elements throughout the entire technological process should be kept to a minimum* $\sum n_{op} \to min$, $\sum n_{inst} \to min$, $\sum n_{oe} \to min$.

The use of CNC machines and machining centers is justified for the manufacture of parts with complex dimensional structures. Probabilistic methods of dimensional analysis in conditions of a large number of sizes are not satisfactory for assessing the decisions made. Therefore, the worst case scenario is taken into account - the Worst-Case tolerancing method. Thus, the second principle (direction) of designing optimization and, consequently, technological processes provides for the following. *The sum of the tolerances of technological sizes that make up the links in the chain of the closing designing size must not exceed the tolerance of this size,* $T \geq \sum \omega_{t_i}$.

The dimensional structure of the part includes many design sizes with their own tolerances $A_c(T_{Ac}^{det\,ail})$, each of which is formed in technology by its own technological size with its own technological tolerance. Optimal is the dimensional structure in which the design dimension $A_c(T_{Ac}^{det\,ail})$ is formed only by it own technological size $A_t(\omega_{At})$ [4]. Then the precision of the technological size goes into the precision of the design size directly and without loss (Figure 4, a). The process involves the processing of surfaces connected by a design dimension with an alternation of a number of technological sizes $T_{Ac}^{det\,ail} = \omega_{A_t}$ (Figure 4, b).

Dimensional structures are often observed in which the technological dimensional chain is closed not only by the designing and its own technological dimensions , but with the involvement of an additional one (possibly several) already existing (historical) technological dimensions (Figure 5). Thus, the required precision of the design size is achieved by increasing the requirements for the precision of the technological sizes that make up the dimensional chain according to the inequality $T_{Ac}^{det\,ail} \geq \omega_{A_t} + \omega_{B_t}$ [4]. The precision of the designing size is ensured at the proper level by improving the precision of the execution of technological sizes.

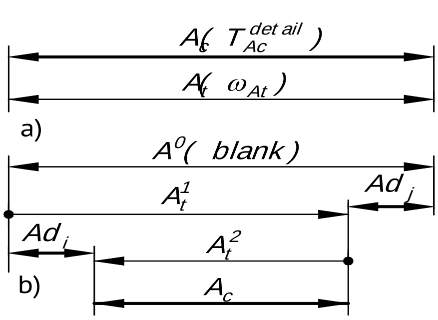

Figure 4. The constructive size is formed through: a) the only one technological size, $T_{Ac}^{det\,ail} = \omega_{A_t}$; b) when machining with the removal of machining allowances Ad , the constructive size is the result of alternating a series of own technological sizes.

The optimality of the above described option in Figure 3 a may be violated, since the locally optimal size A_t may enter as a historical one into another dimensional chain. It will require an increase in its precision and, as a result, a forced increase in the precision of its own designing size A_c. Thus, the third principle (direction) of designing optimization and, consequently, technological processes can be formulated as follows. *The optimal is the dimensional structure, in which each design dimension is formed only by its own technological dimensions.*

Any pair of technological sizes is formed due to the removal of the machining allowance, the goal being an increase in the precision of a certain technological size (Figure 6). The machining allowance in this case is the closing size of the dimensional chain. If both technological dimensions are formed from the same locating datum surface, then the machining allowance tolerance is defined as $\omega_{Ad_i} = \omega_{A_t^{i-1}} + \omega_{A_t^i}$.

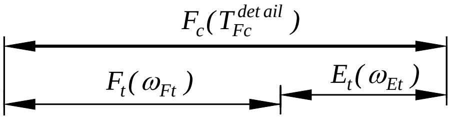

Figure 5. The constructive size is formed through the own technological size and another technological (historical) size.

If there is a change of locating datum surfaces, then the tolerance of the machining allowance increases by the tolerance of the distance between the accepted locating datum surfaces, $\omega_{Ad_i} = \omega_{A_t^{i-1}} + \omega_{A_t^i} + \Delta_{LDS}$.

An increase in the maximum machining allowance ($Ad_{\max} = Ad_{\min} + \omega_{Ad}$) is equivalent to an increase in the depth of cut and the need to increase the number of operation elements. The large depths of cut are especially unacceptable in terms of the use High Speed Machining concept.

From this the fourth principle (direction) of designing optimization and, consequently, technological processes can be formulated as follows. *The number of links in the technological dimensional chain, in which the machining allowance is the closing link, should be, if possible, equal to 3 (the size on the previous operation element, the size on the given operation element and the intermediate size between them - the machining allowance)* $\sum m_j = 3$. This is, in fact, a different formulation of the principle of unity of locating datum. The optimal technological process will consist of similar elementary technological blocks. At the same time, the locating datum must coincide with the designing and measurement datum surfaces.

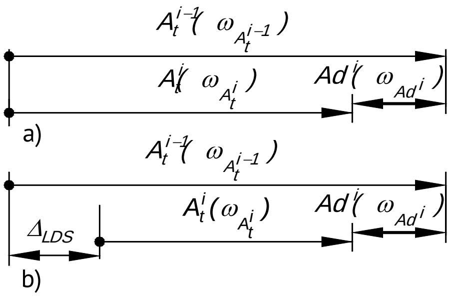

Figure 6. Target transformation of the technological size by removing the machining allowances: a) from only one locating datum surface; b) with the change of locating datum surfaces.

