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Classification of geokhod units and systems based on product cost analysis and estimation for a prototype model production

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Abstract. The paper considers data systematization on a new shield-type heading machine – geokhod. The target of the paper is to classify geokhod components on the basis of their technical and economical production parameters. A prototype model reveals the structure of a geokhod as an assembly unit and identifies its basic characteristics. The paper overviews the methods of product cost estimations, justifies the application of an operation-based approach for a prototype model, provides the results containing product cost data for various geokhod components and technological processes, and gives the data for a material cost structure. Taking into consideration the product cost analysis, geokhod components are classified according to their technical and economical production parameters. Moreover the paper outlines the ways of a classification application for a geokhod manufacturing techniques improvement.

1. Introduction

A shield-type heading machine – geokhod – is currently being developed to be launched into manufacture [1]. High-volume information concerning the structure of geokhod, its design, technological and economical parameters was obtained in the course of research and development work. Efficient use of the information obtained is reached via its systematization. Information systematization can be based on various principles, that is why relevant objectives of research and development work for a geokhod designing in a short term perspective are worth mentioning.

The main part of work at a current phase is a geokhod prototype model development. Geokhod development and its launching into manufacture is a system of procedures which are aimed at production of competitive products. In any case, this aim is pursued by all researches and developments of new products.

One of the key factors of competitiveness is a product cost. It is known that 70% of costs in a product life cycle is determined by the decisions made at an early stage of a product development [2]. It means that it is necessary to obtain objective data on a significance of an influence of machine components on a cost formation at early stages of development and research work.

As a rule the approaches for constructive solutions in terms of their dependence on a cost formation break in three types [3]: design for manufacturing/assembly, re-design to cost, target costing. Each of the mentioned approaches demands an estimation of future costs in a manufacturing of products at different product life cycles. A prototype model of geokhod can serve as an example for a cost estimation as a complex of geokhod research activities has been conducted and design documents have been prepared.

So for justification of further development of competitive geokhod prototype models it is necessary to classify geokhod components according to prototype model cost estimation and analysis in order to systemize information on a research target and develop a background for improvements of a construction and manufacturing techniques.

A research target is a geokhod prototype model that is going through a test production phase at the moment. Geokhod – a shield-type heading machine that moves in a rock mass using geoenvironment [1]. Geokhod prototype is a large-size machine weighing 19800 kg, consisting of a big amount of components (figure 1). Total amount of component names without standard purchased parts equals 1355. Its diameter is 3200 mm, length (without remote equipment) – 4685 mm. Basic material for geokhod components manufacturing is low-alloy structural steel.

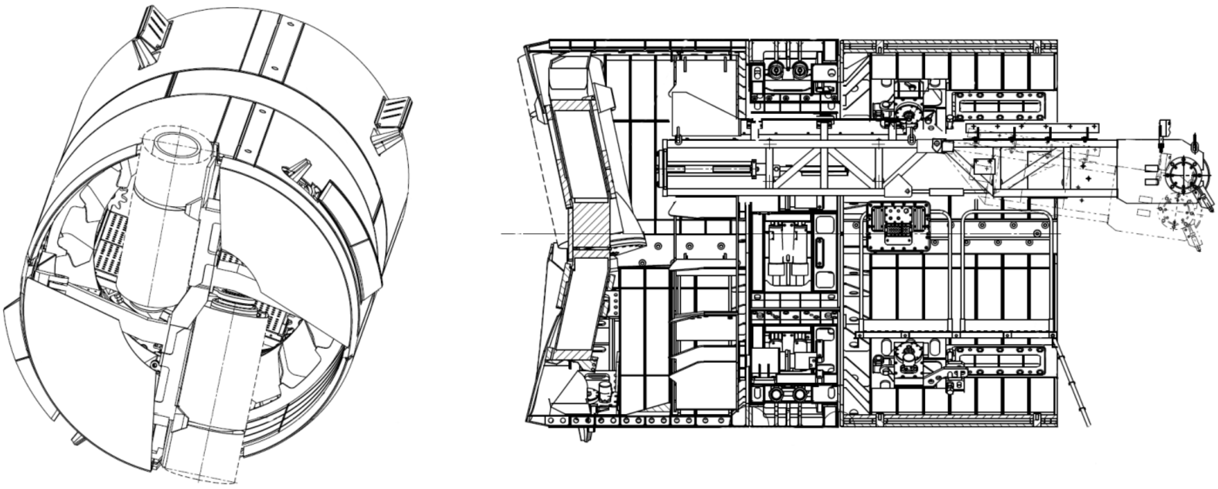

Figure 1. Main view of geokhod prototype model.

