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Payback assessment of the metal–composite technology for modular drill bodies based on an experimentally confirmed increase in cutting head tool life

Nikolay Lubimyi [a, *], ***Andrey Polshin*** [b], ***Boris Chetverikov*** [c], ***Nikolay Zagorodniy*** [d], ***Ardalion Maltsev*** [e], ***Mikhail Bytsenko*** [1, f]

Belgorod State Technological University named after V.G. Shukhov, 46 Kostyukova St., Belgorod, 308012, Russian Federation

[a] https://orcid.org/0000-0002-6131-3217, nslubim@bk.ru; [b] https://orcid.org/0000-0001-5809-4458, info@polshin.ru;
[c] https://orcid.org/0000-0003-1801-6767, await_rescue@mail.ru; [d] https://orcid.org/0000-0002-2997-3282, n.zagorodnij@yandex.ru;
[e] https://orcid.org/0000-0002-0878-3658, ardalion_bgtu@mail.ru; [f] https://orcid.org/0009-0004-2133-885X, b.michutka2005@gmail.com

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ABSTRACT

Introduction. Metal–composite technology (*MCT*) for modular drill bodies, based on an additively manufactured thin-walled metal shell with internal coolant channels followed by metal–polymer infill, offers a way to enhance functional coolant delivery while reducing the additive metal volume. However, industrial adoption requires a transparent techno-economic justification that links manufacturing costs with in-service outcomes under a real drilling program. ***The purpose of the work*** is to assess the payback of *MCT* modular drill bodies using an experimentally validated increase in the tool life of a replaceable carbide cutting head and to outline the economically feasible application domain of the technology. **Methodology.** Two manufacturing routes were compared: a baseline subtractive route for a conventional drill body and the *MCT* route combining SLM shell fabrication, vibro-vacuum polymer infill, and final machining. Payback was evaluated using an integrated model that includes (*a*) manufacturing cost per body represented as variable costs plus one-time batch costs, and (*b*) in-service economics expressed through a cost-per-hole metric driven by the consumption rate of replaceable cutting heads within a fixed drilling program. Industrial drilling trials provided the tool-life input; the end of life of the cutting head was defined by a flank wear criterion of VB = 0.3 mm. **Results and discussion.** Topology optimization of the *MCT* body reduced the *SLM* metal volume and, consequently, the additive manufacturing cost component. Industrial validation demonstrated an increase in cutting-head tool life from 541 holes for the baseline body to 618 holes for the *MCT* body (+14.2%) . For a representative drilling program of 235,000 holes, the model predicts a reduced number of cutting heads and a positive overall economic effect dominated by the in-service component, while the manufacturing component can further shift the balance depending on batch size and one-time setup costs. ***Conclusions.*** The proposed framework enables mapping the economic feasibility of *MCT* drill bodies as a function of batch size, drilling volume, and cutting-head cost, providing decision-support criteria for industrial implementation.

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Introduction

Drilling remains one of the key operations in mechanical engineering and power equipment manufacturing, as holes define datum features, provide flow passages and fastening functions, and account for a significant portion of machining time in serial production programs. In practice, the productivity growth in drilling

*** Corresponding author**
Lubimyi Nikolay S., Ph.D. (Engineering), Associate Professor
Belgorod State Technological University named after V.G. Shukhov,
46 street Kostyukova,
308012, Belgorod, Russian Federation
Tel.: +7 951 136-40-17, **e-mail:** nslubim@bk.ru

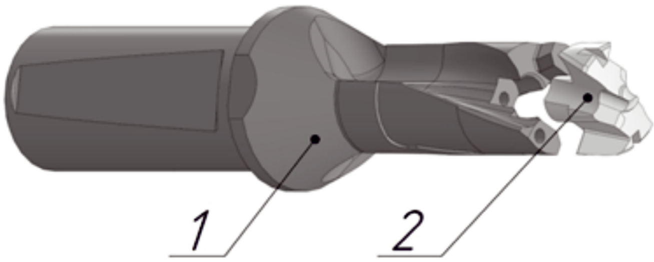


Fig. 1. Model of a modular drill:
1 – drill body (*0.40C-Cr* steel); *2* – carbide cutting head

is constrained not only by the power capabilities of machine tools but also by tool life, stability of hole quality, and predictability of operational costs. Under these conditions, modular (indexable) drills with a replaceable cutting head (*CH*) (Fig. 1) play a particularly important role, where the expensive carbide cutting unit can be replaced separately from the drill body. Such a design reduces the cost of restoring tool functionality; however, it shifts the "economic sensitivity pivot" to a set of interrelated factors: *CH* tool life, reliability of heat removal from the cutting zone, stability of cutting fluid supply (*CFS*), and the service life and cost of the drill body as the load-bearing component.

Traditionally, cutting parameters were selected based on empirical or analytical tool-life models (including the classical *Taylor* tool-life equation). However, in modern manufacturing this approach is insufficient: optimization "by tool life" must be linked to optimization "by part cost", where expenses for machine time, tool changes, downtime, inspection, as well as risks of scrap and deviations from quality specifications are all accounted for. Studies on cutting tool evaluation emphasize that a correct economic interpretation of tool life requires a shift from the narrow metric of "minutes of tool life" to metrics of "cost per unit of output" (e.g., cost per part/operation/hole) and to models that consider the production system as a whole [1]. This logic underpins approaches in which the cutting tool is treated as an element of the production chain rather than as a mere "consumable" isolated from equipment and time costs, and where alternative tooling solutions are compared through a "cost–benefit" ratio under specified quality criteria.

For drilling operations, this formulation is particularly relevant: the hole represents a discrete output unit, and the economic effect can be consistently expressed through the "cost per hole" metric, which depends on the number of holes produced until the cutting edge reaches its end-of-life condition and on the replacement cost of the cutting component. In this sense, even a modest increase in tool life of the replaceable *CH* can yield a significant economic benefit in large-scale drilling programs, as it reduces the number of head replacements, tool-change/setup time, and the risk of tolerance violations during the final stage of wear progression.

The primary physical factor accelerating wear during drilling remains heat generated in the cutting zone and at the chip–tool–workpiece interfaces. When using modular drills, critical performance determinants include not only the geometry and material of the cutting head but also the drill body's ability to ensure efficient *CFS* and heat dissipation. Recent reviews on additive manufacturing of cutting tools [2, 3] identify integrated cooling and optimized *CFS* as one of the most promising directions, since these factors directly influence cutting temperature, wear progression, and consequently tool life [4]. Importantly, the potential of the additive approach is emphasized not as a mere "substitution of the drill body manufacturing technology" but as a functional enhancement of the tool body – achieved through complex-shaped cooling channels (*CC*) (Fig. 2), improved hydrodynamics, integrated nozzle features, reduction of local pressure losses, and precise orientation of fluid streams toward the cutting zone.