Note that the removal of the machining allowance in order to increase the precision of one technological size leads to a decrease in the precision of all other technological sizes associated with the machined surface (Figure 7). Non-target sizes (R_t^i), in this case, are closing in dimensional chains and their tolerance is increased by the tolerance of the machining allowance to be removed ($\omega_{A_t^i} = \omega_{A_t^{i-1}} + \omega_{Ad_i}$). The size takes on an intermediate value $R_t^{i\,int}$ and subsequently as a target size will be brought to the required precision [5].

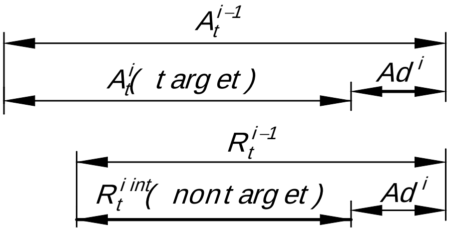

Figure 7. Non-target formed size.

The labor intensity of the technological processes is associated with the removal of machining allowances from the surfaces. And this is the time spent by technological systems, operators, tool consumption etc. The fifth principle (direction) of designing optimization and, consequently, technological processes can be formulated as follows. *The sum (volume sum) of the maximum machining allowances (*$Ad_{k\,max} = Ad_{k\,min} + \omega_{Ad_k}$*) removed from all surfaces of the part should be minimal (*$\sum Ad_k \to min$*) and each maximum machining allowance should not exceed the value allowed to achieve precision,* $Ad_{k\,max} \leq [Ad_k]$.

The detail subjected to machining, is characterized by constructive dimensional structure which reflect, eventually, its functionality. The nature of the constructive dimensional structure is defined by the designer who takes into account the technological features of machine tools, but not in detriment of their functionality. The technological dimensional structure should ensure the formation of the dimensional structure of the part with restrictions imposed by the features of the dimensional structures of technological systems. This is optimally achieved if the designing and technological dimension structures are the same, so that each design dimension is formed exclusively by its own technological dimension [4].

The sixth principle (direction) of designing optimization and, consequently, technological processes can be formulated as follows. *The optimality of technological processes is achieved at the similarity of the technological and constructive dimensional links graphs* [4].

The technological system has its own possibilities for the formation of dimensional structures. The CNC machine-tools and machining centers are being programmed to form epy dimensional structures in absolute and relative coordinates (Figure 8). Additional features are associated with the ability to use the floating zeros. In technological terms, this is the possibility of successive change of locating datum surfaces (locating datum - LD, adjustment datum - AD). The optimal technological dimensional structure in terms of similarity with the designing dimensional structure often must be adapted to the capabilities of the technological system. This can be done by recalculating the designing sizes so that the new designing dimension structure is equivalent to the original. The central problem of technological design optimization is the allocation of tolerances for technological sizes [6,7].

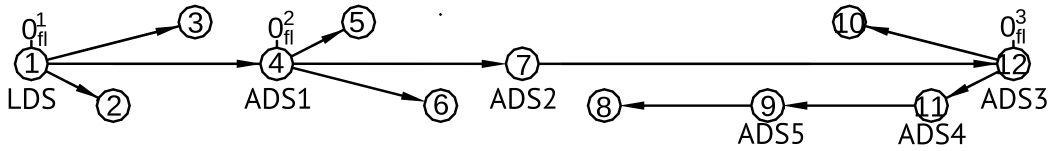

Figure 8. Formation of a dimensional structure on CNC machine-tools.

3. Adapting dimensional structures to the capabilities of CNC machine-tools

Below several variants of combinations of constructive and technological dimensional structures are analyzed. The dimensional chains have been solved at the machining the front surfaces 1, 2, 3 and 4 with the positioning coordinates in relation to surface 0 respectively at 200, 150, 100 and 50 mm in the dimensioning variants according to Figures 9, 11, 13, 15. For forming the constructive sizes A_c, B_c, C_c and E_c all end surfaces (1, - 4) are machined twice, first on the 13th grade, and then on the 11th grade. The cast blank is made with dimensional tolerances corresponding to 16th grade. Depending on the specific variant, each constructive size is formed either only by its own technological size or by its own technological size and other situational size. The need to improve the precision of technological sizes in comparison with the 13th grade for the first stage of machining and the 11th grade at the second stage of machining is analyzed. The number of tolerance units is used as a measure.

The tolerance values of the machining allowances removed at the first and second stages of machining are also analyzed. This is important because the depth of cut is assumed to be equal to the maximum machining allowance, $Ad_{max} = Ad_{min} + \omega_{Ad}$.

The analysis were performed using the worst-case method and worst-case method with error's compensation methods [8,9].