Geokhod is an assembly unit and its structure is rather complicated. Structurally the majority of its components are joined into four units: a head unit, a tail unit, an intermediate unit and a transport unit. Geokhod refers to the first level of a product structure tree, the units – to the second level (figure. 2). Lower levels contain assemblies classified according to their functions. Geokhod units consist of ten systems: an operating mechanism, a head section [5], an external propulsor [6], an operating mechanism of an external propulsor, a loading system, a stabilizing section, counterrotation elements, an operating mechanisms of counterrotation elements, an internal body and an external body of an intermediate unit [7]. The systems include assemblies, subassemblies and parts. As a whole the structure of geokhod is complicated, it includes up to eight levels of a product structure tree.

Geokhod construction determines its technological characteristics in many ways:

- the majority of large-size geokhod components are welded assemblies;
- detachable joints are widely used in the construction;
- extended surfaces demand machining when assembling;
- at a pre-assembling phase low hardness of machined components demands deformation control and compensation while machining [8];
- assembling of numerous components is regulated;
- vast majority of welded parts are made of flat steel and pressure-treated in some cases.

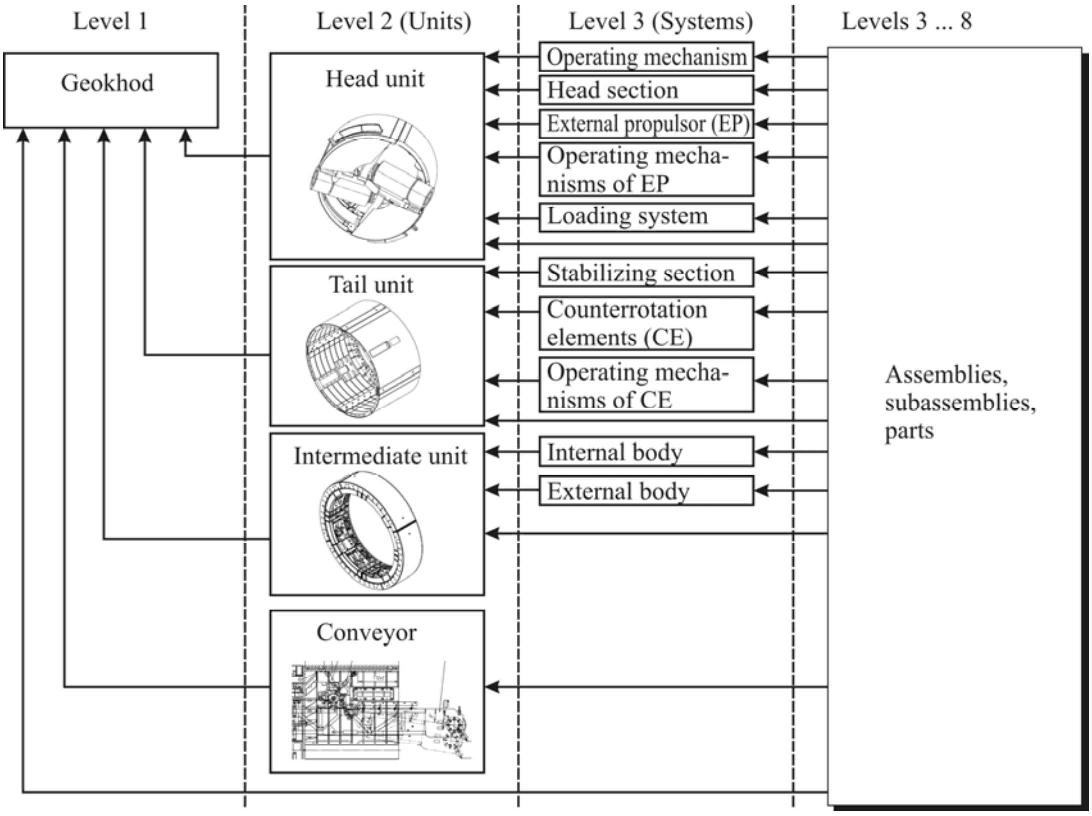

Figure 2. Geokhod structure tree.

That is why assembly techniques, welding, machining and thermal cutting play a significant role in technological processes of construction of geokhod and its components.

2. Product cost estimation technique

There is a great number of various techniques of qualitative and quantitative cost estimation in the process of equipment production. The work [9] overviews and classifies four basic techniques: intuitive technique, analogical technique, parametric technique and analytical technique.

Intuitive and analogical techniques refer to a qualitative product cost estimation which is based on a comparative analysis of a research object and a basic object. A prototype model that is developed and launch into manufacture earlier serves as a basic object. A basic object is similar to a research object in qualitative characteristics. The works [10, 14] demonstrate the application of a qualitative cost estimation when manufacturing a product.

Parametric technique is based on a development of models determining the costs via a function of a number of variables that reveal the characteristics of a prototype model. Model adequacy is estimated using statistical methods of comparing costs with a known cost quantity obtained by an analytical technique or by actual costs in a manufacturing process. Quite often such models are developed on the basis of a regression analysis. The works [4,15,16] give examples of a parametric cost estimation technique application when manufacturing a product.