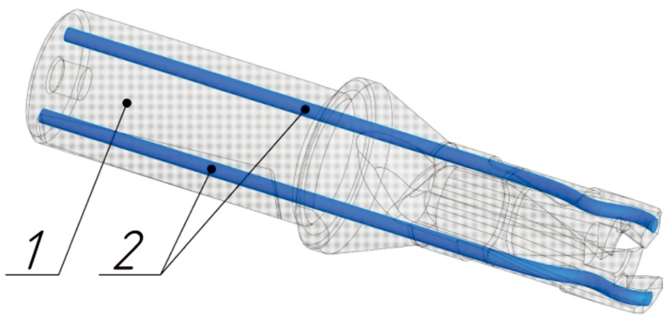


Fig. 2. Design of spatially curved coolant channels (*CC*):
1 – drill body (*0.40C-Cr* steel); *2* – complex-shaped *CC* surfaces

Publications addressing the optimization of internal channels in additively manufactured tool bodies demonstrate that refining channel geometry – particularly by eliminating sharp transitions and optimizing the spatial trajectory of coolant passages – can significantly increase flow rate and velocity, thereby enhancing the cooling effect. For instance, a study on *CFD*-based optimization of internal cooling channels for an additively manufactured milling tool reported a volumetric flow rate increase on the order of tens of percent, which was directly correlated with a potential improvement in tool life attributable to enhanced cooling performance [5]. Research on internal cooling channel architectures further confirms a relationship between channel geometry and both cutting forces and tool life during steel machining, where "cooling performance" emerges as a parameter comparable in significance to cutting parameters and tool material selection [6].

These findings establish a crucial premise: an increase in cutting head tool life can be achieved through structural modifications of the drill body, provided that such modifications ensure more efficient *CFS* and stabilization of the thermal conditions in the cutting zone.

When considering the modular drill body as a functional component with internal *CC* , conventional subtractive manufacturing routes face inherent limitations: curved channels, variable/profiled cross-sections, constant-wall geometry, and integrated nozzles are either unattainable or require expensive and technologically risky operations [7]. This constraint has driven the adoption of additive processes – particularly laser powder bed fusion (*LPBF*/*SLM*) – as an enabling tooling technology capable of fabricating internal channels with complex geometries. However, the enhancement in functionality is almost invariably accompanied by increased manufacturing costs, attributable to the substantial share of machine time, equipment depreciation, powder consumption, post-processing (support removal, heat treatment, surface finishing), and quality inspection.

In Russian references, the economic feasibility of implementing additive manufacturing technologies is also addressed within the framework of payback assessment for innovations in metalworking. For instance, reference [8] emphasizes that the economic effect of digitalization and additive manufacturing must be substantiated through calculations based on classical investment metrics (return on investment – *ROI*, net present value – *NPV*, internal rate of return – *IRR*) and through comparative analysis with conventional manufacturing routes. This requirement stems from the fact that high initial capital expenditures and organizational transformations render "innovativeness" alone an insufficient justification without quantitative financial validation of the outcome.

A distinct strand of Russian research focuses on developing methodological frameworks for assessing the economic efficiency of additive manufacturing that account for the specificities of its cost structure. Reference [9] proposes a modeling framework in which *AM* economic efficiency is interpreted not merely as direct cost reduction but as an outcome influenced by scale factors, part complexity, and the reuse of design assets. The study demonstrates that a significant portion of uncertainty stems from hidden and indirect costs associated with preparation activities, process support, and production organization. This approach reinforces the argument for transparent cost decomposition and the correct selection of comparative metrics when making decisions regarding the feasibility of an additive manufacturing route.

Finally, with regard to *SLM*/*LPBF* for metal components, Russian industrial practice has demonstrated examples of techno-economic feasibility studies performed at the level of specific parts and their production workflows. Reference [10] (using a titanium bracket for aerospace applications as a case study) shows that a correct comparison between conventional and additive manufacturing alternatives requires an operation-by-operation breakdown of technological cost components, including expenditures for raw materials, labor intensity, tooling/fixtures, and cutting tools, as well as consideration of batch size effects on unit cost and production cycle duration. This methodological approach is closely aligned with the task of economic assessment for cutting tools themselves: beyond the manufacturing cost of the technology-application object, one must also account for the influence of the selected process route on the composition and cost of auxiliary production equipment and on key production cycle parameters.

The "high cost" issue of additively manufactured tooling is not merely theoretical but systemic: cost studies of additive manufacturing emphasize that machine time and equipment utilization frequently constitute the primary cost drivers, while post-processing operations (heat treatment, support removal, and mechanical finishing of datum surfaces and mating interfaces) account for a substantial share of total expenses [11–13]. Research on cost modeling and assessment of *SLM*/*LPBF* technology proposes methodologies that decompose total cost by production stage (pre-processing, build, and **post-processing**) and enable accurate allocation of expenses even for mixed builds on a single platform [14]. Reviews of additive manufacturing cost models demonstrate that, despite differences in accuracy and implementation complexity, existing approaches converge on a fundamental principle: the economic viability of an additive route is rarely justified by the mere “ability to print a part”; it must be substantiated either by batch size/equipment utilization economics or by demonstrable in-service performance benefits [12].

It is precisely at this point that a fundamental economic decision arises in cutting tool manufacturing: if an additively manufactured drill body carries a higher unit cost than its conventional counterpart, it’s payback must be justified by operational-phase benefits – such as increased tool life of the cutting component, enhanced productivity, reduced scrap rates, minimized downtime, and/or expanded technological capabilities (enabling machining of materials or under cutting conditions previously unattainable). Contemporary reviews on additively manufactured cutting tools explicitly emphasize the necessity of holistic life-cycle economic assessment: additional manufacturing expenditures may be offset during the application phase through improved functionality and productivity. However, such assessments remain methodologically challenging and lack universally accepted evaluation frameworks [4].

If the tool body is manufactured as a fully metallic additively produced component, its cost rises rapidly with increasing build volume. Therefore, a rational approach is to pursue hybrid/composite solutions, where the additive portion serves as a thin-walled shell that carries functional surfaces and coolant channels, while the internal volume is filled with a material that provides structural support at lower cost and with reduced “additive volume”. Within the metal–composite technology framework [2], this logic is implemented through a “metallic shell + metal-polymer composite infill” architecture: the metallic component defines the geometry of external functional surfaces, mating interfaces, and internal channels, whereas the composite filler provides support for thin-walled zones, damping properties, and load-bearing capacity under secondary loads (including in the shank region during clamping).

Despite the active development of additively manufactured tools and internal cooling systems, a methodological gap persists in practical application. Research frequently demonstrates improvements in cooling performance and tool life as technological effects (reduced temperature, wear mitigation, surface quality enhancement); however, economic justification is typically presented either in overly generalized terms or through abstract cost models insufficiently anchored to specific production programs and the actual nomenclature of replaceable cutting heads.

Nevertheless, for modular drills with a replaceable cutting head, the economic effect is particularly transparent and verifiable: the price of the replaceable head and the number of replacements required over a production program directly translate into monetary costs and time expenditures. Therefore, a correct assessment of metal–composite technology payback must rely not only on the reduction or increase in drill body manufacturing cost but also on an experimentally confirmed increase in cutting head tool life, since this parameter determines the variable cost component “per hole” for a fixed drilling production volume.