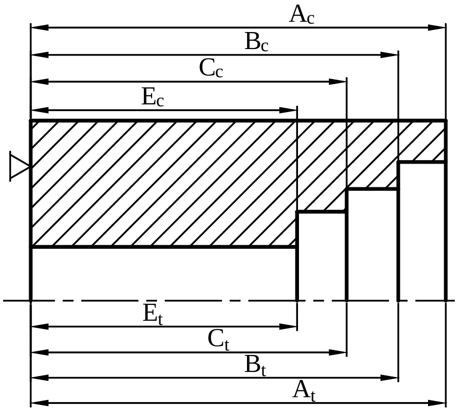

Figure 9. Dimensional constructive and technological structures (variant 1).

Variant 1, (Figure 9). The all constructive sizes are given from constructive base - surface 0 and the technological sizes are formed also from locating datum surface (LDS) – the same surface 0.

From the graphs of dimensional links (Figure 10 b, c) it's clear that the conditions for ensuring the size's precision are optimal because the precision of technological sizes is not greater than precision of constructive sizes:

$$\omega_{A_t^1} \le \omega_{A_c^1},\ \omega_{B_t^1} \le \omega_{B_c^1},\ \omega_{C_t^1} \le \omega_{C_c^1},\ \omega_{E_t^1} \le \omega_{E_c^1},$$
$$\omega_{A_t^2} \le \omega_{A_c^2},\ \omega_{B_t^2} \le \omega_{B_c^2},\ \omega_{C_t^2} \le \omega_{C_c^2},\ \omega_{E_t^2} \le \omega_{E_c^2}. \qquad (1)$$

After the first stage of machining the tolerances of machining allowances for surfaces 1, 2, 3 and 4 should be determined as (Figure 10 d):

$$\omega_{Ad_1^1} = (\omega_{A_t^1} + \omega_{A_t^0}), \qquad \omega_{Ad_2^1} = (\omega_{B_t^1} + \omega_{B_t^0}),$$
$$\omega_{Ad_3^1} = (\omega_{C_t^1} + \omega_{C_t^0}), \qquad \omega_{Ad_4^1} = (\omega_{E_t^1} + \omega_{E_t^0}). \tag{2}$$

Here and below the sizes A_t^0 ,B_t^0 ,C_t^0 and E_t^0 are the dimensions of the blank.

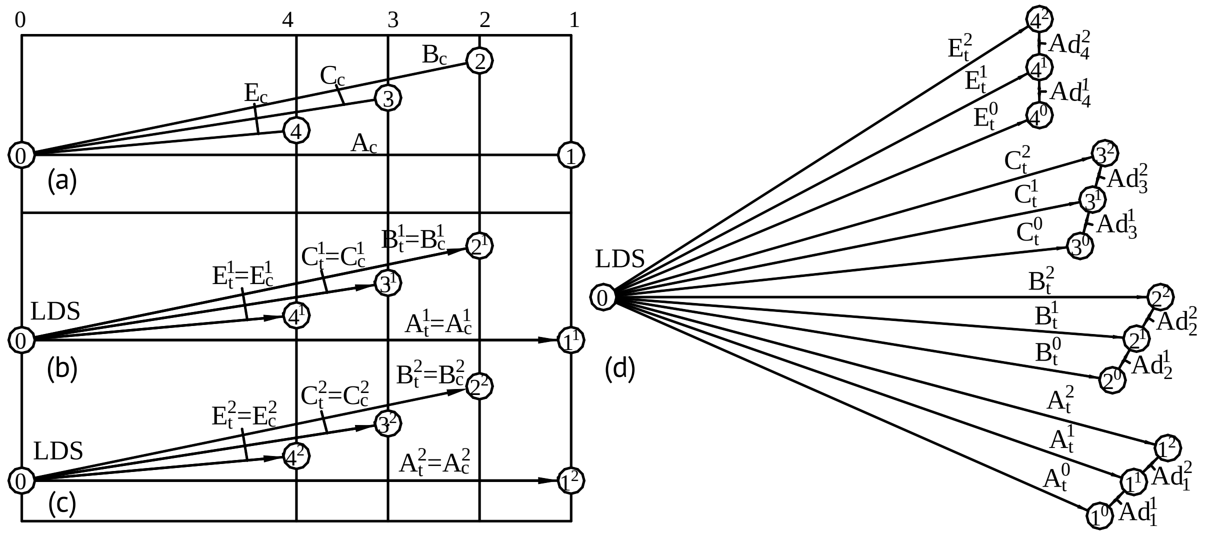

Figure 10. The graphs of dimensional links for: constructive sizes (a), technological sizes (b, c) and machining allowances (d) [10,11].

It can be seen that at the second stage of machining, the effect of error's compensating between the two succesive technological sizes formed by machining is manifested (Figure 10 d):

$$\omega_{Ad_1^2} = (\omega_{A_t^2} + \omega_{A_t^1}) - 2\cdot\omega_{1^2 1^1}^{comp}, \qquad \omega_{Ad_2^2} = (\omega_{B_t^2} + \omega_{B_t^1}) - 2\cdot\omega_{2^2 2^1}^{comp},$$
$$\omega_{Ad_3^2} = (\omega_{C_t^2} + \omega_{C_t^1}) - 2\cdot\omega_{3^2 3^1}^{comp}, \qquad \omega_{Ad_4^2} = (\omega_{E_t^2} + \omega_{E_t^1}) - 2\cdot\omega_{4^2 4^1}^{comp}. \tag{3}$$

It can be seen that there are not situations with fairly high values of the machining allowance's tolerances (greater than 3.62), consequently with fairly high values of the machining allowances (Table 1). The machining strategy according to Figures 9 and 10 is optimal.