Characteristics of geokhod prove that the mentioned techniques are not applicable to a prototype model because of the lack of basic objects for carrying out a comparative analysis. Parametric technique is not applicable either due to the lack of cost models for this product type. Development of such models meets the problem of proving their adequacy that demands known cost quantities. That is why at this stage costs are estimated by an analytical technique.

An analytical technique is based on determining of total costs as a sum of fundamental constituents. An analytical technique breaks in five approaches for a product cost estimation [9]: a breakdown approach, tolerance-based cost models, a feature-based cost estimation, an activity-based costing (ABC) system, an operation-based approach.

A break-down approach [17] is based on an estimation of costs as a sum of their constituents at various stages of a product life cycle which break in two categories: relatively well-structured costs (RWSC) and relatively ill-structured costs (RISC). A break-down approach demands the data on cost resources for all stages of a life cycle while a geokhod prototype model production is devoid of the contents of the following stages: delivery, exploitation, reclamation. Also this approach demands a number of parametric values obtained by collecting and processing data of a production process [17,18]. So in a non-existing industry the costs of a geokhod prototype model cannot be estimated without a number of unfounded assumptions.

Tolerance-based cost models are intended to identify relations between the accuracy of product construction units and costs. The works [19,20] present the examples of such models. Tolerance-based cost models are rather efficient at a designing stage as they contribute to establishing the accuracy demands [9]. A thorough result analysis obtained via the accuracy cost models is incorrect as a number of costs influencing factors are not taken into account by these models.

Cost estimation based on construction units involves methods which classify and identify construction units of products, and reveal appropriate cost values. The examples of the methods are found in the works [21–23]. This approach is widely used in the areas of design automation. The work [9] notes that an estimation based on construction units is not objective enough for such complex machines as a geokhod and the vast majority of its components. Moreover an unsolved problem of a systematization of geokhod components hinders the use of this approach when estimating the production costs.

Estimation systems based on actions simulate relations between products and resources. These systems appear to be the tools for making strategic decisions when manufacturing products [24]. As a rule, ABC systems are more accurate in estimating the costs than classical analytical methods [25]. The use of ABC system for a cost estimation of a geokhod prototype model is highly problematic due to heavy costs for an application and maintenance of this system [26]. Cost validity is rather controversial in this case because the manufacture of machines that are similar to a prototype model is still questionable.

Operation-based approach is a traditional technique of PCE [27], it is based on an estimation of time, materials and factory expenses when manufacturing a product [28]. Operation-based approach is a time-taking approach which demands process planning data [9]. In this paper estimation of costs for a geokhod prototype model manufacturing is done with an operation-based approach taking into account that other approaches are inapplicable in a current situation.

The cost estimation is done by the following set of works:

- Studies of design documents:
    - drawing a scheme of a geokhod structure;
    - analysis of an entrance of geokhod components;
    - making a list of purchased parts;
    - data verification of design documents.
- Development of technological processes for geokhod assemblies and components:
    - development of manufacturing routs for each product;
    - designing of operations;
    - choice of techniques.
- Development of material requirements:
    - defining a type and composition of a work piece;
    - functionality of an excess material and cutting charts of sheet materials;
    - estimating costs for basic and auxiliary materials.
- Labour requirements for technological processes.
- Material cost estimation (raw materials, purchased parts, unfinished parts of an own production).

- Cost calculations.

Product cost calculation is done by a recursive equation which is a an extended version of a cost formula mentioned in [28]. The formula calculates a cost value for a of product the level l:

$$C_l = \sum_{k=1}^{m} q_{l+1,k} C_{l+1,k} + C_M + \left(1 + k_{SI}\right)\left(1 + k_E\right) C_S + C_E + C_F \quad (1)$$

m – a number of product names for level $l+1$; $q_{l+1,k}$ – a number of products k for level $l+1$; $C_{l+1,k}$ – costs for a product k for level $l+1$; C_M – material costs for level l; k_{SI} – social costs; k_E – supplementary benefits; C_S – salary for level l; C_E – energy and fuel costs for technological purposes for level l; C_F – factory expenses for level l.

Material costs are calculated by the formula:

$$C_M = C_{SM} + C_{CP} + C_{SF} + C_T - R \quad (2)$$

C_{SM} – raw material costs; C_{CP} – purchased parts; C_{SF} – unfinished parts of an own production; C_T – transport costs; R – waste processing.

Manufacturing activities break in eight types: blank production, fitting, thermal treatment, coating, electrical installations, etc. There is a certain hourly rate, energy costs and factory costs for each activity type. Cost constituents are calculated by the following formulas:

$$C_S = \sum_{i=1}^{n} R_{Oi} t_{\Sigma i}$$
$$C_E = \sum_{i=1}^{n} R_{Ei} t_{\Sigma i} \quad (3)$$
$$C_F = \sum_{i=1}^{n} k_{Fi} R_{Oi} t_{\Sigma i}$$

n – a number of activities; R_{Oi} – an hourly rate for an activity i; $t_{\Sigma i}$ – labour characteristics for an activity i for level l; R_{Ei} – energy costs for an activity i; k_{Fi} – factory expenses for an activity i.