In summary, several robust conclusions supported by contemporary literature can be identified:

– additive manufacturing of cutting tools provides novel design capabilities (internal channels, functional integration, mass and stiffness optimization), with enhanced cooling and *CFS* representing one of the most promising application directions [4];

– the geometry of internal channels demonstrably influences flow parameters and tool-life potential, as confirmed by both numerical simulations and experimentally-oriented studies [5, 6];

– the cost of additive fabrication and post-processing constitutes a critical barrier to industrial adoption; consequently, the applicability of additive solutions must be substantiated through techno-economic assessment, often requiring consideration of the use phase rather than manufacturing costs alone [12–14];

– economic evaluation of cutting tools is most appropriately performed using cost-per-result metrics and by accounting for the entire production system (machine time, downtime, tool changes), rather than relying solely on tool-life comparisons [1].

Previously, the author team systematically investigated key aspects of developing and substantiating metal–polymer composite structures. Reference [2] demonstrated the technological feasibility of reducing drill body manufacturing costs through *SLM* fabrication of a thin-walled metal shell followed by reinforcement/infill with a metal-polymer composite – focusing on the design-technology principle of "thin shell + metal-polymer" and its potential for material and machine-time savings. Study [7] proposed and validated an economic comparison framework for metal–polymer composite components versus alternative manufacturing technologies, where efficiency is interpreted as the outcome of the ratio between production costs and resulting operational benefits. Work [8] detailed technological solutions for manufacturing metal–composite bodies of modular drills under import substitution conditions, including process organization and manufacturability considerations.

The present work represents the next step in bridging the gap between the design-technological feasibility of metal–composite drill bodies and a rigorous quantitative assessment of their effectiveness that incorporates tooling and operational factors. In contrast to references [2, 7, 8], where the emphasis was placed on selecting the manufacturing principle and on general techno-economic technology comparison, this article establishes in a unified framework a direct linkage among "drill body manufacturing technology, operational performance of the cutting assembly, and economic effect". An efficiency metric is introduced and substantiated, enabling decision-making on the feasibility of *MCT* variant by accounting for both the cost and tool life of the cutting component not merely the production costs of the drill body. Experimental validation of the conclusions was performed using the wear criterion of cutting edges, explicitly demonstrating the influence of *MCT* implementation on overall effectiveness. Additionally, a sensitivity analysis of the final economic effect with respect to key input parameters (additive manufacturing costs (*SLM*), cutting component price, and market rates) was conducted, thereby enhancing the reproducibility of the findings and defining the applicability boundaries of the proposed approach.

The purpose of the present work is to assess the payback of *MCT* for modular drill bodies based on an experimentally confirmed increase in cutting head tool life, and to develop a calculation framework enabling determination of the boundaries for economically feasible *MCT* application under given production input data.

To achieve this purpose, the following ***tasks*** were addressed in the course of the study:

– to review approaches to economic evaluation of cutting tools and to demonstrate the applicability of the "cost per hole" / "unit cost per result" metric for modular drills with a replaceable *CH*;

– to substantiate the role of internal cooling and channel geometry as factors influencing tool life and serving as sources of operational-phase economic benefits, drawing upon research findings on additively manufactured tools and channel optimization;

– to analyze the cost structure of additive manufacturing (*SLM*/*LPBF*) and to show why machine time, equipment utilization, and post-processing constitute the key cost drivers for tool bodies;

– to formulate a payback calculation model for *MCT* that accounts for both the difference in manufacturing costs between the baseline and *MCT* routes and the operational-phase component expressed through the tool life of the replaceable *CH*;

– to perform an economic effect assessment and to define the domain of effective technology application based on experimental tool-life data and production program parameters.

Methods

The object of investigation was the body of a modular drill (*MD*) with a diameter of approximately 20 mm (1.5D configuration), serving as the load-bearing component of a tool equipped with a replaceable carbide *CH* and an internal *CFS* system. The comparison was performed for two technological alternatives for drill body manufacturing, as described in [11].

Alternative ***A*** represents the baseline manufacturing route (subtractive route), implemented as a sequence of machining operations typical for tool-body components: cutoff of a blank from bar stock, complex turning, deep gun drilling of the axial channel Ø6 mm with internal *CFS*, 5-axis milling of helical flute grooves, drilling of radial *CFS* channels, followed by heat treatment (hardening and tempering to *HRC* 32–38), finish turning/grinding, and final inspection. For batch sizes ≥ 100 pcs, the total basic machine time for machining operations (excluding heat treatment) was estimated at approximately 33.6 min/pc [11]; setup operations play a significant role (20–45 min for the first part of a complex operation) along with batch heat treatment (≈ 5 h).

Alternative ***B*** represents *MCT* route. In *MCT*, the drill body is formed as a thin-walled *SLM* shell (*Inconel 625* nickel superalloy) featuring integrated curved constant-wall *CC* for *CFS*. Subsequently, the internal cavities are filled with a metal–polymer composite material (*MPCM*) using a vibro-vacuum impregnation process. Final manufacturing stages comprise support removal/channel cleaning followed by finish turning of functional surfaces and final inspection. The vibro-vacuum process parameters were set as follows: residual pressure of 400 Pa and low-frequency vibration at 40–60 Hz (amplitude 0.2–0.6 mm, duration 3–7 min), ensuring effective degassing and porosity reduction of the composite infill.

For the fabrication of initial metal preforms, a nickel-based heat-resistant superalloy powder *Inconel 625* was employed for selective laser melting (*SLM*). According to the powder specification: particle size distribution 20–63 µm, particle morphology – spherical, bulk density 4.19 g/cm^3, flowability – 20 s. The chemical composition (wt. %) comprises *Cr* 32.2, *Mo* 2.3, *W* 5.2, *Ti* 0.91, *Al* 0.70, *Nb* 0.80, and residual impurities *C* 0.047, *Si* 0.20, *Mn* 0.04, *S* 0.007, *P* 0.003, *O* 0.019, *Fe* 0.5*;* *Ni* – balance. Printing was performed on an *SLM 280HL* system under argon atmosphere with a layer thickness of 30 µm. Detailed process parameters (laser power, scan speed, and scanning strategy) are provided in reference [2].

MPCM encompass a broad range of cold-curing thermosetting polymers. An *MPCM* compound typically consists of a modified polymer matrix (≈ 20 wt. %) filled with fine-dispersed particulate fillers – primarily steel and ceramic particles (≈ 80 wt. %). The metallic or ceramic filler imparts distinctive mechanical and thermal properties to the cured material, while the polymer matrix ensures uniform particle distribution and binding within the compound. Based on practical experience in reinforcing hollow, thin-walled shell structures fabricated by *SLM* metal 3D printing, the metal–polymer *LEO Ferro-Chromium* has proven to be the most rational choice for this application. Its physical, mechanical, and technological characteristics are summarized in Table 1.