Table 1

Variant 1. The values of machining allowance's tolerances

Stage	Machined surfaces							
	1	2	3	4	1	2	3	4
	Worst-case tolerances				Worst-case tolerances with error's compensation			
Ad^1	3.62	3.13	2.74	1.99	3.62	3.13	2.74	1.99
Ad^2	1.01	0.88	0.76	0.58	0.43	0.38	0.32	0.20

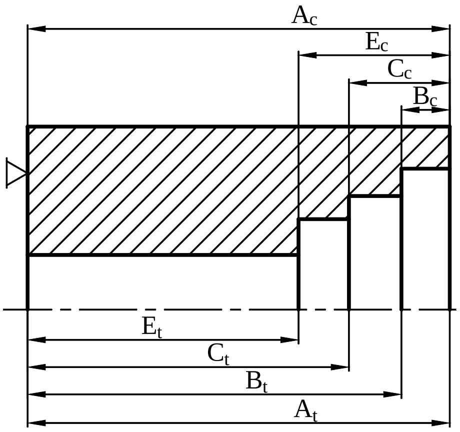

Figure 11. Dimensional constructive and technological structures (variant 2)

Variant 2 (Figure 11). One of constructive sizes is given from constructive base - surface 0 and the rest of the sizes are given from other constructive base - surface 4. The machining is realized by technological sizes formed exclusive from locating datum surface 0 (LDS).

From the graphs of dimensional links (Figure 14, b, c) it's seen that the conditions for ensuring the size's precision are not optimal because the accuracies of technological sizes B_t, C_t and E_t are greater than the precision of respective constructive sizes (table 2).

From Figure 12 d should be that the dimension links for the machining allowances of surfaces 2, 3 and 4 include as constituent elements the machining allowances of surface 1 (Ad_1^1 or Ad_1^2). The tolerances of machining allowances for surfaces 1, 2, 3 and 4 after first stage of machining can be determined as:

$$\begin{aligned}
&\omega_{A_t^1} \le \omega_{A_c^1}, && \omega_{B_t^1} \le \omega_{B_c^1} - \omega_{A_t^1} + 2\cdot\omega^{comp}_{1^1 2^1},\\
&\omega_{C_t^1} \le \omega_{C_c^1} - \omega_{A_t^1} + 2\cdot\omega^{comp}_{1^1 3^1}, && \omega_{E_t^1} \le \omega_{E_c^1} - \omega_{A_t^1} + 2\cdot\omega^{comp}_{1^1 4^1},\\
&\omega_{A_t^2} \le \omega_{A_c^2}, && \omega_{B_t^2} \le \omega_{B_c^2} - \omega_{A_t^2} + 2\cdot\omega^{comp}_{1^2 2^2},\\
&\omega_{C_t^2} \le \omega_{C_c^2} - \omega_{A_t^2} + 2\cdot\omega^{comp}_{1^2 3^2}, && \omega_{E_t^2} \le \omega_{E_c^2} - \omega_{A_t^2} + 2\cdot\omega^{comp}_{1^2 4^2}.
\end{aligned} \tag{7}$$

$$\begin{aligned}
&\omega_{Ad_1^1} = (\omega_{A_t^1} + \omega_{A_t^0}),\\
&\omega_{Ad_2^1} = (\omega_{B_t^1} + \omega_{B_t^0}) + (\omega_{A_t^1} + \omega_{A_t^0}),\\
&\omega_{Ad_3^1} = (\omega_{C_t^1} + \omega_{C_t^0}) + (\omega_{A_t^1} + \omega_{A_t^0}),\\
&\omega_{Ad_4^1} = (\omega_{E_t^1} + \omega_{E_t^0}) + (\omega_{A_t^1} + \omega_{A_t^0})
\end{aligned} \tag{8}$$

Table 2

Variant 2. The measure of the growth of the precision of technological sizes

Stage	A_c, B_c, C_c, E_c	Worst-case method				Worst-case method with error's compensation			
		A_t	B_t	C_t	E_t	A_t	B_t	C_t	E_t
	Number of tolerance units, a; precision grade								
1	250; 13	72; 10 - 11	72; 10 - 11	153; 12	250; 13	81; 10 - 11	81; 10 - 11	184; 12 - 13	330; >13
2	100; 11	35; <9	35; <9	55; 9 - 10	95; 11	39; 9	39; 9	64; 10	114; >11