Recursive calculations of a formula (1) going from the value l = 1 estimate costs for all geokhod components.

3. Results and discussions

Figure 3 presents a bar chart of total costs for geokhod units and systems. The values in the bar chart are given as a percentage of a total geokhod cost. The cost structure shows that an operating mechanism takes a maximum of total costs. Large-size components – a head section and an intermediate section – take considerable part of costs as well. A geokhod head section consists of numerous systems and mechanisms that is why it turns out to be rather costly.

Costs for a component weight unit serve as estimation for a construction complexity of machine components. Figure 4 shows a percentage of a total geokhod cost for a kilogram of a geokhod unit or system. It is worth mentioning that two groups of systems considerably differ in costs. The first group includes such mechanisms as an operating mechanism, an operating mechanism of an external propulsor, an operating mechanism of counterrotation and a transport unit. These components are characterized by high cost values – (9.00…12.33) $\times 10^{-3}$ [%/kg]. The second group includes body components: a head section, an external propulsor, a stabilizing section, a counterrotation element, an internal body and an external body of an intermediate unit. These components are characterized by relatively low cost values – (2.16…3.11) $\times 10^{-3}$ [%/kg]. The second group may also include a conveyor (cost values – 3.08×10^{-3} [%/kg]) though it is equipped with a motor drive.

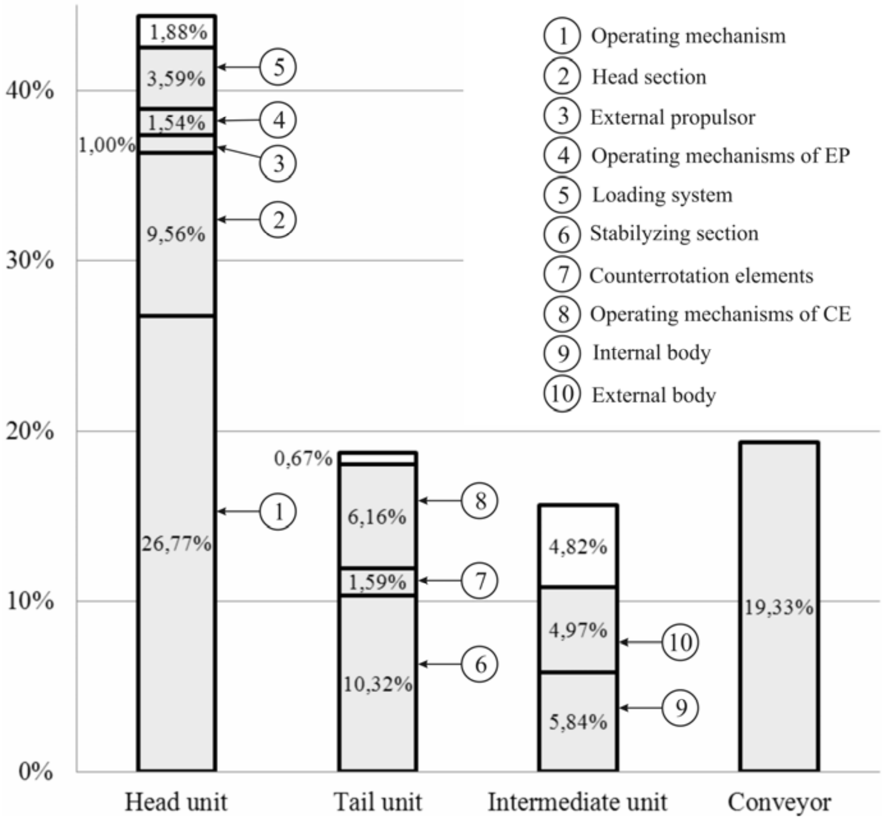

Figure 3. Cost structure for geokhod units and systems.