Table 1

Physical, mechanical and technological characteristics of the metal-polymer *LEO Ferro-Chromium*

Characteristic	Parameter value
Specific gravity of the composition, g/cm^3	2.5
Viability of the prepared composition, min (at 18…20 °C)	45
Vicat softening temperature, °C (according to GOST 15088)	300
Operating temperature, °C	from −120 to + 170
Curing time, hour (at 20 °C): – up to the possibility of machining – full strength	 3.5…4 24
Brinell hardness, MPa (according to GOST 4670)	310
Ultimate strength, MPa: – in compression (according to GOST 4651) – in bending (according to GOST 4648) – in normal separation from steel (according to OST 921476–78)	 230 76 45

Comparison of alternatives was structured to isolate two distinct sources of economic outcome: the difference in drill body manufacturing cost (expressed as a function of variable and one-time batch costs per route) and the operational-phase economics manifested through changes in cutting head tool-life period while maintaining identical cutting head nomenclature and drilling parameters.

Methodology for economic assessment of drill body manufacturing

The economic evaluation of drill body fabrication follows the “variable cost per unit + one-time batch cost” logic, enabling correct comparison of manufacturing routes across different batch sizes – including pilot implementations.

For each alternative, the following notations are introduced: C_{var}^{MCT} is the variable costs for *MCT* route (*SLM* printing, powder consumption, stress relief heat treatment, support removal/channel cleaning, vacuum impregnation with *MPCM*, finish machining, inspection, and overheads); C_{var}^{base} is the variable costs per drill body for the baseline subtractive route (bar stock material, turning/milling operations, deep gun drilling, 5-axis flute machining, grinding, heat treatment, inspection); C_{batch}^{MCT}, C_{batch}^{base} is the one-time batch costs (process preparation, machine setup, tooling/*CNC* programs, support structure design, etc.) for the *MCT* and baseline routes, respectively; K is the batch size (number of drill bodies).

Accordingly, the average manufacturing cost per drill body within a batch is defined by expressions (1)–(2), where one-time batch costs are distributed across K units:

$$\overline{C^{MCT}} = C_{\text{var}}^{MCT} + \frac{C_{batch}^{MCT}}{K}, \quad (1)$$

$$\overline{C^{base}} = C_{\text{var}}^{base} + \frac{C_{batch}^{base}}{K}, \quad (2)$$

To determine the boundary at which the "standalone manufacturing cost of the drill body" (excluding operational-phase costs) becomes identical for both routes, the condition of equal average manufacturing costs is applied. This yields a threshold batch size K_{th}, interpreted as follows: when $K < K_{th}$, the *MCT* route is economically preferable based solely on drill body manufacturing cost (typical for small batches); when $K > K_{th}$, the baseline subtractive route becomes cheaper for the drill body alone, and the feasibility of *MCT* must be substantiated by operational-phase benefits (tool life, process stability, hole quality).

As a transparent input variable for the additive component, calculated data on part volume, support structure volume, printing cost rate per 1 cm^3 and manufacturing time were utilized – summarized in Table 2. This table quantifies the difference between the solid and topologically optimized design variants of the drill body (volumes, support requirements, processing time, and total cost), explicitly demonstrating reduced manufacturing cost achieved through decreased volume of additively printed metal.

Table 2

Calculation of the cost of *SLM* metal 3D printing of the modular drill body in various design variants

Design variant	Part volume (cm^3)	Support volume (cm^3)	Printing cost per 1 cm^3 (part + support) ($)	Manufacturing time (h)	Manufacturing cost ($)
Solid	40.16	2	2.9	12	122.26
Optimized	12.8	5	2.9	7.2	51.62

For the routing (operational) component, consolidated operation sequences were adopted for both the baseline and *MCT* routes, including inspection and heat treatment. Operations that define the fundamental differences between the routes were specifically highlighted: deep-hole drilling and 5-axis machining – as cost-intensive and setup-sensitive stages of the baseline route – versus monolithic shaping through a single additive build operation followed by composite infill and finish machining in the *MCT* route.

The approach to cost decomposition of additive manufacturing into machine time, material consumption, and post-processing blocks aligns with contemporary cost models for *LPBF*/*SLM* processes. These models demonstrate that the key cost drivers are equipment utilization factor, build parameters (orientation, support strategy, layer thickness), and the extent of post-processing required. Furthermore, it is emphasized that for correct batch-size comparison, one must account for cost allocation across multiple parts built simultaneously on a single platform as well as expenses associated with preparatory and concluding operations [15–17].

Methodology for calculating operational-phase economics (via tool life)

Operational-phase economics is structured around the “cost-per-result” concept – the cost of producing a specified number of holes using the same nomenclature of replaceable *CH* but with different tool-life performance when mounted on the compared drill bodies. The methodology comprises three sequential steps:

a) fixation of the experimentally measured tool-life increase as an input parameter;

b) calculation of the required number of cutting heads and the resulting cost savings;

c) verification of the payback condition for the additional manufacturing costs incurred by the *MCT* drill body.

The following parameters are introduced:

N_h is the required number of holes according to the production program;

L_{base} is the baseline tool-life period of a single cutting head (holes/head);

C_{CH} is the price of one replaceable cutting head (or insert set);

γ is the relative increase in cutting head tool life when using metal–composite technology (*MCT*), expressed in fractional form (e.g., $\gamma = 0.20$ corresponds to a +20% improvement).

The required number of cutting heads for the baseline and *MCT* variants is then defined by dependencies (3)–(4). Savings on cutting heads are determined by expression (5):

$$N_{CH}^{base} = \frac{N_h}{L_{base}}, \tag{3}$$

$$N_{CH}^{MCT} = \frac{N_h}{L_{base}(1+\gamma)}, \tag{4}$$

$$\Delta C_{CH} = C_{CH}(N_{CH}^{base} - N_{CH}^{MCT}) = N_h \cdot C_{CH} \frac{\gamma}{L_{base}(1+\gamma)}, \tag{5}$$

Representing tool effectiveness through “cost-per-result” metrics (e.g., cost per hole/operation) and accounting for production losses (tool changes, downtime, and quality deviations) aligns with established approaches to economic evaluation of cutting tools and drilling operations. These approaches demonstrate that the economic optimum is determined not solely by tool life but by the total system cost [1, 18–19].

The cost difference between drill bodies is expressed as the difference in average manufacturing costs (6). The payback condition for *MCT* justified “by cutting heads alone” is defined by equation (7). From this condition, the threshold tool-life increase γ^* is derived (8), along with equivalent formulations (9)–(10) that enable evaluation of the required tool-life improvement for a given hole-count program and drill-body cost differential:

$$\Delta C_{body} = \overline{C^{MCT}} - \overline{C^{base}}, \tag{6}$$

$$\Delta C_{CH} \geq \Delta C_{body}, \tag{7}$$

$$\frac{\gamma^*}{1+\gamma^*} = \frac{\Delta C_{body} \cdot L_{base}}{N_h \cdot C_{CH}}, \tag{8}$$

$$\gamma^* = \frac{r}{1-r}, \tag{9}$$

$$r = \frac{\Delta C_{body} \cdot L_{base}}{N_h \cdot C_{CH}}, \tag{10}$$

The practical significance of this analytical block is as follows: if the experimentally measured tool-life increase **γ** exceeds the threshold value γ^*, then the additional manufacturing costs of the *MCT* drill body are fully offset by the reduced consumption of replaceable cutting heads – even without accounting for secondary operational benefits such as downtime reduction, improved hole quality, or enhanced process stability.

