Economic efficiency of the application of additive technologies based on laser direct metal tooling in the production of aircraft parts

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Abstract. The paper discusses the issues of the feasibility study on the integration of additive manufacturing technologies into classical technological chains. Using the aviation part as an example, we consider a model for the formation of technological costs for the classic and proposed versions of its manufacturing technology. A comparative parametric analysis of the cost of production of aircraft parts of this type was performed according to two options.

1. Introduction
The effectiveness of the technology when it is introduced into the production process under equal initial conditions is determined by two criteria: the duration of the production cycle and the cost per one part. With the same final quality of the part, it is precisely these two criteria that collectively affect the final choice of production technology.

Additive technologies today are increasingly seen as an alternative to traditional procurement technologies (stamping (forging), various types of casting). The workpiece obtained by this technology is, in fact, a finished part, with the exception of surfaces that have special requirements for accuracy, roughness, the shape of this surface, as well as its location relative to the design base of the part [1-6]. The profitability of the production of blanks obtained by additive technologies is the higher, the more complicated the configuration of the final parts, the greater their nomenclature and the smaller the annual production volume. The greatest productivity in the application of additive manufacturing technologies can be obtained by integrating them into technological equipment for machining [7,8]. This allows you to reduce: the amount of equipment and the length of the process; logistics costs (up to 30% of the cost of the part); costs for primary and auxiliary personnel; production area. This is most relevant for high-tech industries, such as aircraft manufacturing, rocket science, etc.

In this work, using the example of an aircraft part, a “paw” type bracket investigates the effectiveness of the use of additive technologies based on direct laser growth.

2. Research methodology
Consider the options for technological processes of manufacturing parts of the aircraft bracket type "foot". For comparison, we choose the traditional standard technological process as the main technology option and the technological process variant using the additive cycle as promising. In this paper, for the
implementation of additive technologies, we perform a topological analysis of the part and consider the thus obtained technological model of the geometry of the part of the bracket type “foot” (figure 1).

Topological analysis reflects the main stages in the formation of the geometry of the finished part from the workpiece using both classical technologies for the production of aircraft parts and additive manufacturing technologies. Classical technology loses significantly in the duration and length of the production cycle (figure 2).

After optimizing the geometry of the part, the technology of its manufacture in an additive production cycle will look as follows (figure 3).
Consider the production cycle $C_2$ using additive manufacturing technologies of the part as promising. The technical and economic effect of $T_\theta$ is determined by the influence of costs on the basic equipment, technological equipment and the content of the specialists involved in the work. A comparative analysis of specialists is given on table 1.

**Table 1.** Comparative analysis of the necessary specialists for technology options $C_1$ and $C_2$.

| $C_1$ - Traditional manufacturing technology | $C_2$ - Laser-aided Direct Metal Tooling technology (DMD) |
|-----------------------------------------------|-------------------------------------------------------|
| Part constructor                              | Part constructor                                      |
| Production Engineer                           | 3D-Printer operator                                   |
| 0                                             | Technologist                                          |
| 0                                             | Economist                                             |
| Pre-Production Designer                       | Control specialist                                    |
| Auxiliary production technologist             |                                                      |
| CNC machine technologist                      | 0                                                     |
| CNC machine operator                          | 0                                                     |
| Auxiliary production controller               | 0                                                     |
| Locksmith                                     | 0                                                     |
| Foundry technologist                          | 0                                                     |
| Annealing Furnace operator                    | 0                                                     |
| Plating bath operator                         | 0                                                     |
| Transport operator                            | 0                                                     |

As can be seen from table 1, when implementing the promising technological cycle $C_2$, there is a multiple reduction in the range of equipment and specialists.

3. **Practical significance**

Performing a technical and economic comparison, consider a simulation model of traditional technologies as a form of production organization (denote $C_1$) and a model of production using additive technologies $C_2$. The model takes into account the effect of $\alpha$ - criteria: the number of equipment (depreciation), items necessary technological equipment (cost and based on the number of items), the number of specialists (labor times). The parameter of the annual program of production of details is considered identical for two compared forms of the organization of productions $C_1$ and $C_2$: $N = N_1 = N_2$.

The cost of production details determine the cost of materials $Z_m$, the cost of maintenance and operation of equipment $Z_o$, the cost of maintenance and operation of production facilities $Z_s$, the cost of wages of the main production workers $Z_w$. Consider the mechanism of formation of these costs in the production environment.

Per part unit at $N = 1$, material costs are determined by the amount of material consumption $N_m$, the cost of material $P_m$, the impact of transport costs $K_m$, the value of the waste material $(N_d \cdot P_d)$:

$$Z_m = N_m \cdot P_m \cdot K_m - N_d \cdot P_d$$  \hspace{1cm} (1)
The cost of maintenance and operation of equipment are determined by the cost of depreciation of equipment $Z_a$, repair of equipment $Z_v$, the cost of equipment $Z_p$, tools cost $Z_t$, technological costs $Z_w$ 

\[ Z_o = Z_a + Z_v + Z_p + Z_t + Z_w \]  
(2)

Transform the expression (2) taking into account the total cost of all technological operations $i = (1 \ldots m)$ compared cycles $C_1$ and $C_2$ using Fig. 2, 3 data on the number of equipment and personnel required. Regrouping mathematically (2) we obtain (3). The parameters of expression (2) are grouped so that it is convenient to automate the calculations in the future, and are given to the common denominator $(F_m \cdot 100)$ – the given annual production time of the part.