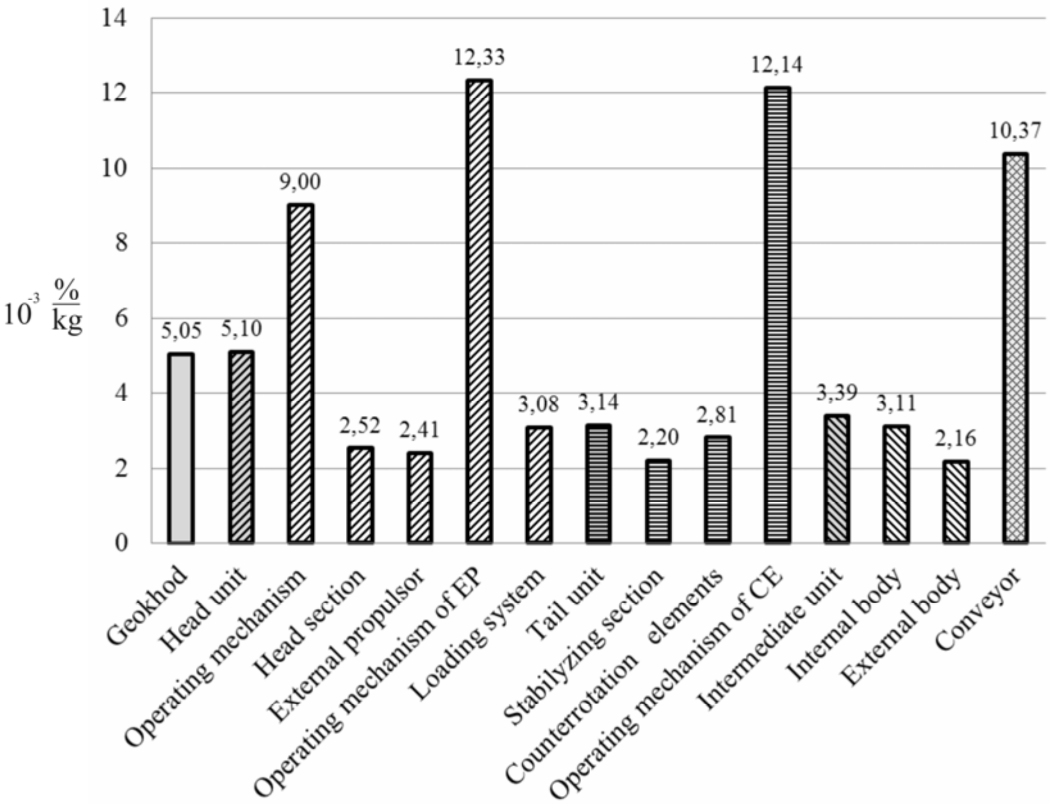

Figure 4. Costs for geokhod units and systems.

Figure 5 presents a bar chart of labour characteristics for technological processes of geokhod units and systems. The bar chart shows that there are no explicit relations between labour intensity characteristics of geokhod components and total product costs. Labour intensity characteristics (for a weight unit of a component) serve as estimation for a work complexity of machine components.

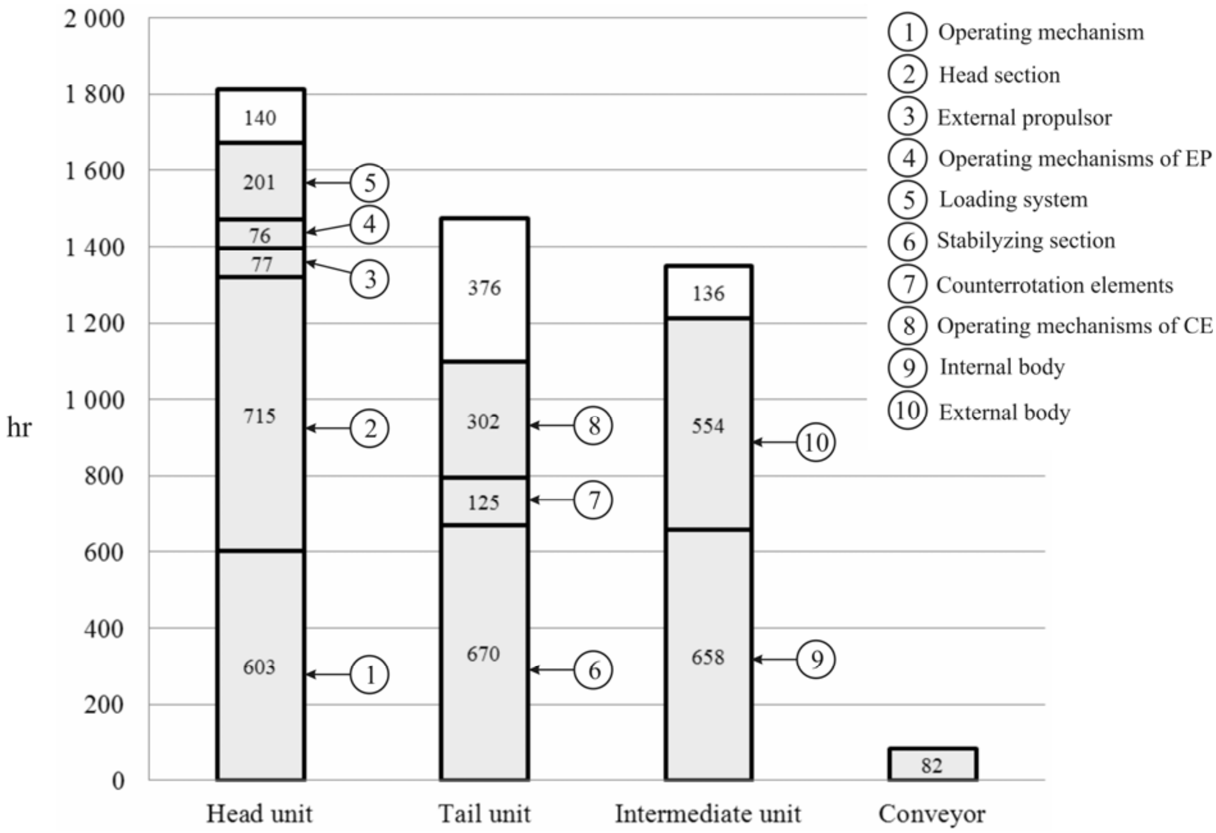

Figure 5. Labour intensity structure for geokhod units and systems.