Industrial trials and statistical processing

The experimental segment (Fig. 3), providing the input parameter **γ**, was conducted as industrial drilling trials on an actual component *SR869921-2024 DN800 mm* using a *Vision Wide Tech VB-3016* portal milling machine with through-spindle coolant supply (up to 25 bar) at a coolant temperature of 22–30 °C. A *FENGYI QD-203-S1/A F7058* carbide cutting head was employed; drilling was performed without tool retraction. Cutting parameters: cutting speed V = 51 m/min, spindle speed n = 800 rpm, feed rate S = 0.1625 mm/rev, hole depth 30 mm, hole diameter 20.3 mm.

a

b

Fig. 3. Experimental setup and tool clamping during tool-life tests:
a – modular drill mounted in the holder (tool clamping): *1* – holder; *2* – drill body manufactured using the *MCT*; *3* – modular carbide cutting head; *b* – *Vision Wide Tech VB-3016* portal milling machine

Tool failure criteria were established in accordance with *GOST 19265–73* and included: flank wear criterion VB = 0.3 mm; surface roughness exceeding Ra > 12.5 μm; dimensional deviations of hole geometry beyond tolerance limits; and attainment of a spindle torque corresponding to 50 % of nominal spindle power (monitored via *CNC* sensor).

The flank wear criterion VB = 0.3 mm was adopted as the primary end-of-life threshold because it is normatively established and widely applied in metal-cutting practice for drill tool-life assessment. This value complies with *GOST 19265–73*, which permits flank wear as the principal criterion for terminating the tool-life period. At drilling conditions, VB ≈ 0.3 mm corresponds to the transition from normal (stable) wear to accelerated wear, where cutting forces and spindle torque increase substantially, process stability deteriorates, and the risk of hole-quality violations rises. In the considered production environment, reaching VB ≈ 0.3 mm was accompanied by elevated spindle loading and degraded surface finish; therefore, this threshold was additionally corroborated by technological acceptability criteria (roughness, geometry compliance, and tolerances), ensuring robustness and reproducibility in comparing baseline and *MCT* variants.

Testing was conducted in series, with five independent trials performed for each drill variant (five replaceable cutting heads worn to end-of-life per variant). The inspection protocol comprised: visual inspection and flank-wear measurement every 50 holes; surface roughness and hole geometry assessment every 100 holes; and concurrent benchmarking against a serial-production baseline drill.

The measured tool-life periods were: 618 holes to ***VB*** = 0.3 mm for the composite (*MCT*) drill body versus 541 holes for the conventional baseline, corresponding to a relative tool-life increase $\gamma \approx 14.2$ %. This tool-life value was subsequently used as the input parameter in the payback calculation (Eqs. 3–10).

Statistical processing was performed on a sample of ***N*** = 5 tool-life measurements per variant (number of holes to ***VB*** = 0.3 mm). For each group, the arithmetic mean $\bar{T}$ and standard deviation *s* were calculated, along with the 95 % confidence interval for the mean $\bar{T} \pm t_{0.975,\ n-1}\frac{s}{\sqrt{n}}$, ($n = 5$). To verify the significance of differences between variants, a two-tailed *Welch's* ***t***-test for independent samples with unequal variances was applied at significance level $\alpha = 0.05$. In addition to the p-value, effect size (standardized mean difference) was evaluated to interpret the practical significance of the tool-life improvement. Averaged wear progression curves «***VB*** – ***N***» and «load – ***N***» were constructed at inspection points (every 50 holes) by computing mean values and standard deviations across the five repetitions, thereby representing the reproducibility of wear dynamics and load evolution.

Results and Discussion

The economic effect at the drill body manufacturing stage for *MCT* route is primarily achieved through a reduction of the additive metal build volume while preserving functional requirements (external working surfaces, mating interfaces, and geometry of internal *CFS* channels). Within the developed drill body design, the transition from a solid model to a topologically optimized variant reduced the volume of printed metal from 42.16 cm^3 to 17.8 cm^3. Concurrently, the support structure volume increased from 2 cm^3 to 5 cm^3 – a typical trade-off for lightweight shell structures, where additional supports are required to maintain geometric stability during the layer-by-layer build process.

This outcome aligns with design for additive manufacturing (*DfAM*) research, where topology optimization coupled with integrated internal channel design is recognized as an effective approach to reduce material consumption of cutting tools while maintaining *CFS* functionality and specified mating interfaces [20].

The interpretation of the result is that, for a tool body, additive manufacturing is advantageous when employed as a means to "create functionality" (channels of complex geometry and a shell with specified surfaces) rather than as a method to "print the entire metal volume". Topology optimization within the *MCT* framework effectively transfers a portion of the volume from "expensive" *SLM* metal to a "low-cost" and technologically feasible infill phase, while preserving the structural suitability of the drill body for finish machining and assembly (Table 1).

The operational-phase effect of *MCT* for the considered tool was evaluated through the tool life of the replaceable carbide cutting head during drilling under industrial conditions (Figs. 4, 5). The flank-wear criterion ***VB*** = 0.3 mm was adopted as the end-of-life threshold (in combination with roughness/geometry control and spindle-load limitation).

In industrial trials with statistical repetitions ($n = 5$ for each drill body manufacturing variant, with a separate cutting head used per repetition), the baseline drill demonstrated an average tool life of $\bar{T} = 541$ holes with a standard deviation of $s = 22.37$ holes; the 95 % confidence interval for the mean was [513.22; 568.78] holes. For the drill with an *MCT*-manufactured body, the average tool life was higher, reaching $\bar{T} = 618$ holes with $s = 23.95$ holes and a 95 % confidence interval of [588.26; 647.74] holes. Consequently, the observed resource increase of 77 holes (approximately 14%) is statistically confirmed: the difference between the means is significant according to a two-tailed *Welch's* ***t***-test ($t = 5.254$; $p = 0.00078$; $\alpha = 0.05$), allowing the conclusion of a statistically significant improvement in tool life when employing an *MCT* drill body.

The obtained result has practical relevance: under identical cutting head nomenclature and comparable drilling conditions, the tool-life period amounted to 618 holes for the drill with a *MCT*-manufactured body versus 541 holes for the standard (baseline) variant, yielding a tool-life increase of 14.2 %.