\[ Z_{\Sigma o} = \frac{\sum_{i=1}^{m}((P_a Y_a T_i) \cdot k_a + (P_v Y_v T_i) \cdot k_v + (P_p Y_p T_i) \cdot k_p + (P_t Y_t T_i) \cdot k_t + (P_w Y_w T_w) \cdot k_w)}{F_m \cdot 100} \]  
(3)

where, $P_a$, $P_v$, $P_p$, $P_t$, $P_w$ – the cost of equipment, repair of machinery, equipment, tool and process costs, respectively; $Y_a$, $Y_v$, $Y_p$, $Y_t$, $Y_w$ – cost standards for use of equipment, equipment repair, equipment, tool and process costs, respectively; $T_i$, $T_t$, $T_w$ – is the execution time of the process equipment, repair, equipment, tools and technology costs, respectively; $k_a$, $k_v$, $k_p$, $k_t$, $k_w$ – factors that take into account the load of equipment, repair work norms, tool consumption, technological costs norms, respectively; $F_m$ – given annual production time of the part.

Considering all technological operations $i = (1 \ldots m)$ compared cycles $C_1$ и $C_2$, determine the cost of maintenance and operation of production areas $Z_s$ (4):

\[ Z_{\Sigma s} = \frac{\sum_{i=1}^{m}((P_a Y_a T_i) \cdot k_a)}{F_m \cdot 100} \]  
(4)

Wages cost of the main production workers $Z_r$ (5):

\[ Z_{\Sigma r} = \frac{\sum_{i=1}^{m}((P_r T_m) \cdot k_s)}{F_m \cdot 100} \]  
(5)

Let's introduce the designation: $F_x = ((F_m \cdot 100)^{-1})$ (6) and grouping the expressions (1-5) we get the expression of the total cost of production of each part (7):

\[ Z_x = (N_m \cdot P_m \cdot K_m - N_d \cdot P_d) + F_x \cdot \sum_{i=1}^{m}((P_a Y_a T_i) \cdot k_a + (P_v Y_v T_i) \cdot k_v + (P_p Y_p T_i) \cdot k_p + (P_t Y_t T_i) \cdot k_t + (P_w Y_w T_w) \cdot k_w + (P_s Y_s T_s) \cdot k_s + (P_r T_m) \cdot k_s) \]  
(7)

Expression (7) allows to define influence of technological alpha - criteria of production on the cost price of production of unit of a product. Let us perform the transformation (7) in relation to the compared forms of organization of production $C_1$ и $C_2$.

\[ Z_{\Sigma C1} = (N_m \cdot P_m \cdot K_m - N_d \cdot P_d) + F_x \cdot \sum_{i=1}^{m}((P_a Y_a T_i) \cdot k_a + (P_v Y_v T_i) \cdot k_v + (P_p Y_p T_i) \cdot k_p + (P_t Y_t T_i) \cdot k_t + (P_w Y_w T_w) \cdot k_w + (P_s Y_s T_s) \cdot k_s + (P_r T_m) \cdot k_s) \]  
(8)
\[ Z_{\Sigma C2} = (N_m \cdot P_m \cdot K_m) + F_2 \cdot \sum_{i=1}^{5} \left( (P_a \cdot Y_a \cdot T_a) \cdot k_a + (P_b \cdot Y_b \cdot T_b) \cdot k_b + (P_p \cdot Y_p \cdot T_p) \cdot k_p + (P_t \cdot Y_t \cdot T_t) \cdot k_t + (P_w \cdot Y_w \cdot T_w) \cdot k_w + (P_s \cdot Y_s \cdot T_s) \cdot k_s + (P_r \cdot T_m) \cdot k_s \right) \]  

\( (9) \)

Obviously, the expressions (7) and (8) are identical. At the same time, the number of operations \( i = 18 \) for the case \( C_1 \) and \( i = 5 \) for \( C_2 \), according to (9). Waste \( (N_d \cdot P_d) \) is also minimized for \( C_2 \).

By performing simulation modeling assuming in the first approximation equal to all the values of parameters in terms of costs for expressions (8) and (9) we get almost three times the excess cost of production options \( C_1 \) and \( C_2 \):

\[ Z_{\Sigma C1} \approx 3 \cdot Z_{\Sigma C2} \]  

\( (10) \)

By performing the simulation in the second and third approximation, by entering the differentiated values of the parameters in the values of costs for expressions (8) and (9), we obtain the excess cost of production options \( C_1 \) and \( C_2 \) with an increasing effect according to the inequality:

\[ Z_{\Sigma C1} \gg Z_{\Sigma C2} \]  

\( (11) \)

Thus, on the basis of (10) and (11) the equality is fulfilled (12):

\[ T_\theta = (Z_{\Sigma C2} - Z_{\Sigma C1}) > 0 \]  

\( (12) \)

This allows us to draw a conclusion about the positive technical and economic effect of \( T_\theta \) for the application of the proposed version of the technology \( C_1 \).

4. Conclusions

The stage of topological analysis, as the stage of methodology, is important for the search for additional resources and the release of specialists and technological equipment, as the economic basis for the transition of production from the application of classical technologies to the form of production using additive technologies. The consequence of this is a reduction in the cost of maintaining and operating the equipment. Reduction of space and personnel, the cost of their maintenance. This makes the use of additive production cycles in the manufacture of aircraft parts more efficient than traditional production cycles. Significantly reduced production, workshop costs, which allows you to get a significant technical and economic reserve for the complexity of preparing the production of aircraft products.

The methodology proposed in this work for evaluating the technical and economic efficiency of the use of additive technologies will allow high-tech enterprises in the aviation industry to more confidently enter the planning of their own investment policies and strategies for re-equipment, development of both existing production of aircraft components and newly created ones.

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