Figure 6 shows labour intensity values for a kilogram of unit weight or system weight. The bar chart analysis reveals two systems with high values of labour intensity – an operating mechanism of an external propulsor and an operating mechanism of a counterrotation element. At the same time other components – an operating mechanism, a conveyor and a loading system – have moderate values of labour intensity. In the majority of cases the mechanisms of these components are applied in purchased products.

Analyzing the structure of labour intensity for different activity types (figure 7), it is worth saying that technological processes of machining take the biggest values of labour intensity. In average labour intensity of machining takes 57%, components equipped with mechanisms – 62…78% (an operating mechanism, an operating mechanism of an external propulsor, an operating mechanism of a counterrotation element, a transport unit and a conveyor) and intermediate units with high accuracy demands. The mentioned components also demand assembly and welding works (15…26%). Welding of units of an average level of accuracy – a head unit, an external propulsor, a stabilizing section and a counterrotation element – takes 19…29%.

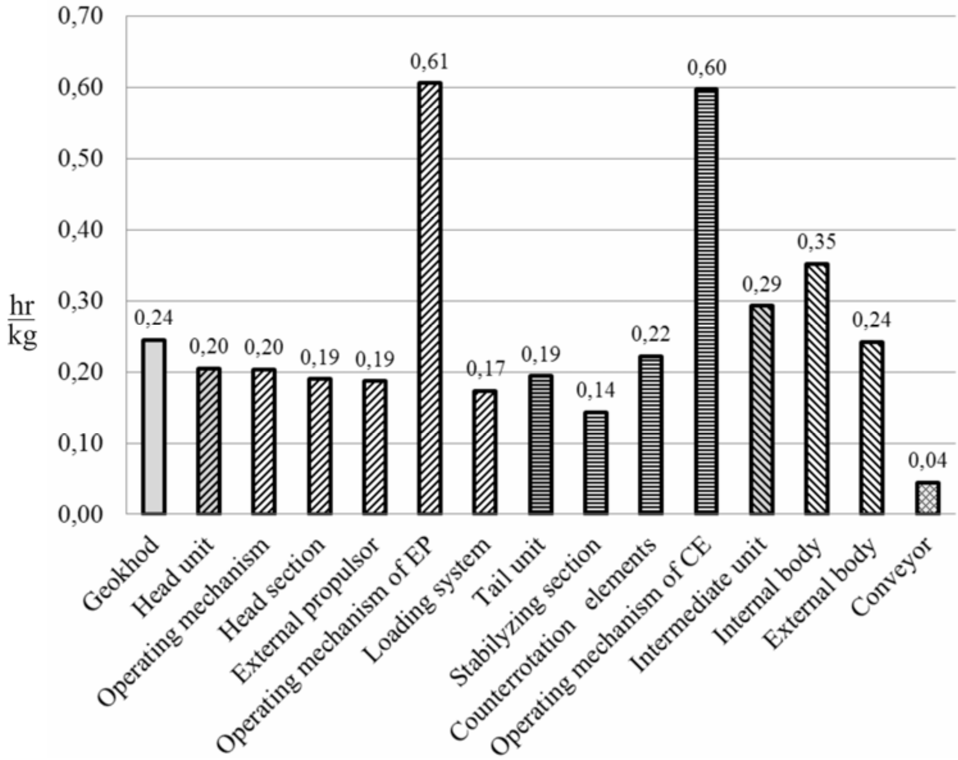

Figure 6. Specific labour intensity for geokhod units and systems.