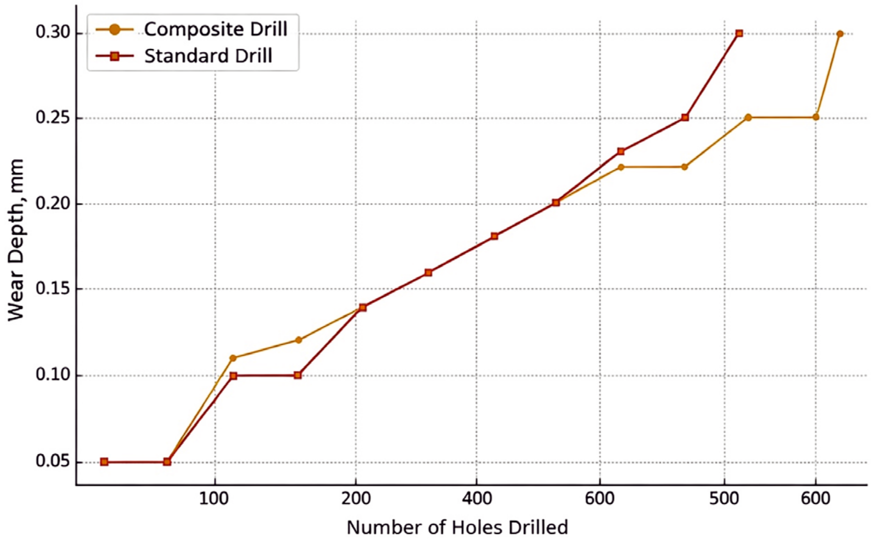


Fig. 4. Comparison of cutting head wear progression for the baseline and *MCT* drill bodies (*VB*)

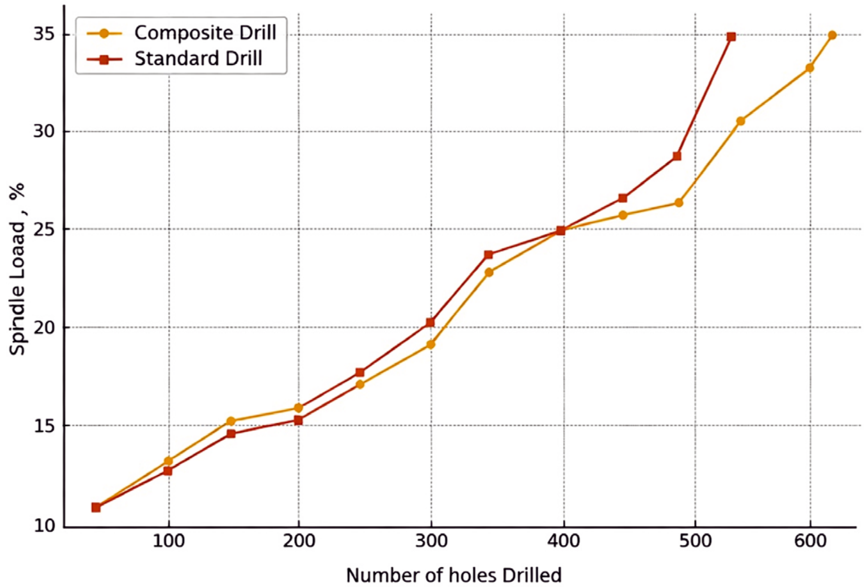


Fig. 5. Comparison of spindle torque (load) evolution during drilling for the baseline and *MCT* drill bodies

The presence of additively fabricated internal cutting fluid supply channels is regarded in the literature as one of the most effective means of wear reduction through directed fluid delivery and enhanced cooling efficiency in the cutting zone. Experimental comparisons of additively manufactured tools featuring improved *CFS* against conventional counterparts demonstrate reduced wear progression and improved process stability, which subsequently translates into operational-phase economic benefits [21–23].

Substantively, this tool-life increase is significant for two reasons. First, it pertains not to "ideal laboratory" conditions but to an actual production operation on a real component, thereby reflecting the combined influence of *CFS*, thermal conditions, and process stability under industrial constraints. Second, in modular tooling the tool life of the replaceable *CH* translates directly into economics: fewer head replacements mean reduced direct procurement costs for cutting heads and decreased machine downtime for tool changes while maintaining the same production output.

The payback assessment is built upon the integration of two effect components: the manufacturing-stage effect (difference in average drill body costs per batch, accounting for both one-time setup and variable per-unit expenses), and the operational-phase effect (savings on cutting heads attributable to the extended tool life).

When evaluating the effectiveness of *MCT*-manufactured drill bodies for small-batch production, the average *MCT* body cost $\overline{C^{MCT}}$ is assumed to lie within an interval defined by *SLM* build time and shell mass, post-processing volume, metal–polymer material cost, and overhead allocation. For drill bodies produced via the baseline subtractive route, $\overline{C^{base}}$ is highly sensitive to production preparation costs (setup, tooling, complex 5-axis toolpaths, deep-hole drilling). When assessing the total cost of a complete modular drill (body + *CH*), the cutting head price remains independent of the body manufacturing route; consequently, the *MCT* economic advantage manifests exclusively through the reduced number of head replacements (Eqs. 8–10).

MCT implementation is justified when at least one of the following conditions holds:

1) batch size and nomenclature: $K_{batch} < K_{barrier}$ – *MCT* offers a nominal cost advantage for the drill body owing to low production preparation expenses and high process automation (typical for pilot batches, frequent design iterations, or customized coolant channel geometries);

2) operational-phase benefit: $\gamma \geq \gamma^*$ – the tool-life gain of the cutting head compensates for the drill body price differential. For large hole counts N_h and high cutting head prices C_{CH} the threshold tool-life increase γ^* becomes very low;

3) technological constraints of the baseline route: curved/equidistant coolant channels are required that cannot be achieved subtractively without functional compromises; thermal management stability, hole quality, and process repeatability are critical;

4) infrastructure constraints: limited availability of deep-hole drilling or 5-axis machining capacity, or high tooling/setup costs. Where *SLM* and vacuum impregnation capabilities exist, *MCT* substantially lowers the entry barrier.

The proposed framework explicitly links technology with economics. First, for small-batch import-substitution production (a typical drill body case), *MCT* delivers low initial setup costs (small $\overline{C^{MCT}}$), while geometric complexity is transferred into machine time rather than specialized tooling. Next, the complex-shaped channels and the composite shank provide a tool-life increase (γ), which can be directly compared with γ^* using equations (8)–(10). This defines the domain of effective application the complex-shaped internal channels and optimized coolant hydrodynamics yield a measurable tool-life gain (γ), which can be directly compared with the cost differential γ^* using Eqs. (8)–(10). This relationship defines the domain of economically effective MCT application.

For the tube sheet manufacturing program *SR869921-2024*, *DN 800*, the total workload comprises $N_h = 500 \times 470 = 235{,}000$ holes, each 30 mm deep. The baseline tool-life period for the replaceable cutting head is taken as $L_{base} = 541$ holes (based on operational data from comparable tooling).

Cost rates and price levels were selected from open Russian sources:

– metal *SLM* 3D printing – from 230 RUB/cm^3 (Center for Additive Technologies, Voronezh);

– deep-hole drilling as a service – from 900 RUB per norm-hour (COMETAL production exchange);

– *CNC* milling/turning – 1,300–2,000 RUB/h based on workshop price lists (turning operations 1,100–1,600 RUB/h;

– milling up to HRC 40: 1,800–2,175 RUB/h;

– heat treatment for small batches: 65–85 RUB/kg.

The price range for replaceable cutting heads spans *FENGYI* positions at USD 88 (small diameters, retail) to *ISCAR SUMOCHAM* at USD 186 (medium diameters). For calculations, a mean price converted at the exchange rate prevailing in September 2025 was adopted. The *FENGYI* and *SUMOCHAM* product lines were additionally documented to confirm the comparability of the cutting heads used in the analysis.