After the second stage of machining the situation is a similar, except that the phenomenon of error’s compensation is manifested:

$$\begin{aligned}
&\omega_{Ad_1^2} = (\omega_{A_t^2} + \omega_{A_t^1}) - 2\cdot\omega^{comp}_{1^1 1^2},\\
&\omega_{Ad_2^2} = (\omega_{B_t^2} + \omega_{B_t^1}) - 2\cdot\omega^{comp}_{2^1 2^2} + (\omega_{A_t^2} + \omega_{A_t^1}) - 2\cdot\omega^{comp}_{1^1 1^2},\\
&\omega_{Ad_3^2} = (\omega_{C_t^2} + \omega_{C_t^1}) - 2\cdot\omega^{comp}_{3^1 3^2} + (\omega_{A_t^2} + \omega_{A_t^1}) - 2\cdot\omega^{comp}_{1^1 1^2},\\
&\omega_{Ad_4^2} = (\omega_{E_t^2} + \omega_{E_t^1}) - 2\cdot\omega^{comp}_{4^1 4^2} + (\omega_{A_t^2} + \omega_{A_t^1}) - 2\cdot\omega^{comp}_{1^1 1^2}.
\end{aligned} \tag{9}$$

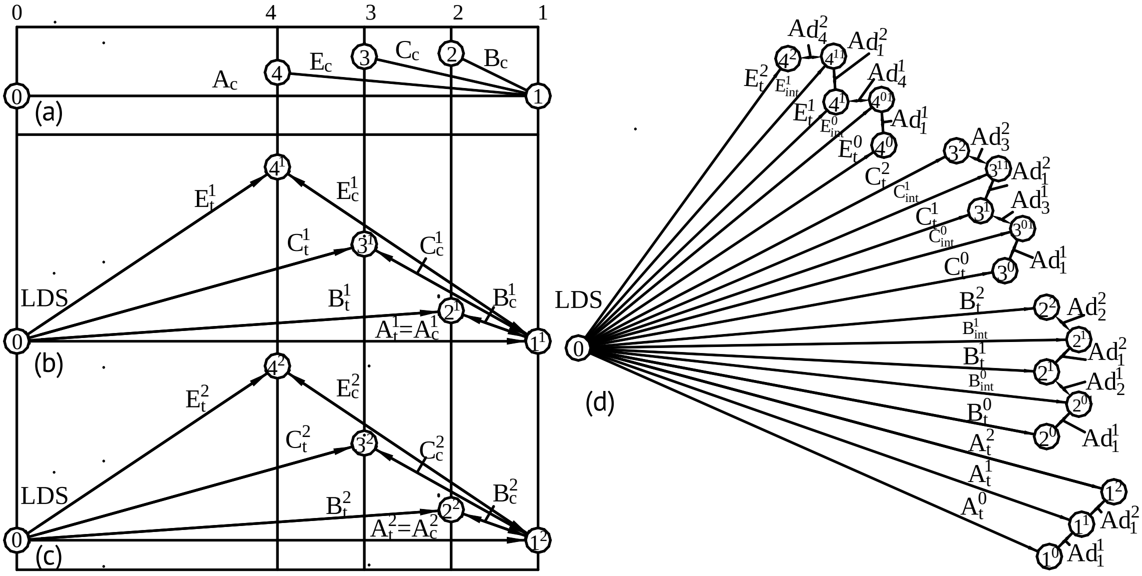

Figure 12. Example of the graphs of dimensional links for: constructive sizes (a), technological sizes (b, c) and machining allowances (d) [10].

Table 3

Variant 2. The values of machining allowance’s tolerances

Stage	Machined surfaces							
	1	2	3	4	1	2	3	4
	Worst-case tolerances				Worst-Case tolerances with error’s compensation			
Ad^1	3,62	6,75	6,36	5,61	3,62	6,75	6,36	5,61
Ad^2	1,01	1,89	1,77	1,59	0,43	0,81	0,75	0,63

$$\begin{aligned}
&\omega_{A_t^1} \le \omega_{A_c^1}, && \omega_{B_t^1} \le \omega_{B_c^1} - \omega_{A_t^1} + 2\cdot\omega^{comp}_{1^1 2^1},\\
&\omega_{C_t^1} \le \omega_{C_c^1} - \omega_{B_t^1} + 2\cdot\omega^{comp}_{2^2 3^1}, && \omega_{E_t^1} \le \omega_{E_c^1} - \omega_{C_t^1} + 2\cdot\omega^{comp}_{3^1 4^1},\\
&\omega_{A_t^2} \le \omega_{A_c^2}, && \omega_{B_t^2} \le \omega_{B_c^2} - \omega_{A_t^2} + 2\cdot\omega^{comp}_{1^2 2^2},\\
&\omega_{C_t^2} \le \omega_{C_c^2} - \omega_{B_t^2} + 2\cdot\omega^{comp}_{2^2 3^2}, && \omega_{E_t^2} \le \omega_{E_c^2} - \omega_{C_t^2} + 2\cdot\omega^{comp}_{3^2 4^2}.
\end{aligned} \tag{10}$$

It can be observe that there are many situations with fairly high values of the machining allowance's tolerances (greater than 3,62), consequently with fairly high values of the machining allowances (Table 3).

Variant 3 (Figure 13). One of constructive sizes is given from constructive base - surface 0 and the rest of the sizes are given in chain from the surface 4. The machining is realized by technological sizes from locating datum surfaces 0 (LDS).