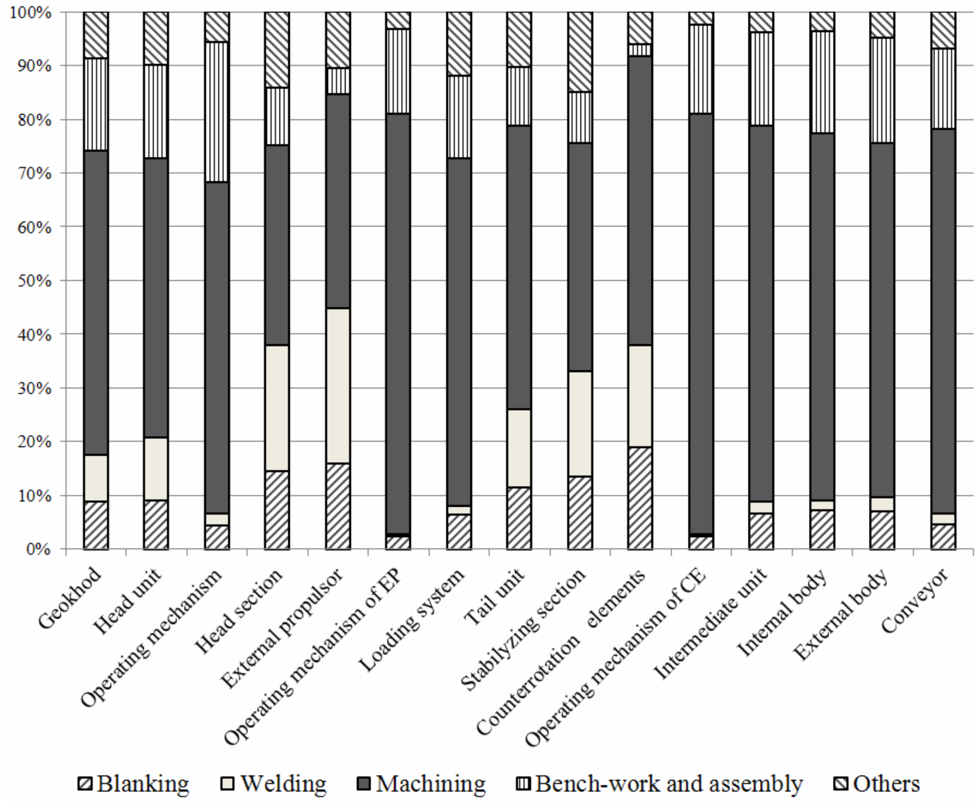

Figure 7. Labour intensity for various activity types

Material costs take an essential part of a production cost (58%). An operating mechanism, a conveyor, an operating mechanism of an external propulsor and a counterrotation element are the most

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costly (figure 8). Cost structure analysis (figure 9) shows high costs of purchased components mentioned above (85…96%).

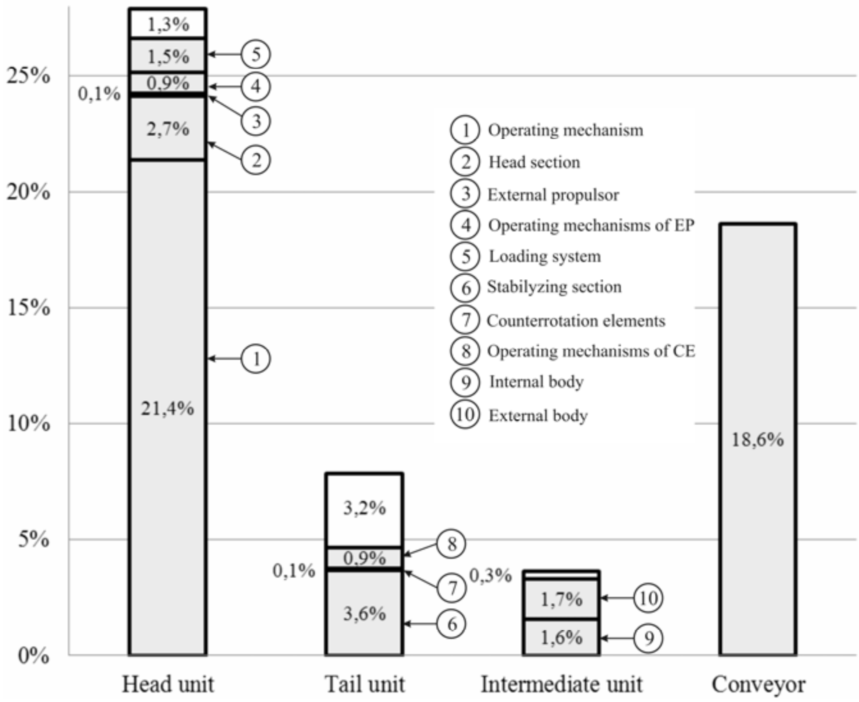

Figure 8. Material costs for geokhod units and systems (a percentage of a total geokhod cost)