The baseline manufacturing route [11] comprises: turning preparation of the blank (0.50 h), deep-hole drilling of internal *CFS* channels (0.70 h), 5-axis machining of helical flutes (0.80 h), finish grinding (0.30 h), and inspection (0.20 h). Applying the following machining rates – turning: 1,300 RUB/h; deep-hole drilling: 1,000 RUB/h; 5-axis machining: 2,000 RUB/h; inspection: 1,200 RUB/h – the variable manufacturing cost per drill body is obtained as:

$$C_{\text{var}}^{base} = 3580 \text{ RUB/body} \tag{11}$$

The *MCT* manufacturing route comprises:

SLM printing of the thin-walled shell (printed volume 17.8 cm^3 including transition zones; printing cost = 17.8 × 230 = 4,100 RUB),

– support removal/channel cleaning (0.30 h),

– vacuum degassing and metal–polymer composite (*MPCM*) impregnation (0.50 h + material cost 1,500 RUB),

– low-temperature stress-relief heat treatment (mass 0.25 kg = 20 RUB),

– finish turning (0.50 h),

– inspection (0.20 h).

Applying the machining rates specified earlier (turning/finish operations: 1,300 RUB/h; auxiliary operations: 1,200 RUB/h), the total variable manufacturing cost per drill body is obtained as:

$$C_{\text{var}}^{MCT} = 7{,}496 \text{ RUB/body.} \quad (12)$$

One-time batch costs were adopted based on data from *MIG LLC*, Voronezh: C_{var}^{base} = 80,000 RUB (tooling / *CNC* programs / setup operations), C_{var}^{MCT} = 30,000 RUB (process route sheets).

The threshold batch size ***K*** for drill bodies is defined by equation (13):

$$K_{barrier} = \frac{50{,}000}{7{,}496 - 3{,}580} \approx 12.8 \text{ pcs.} \quad (13)$$

For the *NATEK* pilot implementation, a batch size of ***K*** = 15 drill bodies is convenient: at this point $\overline{C^{MCT}}$ =12,496 RUB/unit and $\overline{C^{base}}$ =16,913 RUB/unit, meaning the *MCT* route is cheaper by 4,418 RUB per body (a total saving of 66,255 RUB for a batch of 15 bodies).

Based on trial results obtained under identical tooling and cutting parameters, the baseline cutting head delivered a tool-life period of L_{base} = 541 holes, whereas the same cutting head mounted on an *MCT*-manufactured drill body achieved L_{MCT} =618 holes. The relative tool-life increase amounted to γ = (618−541)/541≈14.2%. For the tube-sheet manufacturing program *SR869921-2024*, *DN 800*, the total workload comprises ***N*** = 500×470=235,000 holes.

The economic effect is formally expressed through the "cost per hole" attributable to cutting heads. Denoting the price of a replaceable cutting head as C_{CH} (RUB), the specific cost per hole equals C_{CH}/L, where ***L*** is the tool-life period of the given head expressed in holes. When transitioning from the baseline to the *MCT* drill body, the savings ΔZ_{CH} on cutting heads over the entire production program are:

$$\Delta Z_{CH} = N_h \cdot C_{CH} \left(\frac{1}{L_{base}} - \frac{1}{L_{MCT}} \right). \quad (14)$$

For the Russian market, actual prices of premium-grade replaceable cutting heads were adopted: *FENGYI QD-203-S1/A F7058* at USD 88 per unit and *ISCAR SUMOCHAM* at USD 186 per unit; conversion to rubles was performed using the exchange rate prevailing in September 2025. The resulting savings range attributable solely to reduced cutting-head consumption is as follows:

– at C_{CH} = 7,350 RUB "*FENGYI*": $\Delta Z_{CH} = 0.4\times10^6$ RUB;

– at C_{CH} = 15,600 RUB "*ISCAR*": $\Delta Z_{CH} = 0.84\times10^6$ RUB;

– at the average price C_{CH} = 11,460 RUB: $\Delta Z_{CH} = 0.62\times10^6$ RUB.

The same magnitudes can be conveniently expressed in terms of the number of *CH* required. For ***N*** = 235,000 holes, the baseline variant requires 235,000/541 = 435 cutting heads, whereas the *MCT* variant requires 235,000/618 = 381 heads – i.e., 54 fewer head replacements. Even without accounting for the drill body cost difference, the cutting heads alone yield savings in the range of 0.40–0.84×10^6 RUB, depending on the actual procurement price of the head (a realistic average estimate being 0.62×10^6 RUB).

The cost difference in drill bodies further shifts the balance in favor of *MCT*. The average manufacturing cost of an *MCT* drill body for the pilot batch ($\boldsymbol{K}$ = 15 pcs) is approximately 4,400 RUB/unit lower than that of the conventional subtractive drill body – primarily due to elimination of labor-intensive deep-hole drilling and 5-axis finishing operations. For the pilot implementation, this translates into an additional saving of 397,500 RUB for the entire batch of bodies. When expressed as "cost per hole", the body-related contribution is modest (approximately 0.11 RUB/hole) compared with the head-related effect; nevertheless, it remains consistently positive.

Finally, the reduced frequency of head changes translates into downtime reduction. A difference of 54 replacements, with a typical changeover time of 3–5 min per replacement and a machine-time rate of approximately 2,000 RUB/h, yields an additional saving of 5,000–10,000 RUB. Although this amount is small relative to the savings on cutting heads themselves, it reinforces the overall positive economic outcome.

Based on trial results, the 14.2% tool-life increase of the cutting head mounted on the composite DB already yields a positive economic effect. Within the 235,000-hole production program, savings attributable solely to reduced cutting head consumption amount to $0.62{\times}10^6$ RUB. When combined with the lower manufacturing cost of the *MCT* pilot batch of drill bodies (approximately 397,500 RUB) and the modest reduction in machine downtime, the overall economic outcome remains positive. With the observed tool-life period $\boldsymbol{L}_{\boldsymbol{MCT}}$ =618 holes, the payback condition is satisfied with a substantial margin: the threshold tool-life increase $\boldsymbol{\gamma}^*$ for the *NATEK* production program volume is close to zero, whereas the achieved +14.2 % gain substantially exceeds this threshold.