From the graphs of dimensional links (Figure 14, b, c) it's seen that the conditions for ensuring the size's precision are not optimal because the accuracies of technological sizes B_t, C_t and E_t are greater than the precision of respective constructive sizes:

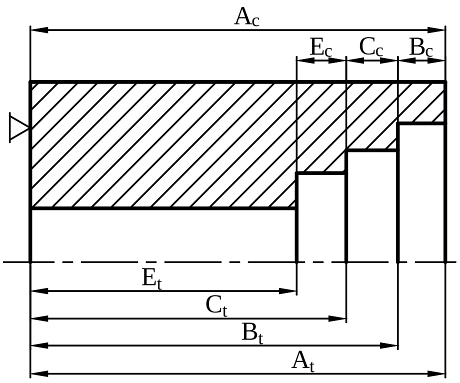

Figure 13. Dimensional constructive and technological structures (variant 3)

Table 4

Variant 3. The measure of the growth of the precision of technological sizes

Stage	$A_c, B_c,$ C_c, E_c	Worst-case method				Worst-case method with error's compensation			
		A_t	B_t	C_t	E_t	A_t	B_t	C_t	E_t
	Number of tolerance units, a; precision grade								
1	250; 13	72; 10 - 11	72; 10 - 11	96; 11	116; 11 - 12	81; 10 - 11	81; 10 - 11	140; 11 - 12	130; 11 - 12
2	100; 11	35; <9	35; <9	47; 9 - 10	57; 9 - 10	39; 9	39; 9	68; 10	63; 10

From Figure 14 d should be that the dimension links for the machining allowances of surfaces 2, 3 and 4 include as constituent elements the machining allowances of previous machined surface. The tolerances of machining allowances for surfaces 1, 2, 3 and 4 after first stage of machining can be determined as:

$$\omega_{Ad_1^1} = (\omega_{A_t^1} + \omega_{A_t^0}), \qquad \omega_{Ad_2^1} = (\omega_{B_t^1} + \omega_{B_t^0}) + (\omega_{A_t^1} + \omega_{A_t^0}),$$
$$\omega_{Ad_3^1} = (\omega_{C_t^1} + \omega_{C_t^0}) + (\omega_{B_t^1} + \omega_{B_t^0}), \qquad \omega_{Ad_4^1} = (\omega_{E_t^1} + \omega_{E_t^0}) + (\omega_{C_t^1} + \omega_{C_t^0}). \tag{11}$$

After the second stage of machining the situation is a similar, except that the phenomenon of error's compensation is manifested:

$$\omega_{Ad_1^2} = (\omega_{A_t^2} + \omega_{A_t^1}) - 2 \cdot \omega^{comp}_{1^1 1^2},$$
$$\omega_{Ad_2^2} = (\omega_{B_t^2} + \omega_{B_t^1}) - 2 \cdot \omega^{comp}_{2^1 2^2} + (\omega_{A_t^2} + \omega_{A_t^1}) - 2 \cdot \omega^{comp}_{1^1 1^2},$$
$$\omega_{Ad_3^2} = (\omega_{C_t^2} + \omega_{C_t^1}) - 2 \cdot \omega^{comp}_{3^1 3^2} + (\omega_{B_t^2} + \omega_{B_t^1}) - 2 \cdot \omega^{comp}_{2^1 2^2}, \tag{12}$$
$$\omega_{Ad_4^2} = (\omega_{E_t^2} + \omega_{E_t^1}) - 2 \cdot \omega^{comp}_{4^1 4^2} + (\omega_{C_t^2} + \omega_{C_t^1}) - 2 \cdot \omega^{comp}_{3^1 3^2}$$