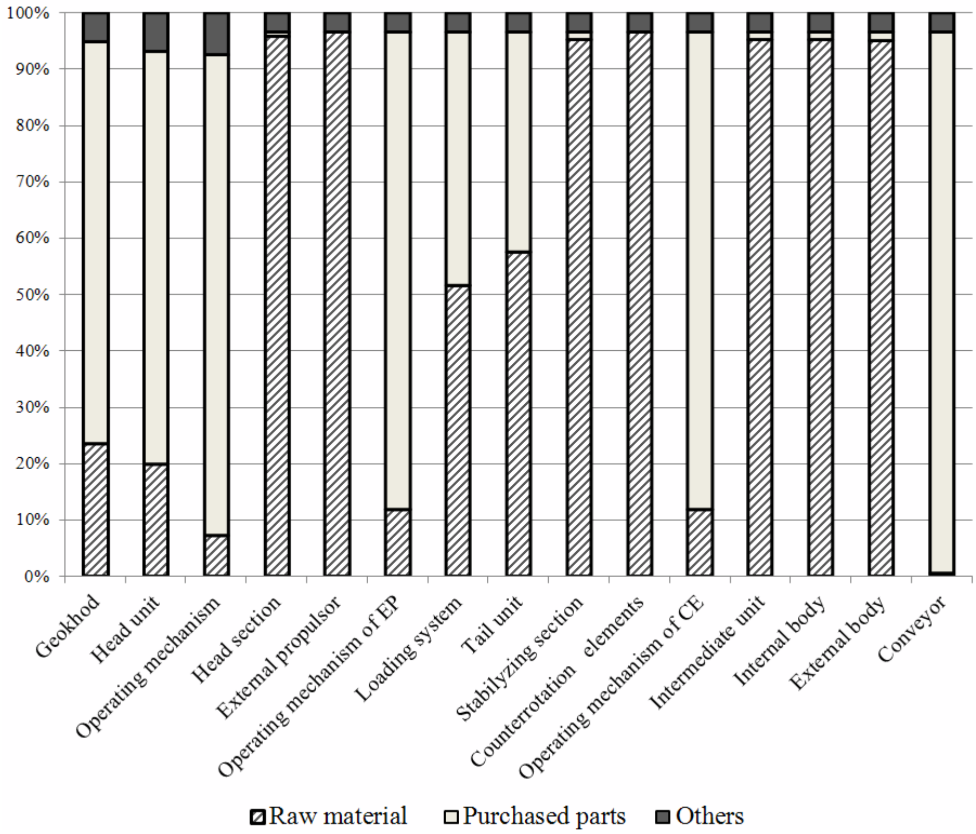

Figure 9. Material cost structure for geokhod units and systems

Cost structure reveals a number of classification parameters for geokhod components; the categories of parameters characterize efficiency, construction and production complexity of components. Parameters and categories are given in the Table 1.

Table 1. Classification parameters and categories of geokhod components.

Classification parameter	Category	Criteria of a category affiliation	Examples
Construction complexity	Low	$C_{rel} \leq 4\times10^{-3}$ [%/kg]	Counterrotation element
	Average	$C_{rel} = (4\ldots8)\times10^{-3}$ [%/kg]	Head unit
	High	$C_{rel} > 8\times10^{-3}$ [%/kg]	Operating mechanism
Production complexity	Moderate	$T_{rel} \leq 0.4$ hr/kg	Head unit
	High	$T_{rel} > 0.4$ hr/kg	Operating mechanism of external propulsor
Production type	Other units	All the rest	Tail unit
	Welded units	$r_W^a > 13\%$ and $r_M^b \leq 40\%$	External propulsor
	Accurate units	$r_M > 60\%$ and $r_W \leq 13\%$	Internal body
Purchased components	Low	$r_{CP}^c \leq 30\%$	Stabilizing section
	Moderate	$r_{CP} = (30\ldots70)$ %	Loading system
	High	$r_{CP} = (70\ldots100)$ %	Transport section

[a] Labour intensity of machining in technological processes for a considered component.
[b] Welding labour intensity in technological processes for a considered component.
[c] Material costs for purchased products .

Categories within the same classification group are given in the order of increasing product costs. Thus, classification contributes to design and manufacturing techniques improvement in terms of product profitability.

Classification details and various categories are determined by the level of geokhod structure studies. Current classification is worked to the third level (level of systems). Studies of higher levels are connected with the difficulties caused by an exponential growth of product quantity. Classification revision of a detailed structure studies is reasonable for solution of the problems connected with development of design techniques of efficient constructions and methods. Also classification revision can be caused by significant changes in a design and materials of a geokhod (for example, [29]), and an essential increase of new production technologies (for example, [30]).

4. Conclusion

- Geokhod prototype consists of a large number of products varying in constructive and technological parameters, related by complicated hierarchical entrance relations. Representative geokhod structure is created by units and systems – the interrelated components of the second and third design level.
- The product cost assessment for a geokhod prototype including its components is done by an operation-based approach. Obtained values of economic parameters of geokhod and its components serve as basic parameters for a high-quality comparison of various machine designs and manufacturing technologies.

- The structure and the type of product costs of geokhod units and systems show design and technological characteristics of products and form a basis for the formation of quantitative criteria of a product classification.
- The classification of geokhod components is developed on the basis of product cost assessment parameters. The classification can be used for a design and manufacturing techniques improvement of geokhod units and systems.
- Homogeneity of product cost parameters for the same classification group contribute to the development of cost assessment techniques, efficiency of geokhod design and manufacturing techniques based on the developed classification and parameter-based approach or an analogical technique.

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