Conversely, to estimate the maximum economically viable batch size of *MCT*-manufactured drill bodies $\boldsymbol{K}_{\mathbf{max}}$ justified solely by the tool-life gain, the following expression is derived:

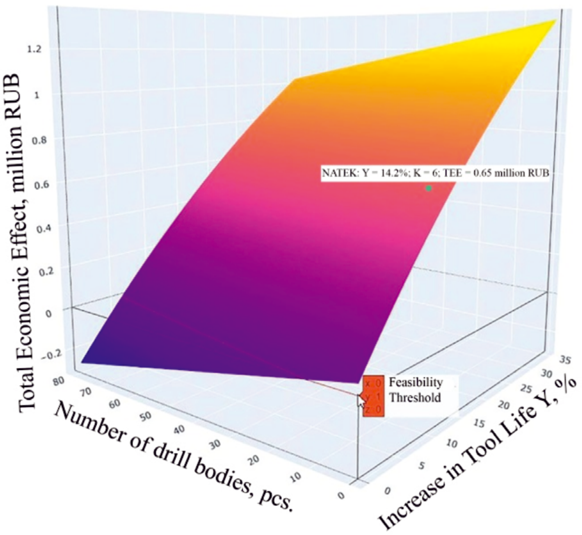
$$K_{\max} = \frac{\Delta Z_{CH} - \Delta C_{CH}}{\Delta C_{\text{var}}} = \frac{0.62 \times 10^6 + 50,000}{3.916} = 114 \text{ bodies.} \quad (15)$$

Based on the derived dependencies and experimental tool-life data, an interactive model was developed (Fig. 6) enabling evaluation of the economic benefit as a function of cutting-head tool-life increase and production batch size of *MCT*-manufactured drill bodies (viewing the interactive chart is recommended using the latest version of the *Google Chrome* browser).

Thus, with a cutting head tool-life of 618 holes per unit, the observed 14.2 % tool-life gain economically justifies the production of several hundred *MCT*-manufactured drill bodies. Production programs below the threshold batch size $\boldsymbol{K}_{\mathbf{max}}$ are paid back with a substantial margin. Programs exceeding $\boldsymbol{K}_{\mathbf{max}}$ would require supplementary justification of economic feasibility through additional operational benefits. In practice, drill body procurement volumes are typically limited to single- or double-digit quantities; consequently, the *NATEK* pilot implementation comprised a batch of $\boldsymbol{K}$ = 15 units.

The obtained results – both the cutting head tool-life improvement and the payback assessment – reflect the conditions of a specific production site and a defined manufacturing program. The generalizability of the conclusions is influenced by equipment characteristics and *CFS* system parameters (machine type, actual pressure/flow rate, *CFS* temperature range), workholding stability, organizational practices for tool management, as well as enterprise-specific machine-time rates and procurement prices. Accordingly, the numerical values of the economic effect should be interpreted as a scenario-based calculation for the given input dataset, whereas the proposed methodology is intended for recalibration to specific production conditions by substituting actual parameters.

Experimental verification was performed for a single modular drill size (20 mm diameter, 1.5D configuration) and one workpiece material–cutting parameter pair. Therefore, quantitative transfer of the observed tool-life gain – and consequently the payback assessment – to other diameters, drilling depths, workpiece materials, or cutting regimes requires additional validation. Nevertheless, the model structure (based on tool-life period and replaceable cutting head cost) retains its applicability and enables the methodology to serve as a parametric framework when an experimentally confirmed tool-life value is available for alternative conditions.



a *b*

Fig. 6. Economic effect assessment and access to the interactive model:
a – static plot of the economic effect as a function of cutting head tool-life increase and drill-body production batch size; *b* – *QR* code linking to the interactive *HTML* chart

An additional constraint is the potential variability in *SLM*-fabricated thin-walled shell and internal *CFS* channel quality. Geometric deviations of channels, internal surface roughness, residual porosity, and differences in post-processing may alter *CFS* hydrodynamics and the thermal conditions in the cutting zone, ultimately affecting the reproducibility of the operational-phase tool-life benefit. Therefore, industrial implementation of *MCT* should be accompanied by quality control procedures for shell fabrication, with periodic verification of the actual tool-life gain recommended as an input parameter for the economic model.

Future research should be directed toward expanding the applicability domain of the obtained results:

1) verification of the payback model on an expanded sample of production programs (varying drilling volumes N_h, replaceable cutting head prices, and maintenance conditions), including explicit accounting of head replacement time and associated equipment downtime as a distinct economic factor;

2) generalization of experimental tool-life data for various workpiece materials and drilling parameters (cutting speed, feed rate, depth), as well as for different internal *CFS* channel geometries and supply pressures, with development of empirical correction coefficients for the calculation model;

3) improvement of drill body manufacturing cost estimation for the *MCT* route through separate accounting of *SLM* operations, support removal, channel cleaning, vibro-vacuum impregnation, and finish machining – including analysis of equipment utilization factor and material loss effects;

4) investigation of durability and reliability of the metal–polymer infill within the tool body under cyclic thermomechanical loading (temperature fields, vibrations, contact loads in the clamping zone), along with assessment of how internal infill defects affect drill body service life and reproducibility of the operational-phase benefit;

5) development of guidelines for selecting the application domain of *MCT*-drill bodies depending on production type (single-piece/small-batch/serial), required hole quality, and availability of technological capacities, with creation of standardized "feasibility maps" for practical industrial implementation.

Implementation of these directions will enable: improved accuracy in forecasting the economic effect of *MCT* adoption; determination of stable boundaries for its economically justified application across various production types and programs; and formulation of practical recommendations for selecting drill body design parameters and drilling regimes that ensure the required technology payback.

Conclusion

It has been demonstrated that applying topology optimization to the modular drill body design within the *MCT* framework reduces the *SLM*-printed metal part from 42.16 cm^3 to 17.8 cm^3. Under the computational scenario adopted in this study (a unified set of price data and process parameters; cost calculation for a single drill body based on the specified *SLM* shell fabrication route followed by metal–polymer composite infill), this translates into a reduction of the estimated SLM manufacturing cost for the metallic shell from USD 122.26 to USD 51.62.

This 42.2% reduction pertains specifically to the *SLM* printing cost component of the metallic part (shell) and does not represent a direct estimate of the total *MCT* drill body manufacturing cost, which additionally encompasses *MPCM* impregnation, preparation activities, post-processing, and other variable and one-time expenses as defined by the proposed *MCT* route.

Industrial drilling trials with the end-of-life criterion set at flank wear ***VB*** = 0.3 mm experimentally confirmed an increase in tool life of the replaceable carbide cutting head: 618 holes for the *MCT*-manufactured body versus 541 holes for the baseline variant, corresponding to a 14.2% improvement in tool-life.

An integrated payback assessment methodology has been proposed and validated, combining comparative analysis of drill body manufacturing costs (accounting for both one-time and variable expenses) with operational-phase economics expressed through reduced cutting head consumption for a given drilling production program.

The economic benefit of *MCT* implementation is shown to be two-fold: for small batches it may arise primarily from reduced drill body manufacturing costs, whereas for substantial drilling volumes it is driven by operational savings attributable to the extended tool life of the replaceable cutting head.

The applicability boundaries of the results have been formulated: the numerical values of the economic effect presented herein relate to the specific scenario examined in this paper – a single drill size of 20 mm diameter, 1.5D configuration; one workpiece material and selected cutting parameters; price data and exchange rates fixed at the time of calculation. When production conditions change – *SLM* printing cost, cutting head price, batch size, drilling program volume – the proposed methodology enables determination of the domain in which the *MCT* route remains economically justified. Typically, *MCT* becomes preferable for small-batch or specialized production, as well as for high-volume drilling operations with expensive replaceable heads, where the operational-phase economic contribution becomes dominant.

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Conflicts of Interest

The authors declare no conflict of interest.