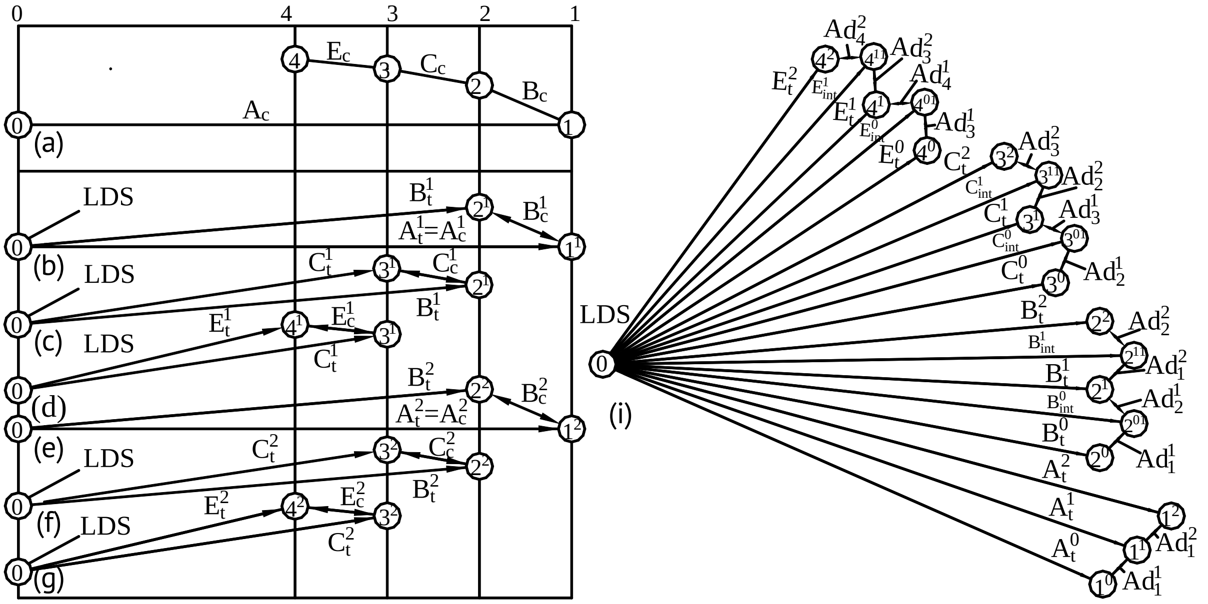

Figure 14. Example of the graphs of dimensional links for: constructive sizes (a), technological sizes (b, c, d, e, f, g) and machining allowances (i) [10].

Table 5

Variant 3. The values of machining allowance's tolerances

Stage	Machined surfaces							
	1	2	3	4	1	2	3	4
	Worst-case tolerances, mm				Worst-Case tolerances with error's compensation, mm			
Ad^1	3.62	6.75	5.87	4.73	3.62	6.75	5.87	4.73
Ad^2	1.01	1.89	1.64	1.34	0.43	0.81	0.70	0.52

It can be observed (Table 5) that there are many situations with fairly high values of the machining allowance's tolerances (greater than 3.62), consequently with fairly high values of the machining allowances.

Variant 4 (Figure 15). One of constructive sizes is given from constructive base - surface 0 and the rest of the sizes are given in chain from the surfaces 1, 2 and 3. The machining is realized by technological sizes formed from locating datum surface 0 (LDS) and in chain from adjustment datum surfaces 1, 2, 3 (ADS1, ADS2, ADS3).

From the graphs of dimensional links (Figure 16 b, c) it's seen that the conditions for ensuring the size's precision are optimal because the precision of technological sizes is not greater than precision of constructive sizes:

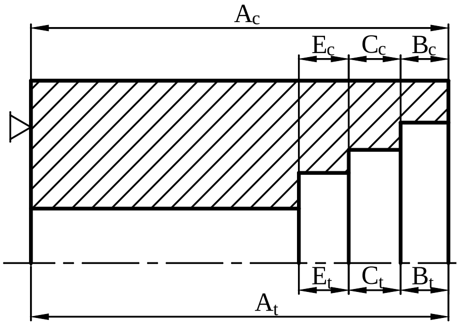

Figure 15. Dimensional constructive and technological structures (variant 4).

$$\omega_{A_t^1} \le \omega_{A_c^1}, \quad \omega_{B_t^1} \le \omega_{B_c^1}, \quad \omega_{C_t^1} \le \omega_{C_c^1}, \quad \omega_{E_t^1} \le \omega_{E_c^1},$$
$$\omega_{A_t^2} \le \omega_{A_c^2}, \quad \omega_{B_t^2} \le \omega_{B_c^2}, \quad \omega_{C_t^2} \le \omega_{C_c^2}, \quad \omega_{E_t^2} \le \omega_{E_c^2}. \qquad (13)$$

From figure 16 d should be that the dimension links for the machining allowances of surfaces 2, 3 and 4 include as constituent elements the all machining allowances of previous machined surface. The tolerances of machining allowances for surfaces 1, 2, 3 and 4 after first stage of machining can be determined as [10]:

$$\omega_{Ad_1^1} = (\omega_{A_t^1} + \omega_{A_t^0}), \qquad \omega_{Ad_2^1} = (\omega_{B_t^1} + \omega_{B_t^0}) + (\omega_{A_t^1} + \omega_{A_t^0}),$$
$$\omega_{Ad_3^1} = (\omega_{C_t^1} + \omega_{C_t^0}) + (\omega_{B_t^1} + \omega_{B_t^0}) + (\omega_{A_t^1} + \omega_{A_t^0}), \qquad (14)$$
$$\omega_{Ad_4^1} = (\omega_{E_t^1} + \omega_{E_t^0}) + (\omega_{C_t^1} + \omega_{C_t^0}) + (\omega_{B_t^1} + \omega_{B_t^0}) + (\omega_{A_t^1} + \omega_{A_t^0}).$$

After the second stage of machining the situation is a similar, but with the manifestation of the phenomenon of error's compensation:

$$\omega_{Ad_1^2} = (\omega_{A_t^2} + \omega_{A_t^1}) - 2\cdot\omega_{1^1 1^2}^{comp},$$
$$\omega_{Ad_2^2} = (\omega_{B_t^2} + \omega_{B_t^1}) - 2\cdot\omega_{2^1 2^2}^{comp} + (\omega_{A_t^2} + \omega_{A_t^1}) - 2\cdot\omega_{1^1 1^2}^{comp},$$
$$\omega_{Ad_3^2} = (\omega_{C_t^2} + \omega_{C_t^1}) - 2\cdot\omega_{3^1 3^2}^{comp} + (\omega_{B_t^2} + \omega_{B_t^1}) - 2\cdot\omega_{2^1 2^2}^{comp} +$$
$$+ (\omega_{A_t^2} + \omega_{A_t^1}) - 2\cdot\omega_{1^1 1^2}^{comp}, \qquad (15)$$
$$\omega_{Ad_4^2} = (\omega_{E_t^2} + \omega_{E_t^1}) - 2\cdot\omega_{4^1 4^2}^{comp} + (\omega_{C_t^2} + \omega_{C_t^1}) - 2\cdot\omega_{3^1 3^2}^{comp} +$$
$$+ (\omega_{B_t^2} + \omega_{B_t^1}) - 2\cdot\omega_{2^1 2^2}^{comp} + (\omega_{A_t^2} + \omega_{A_t^1}) - 2\cdot\omega_{1^1 1^2}^{comp}$$

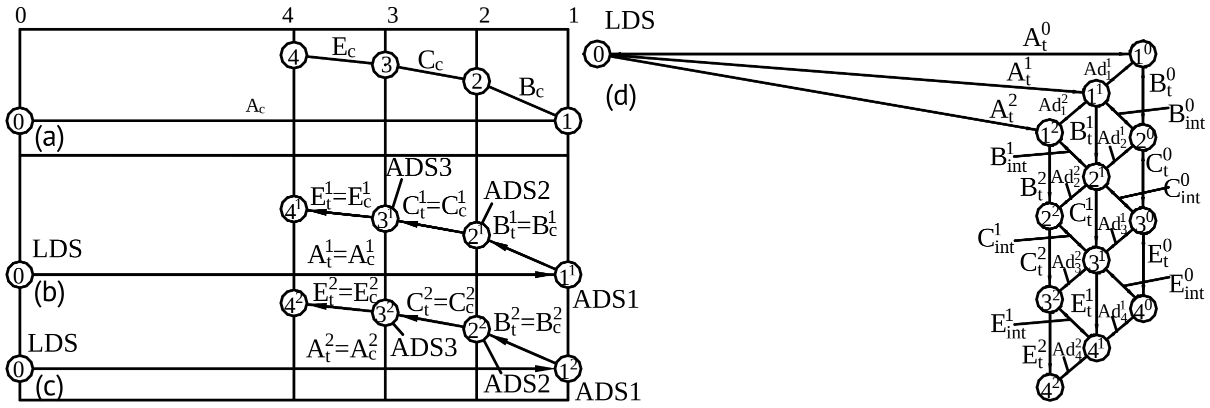

Figure 16. Example of the graphs of dimensional links for: constructive sizes (a), technological sizes (b, c) and machining allowances (d) [10,11].

Table 6

Variant 4. The values of machining allowance's tolerances

Stage	Machined surfaces							
	1	2	3	4	1	2	3	4
	Worst-case tolerances, mm				Worst-Case tolerances with error's compensation, mm			
Ad^1	3.62	5.61	7.60	9.59	3.62	5.61	7.60	9.59
Ad^2	1.01	1.65	2.26	2.84	0.43	0.57	0.74	0.94

It can be observe that there are many situations with fairly high values of the machining allowance's tolerances (greater than 3.62), consequently with fairly high values of the machining allowances (Table 6).

4. Conclusions

1. Modern trends in technological development are related to the increasing use of numerically controlled machine tools. This is reflected in the fact that the number of technological operations, the number of installations and the number of operation elements throughout the entire technological process should be kept to a minimum.
2. The reduction of product series implies higher requirements for the robustness of technologies designed in such a way that the worst case scenario is taken into account - the Worst-Case tolerancing method. So, the sum of the tolerances of technological sizes that make up the links in the chain of the closing designing size must not exceed the tolerance of this size.
3. One of the most effective ways to improve the design of mechanical processing technologies is the creation of optimal technological dimensional structures, which are based on optimal primary structural elements such as: a) the optimal is the dimensional structure, in which each design dimension is formed only by its own technological dimensions; b) the number of links in the technological dimensional chain, in which the machining allowance is the closing link, should be, if possible, equal to 3 (the size on the previous operation element, the size on the given operation element and the intermediate size between them - the machining allowance).
4. The optimality of technological processes is achieved at the similarity of the technological and constructive dimensional links graphs.
5. Real constructive dimensional structures are very complex and varied, so that the optimality of some sequences of the structure excludes ensuring the optimality of other sequences. Reciprocal structural adaptations are necessary.
6. The machining allowance is an indispensable element of the technological dimensional links and, in addition to the geometric character (value, tolerance), it also has the role of cutting depth, which is limiting for machining precision and for consumptions. So, each maximum machining allowance should not exceed the value allowed to achieve precision and the sum (volume sum) of the maximum machining allowances removed from all surfaces of the part should be minimal.

The paper was presented at the works of the ModTech 2018 International Conference, 13 - 16 June 2018, Constanta, Romania

Conflicts of Interest: The author declares no conflict of interest.

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Citation: Stroncea A. Improving the designing of mechanical technologies through optimized dimensional structures. *Journal of Engineering Science* 2023, 30 (1), pp. 8-21. https://doi.org/10.52326/jes.utm.2023.30(1).01.

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