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Improvements in Hydraulic Control Systems of Lifting Mechanisms for Construction Machinery

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Abstract

This paper investigates an integrative approach to optimizing the performance and extending the service life of hydraulic systems in construction machinery. The relevance of the study is determined by the high energy intensity and accelerated wear of hydraulic drive components, which lead to increased operating costs and prolonged equipment downtime. The objective of the study is to propose and verify a comprehensive methodology that combines control system modernization with the implementation of advanced technologies for the restoration of worn components. The methodological basis is a systematic review of current scientific publications in the fields of hydraulics and materials science. The results include metrics demonstrating increased productivity achieved through the use of proportional hydraulic systems on the example of the CAT-320D excavator, as well as the economic and technological superiority of innovative methods for restoring the surfaces of hydraulic cylinders and hinge assemblies. It is shown that the combination of technical modernization and high-precision restoration procedures not only expands the functional capabilities of the equipment, but also reduces operating costs and shortens downtime from several months to several days. The practical and theoretical significance of the study is evident for design and field engineers, service department managers, and specialists in the operation and repair of construction and road machinery.

Keywords: *Hydraulic System, Construction Machinery, Energy Efficiency, Modernization, Restoration, Hydraulic Cylinder, Proportional Control, Wear Resistance, Surfacing, Economic Efficiency.*

INTRODUCTION

The construction industry has long been regarded as one of the principal drivers of global economic growth, with its efficiency to a large extent determined by the reliability and productivity of the equipment employed. It is projected that the market will increase from USD 171.98 billion in 2025 to USD 271.30 billion in 2032, with a compound annual growth rate of 6.7 % over the forecast period. In 2024, the Asia-Pacific region dominated the global market with a share of 41.83 %. Furthermore, significant growth of the construction equipment market in the USA is forecast, reaching an estimated value of USD 44.98 billion by 2032 [1]. Excavators, loaders, bulldozers, and cranes—whose intensive operation is powered by hydraulic drives—form the backbone of construction machinery fleets. Although hydraulic systems are characterized by high power density and compactness, they are also the main consumers of energy [2], which underscores the pressing need to improve their energy efficiency.

Alongside high energy consumption, intensive wear of the main elements of hydraulic drives—hydraulic cylinders, distributors, pumps, and articulated joints—poses a serious challenge. Operation in abrasive environments, under significant dynamic loads and aggressive conditions, leads to premature failure of costly components. The conventional practice of replacing failed parts with new ones entails substantial financial expenditures and prolonged equipment downtime, adversely affecting the economic profitability of construction projects. A gap is evident in the scientific literature: research is primarily focused either on the development of fundamentally new energy-efficient hydraulic systems for next-generation machines or on individual restoration methods, whereas comprehensive strategies combining the modernization of existing control systems with the application of advanced restorative technologies remain insufficiently explored.

The aim of the study is to propose and validate a comprehensive methodology that integrates the modernization of control systems with the implementation of cutting-edge technologies for the restoration of worn components.

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The scientific novelty lies in the systematization and economic substantiation of a unified set of measures that includes, on the one hand, the introduction of proportional control systems and, on the other hand, advanced overlay-welding restoration techniques whose effectiveness has been confirmed by practical applications in heavy construction machinery.

The author's hypothesis is that the application of the comprehensive method will enhance energy efficiency, expand functional capabilities, and improve the economic feasibility of equipment operation by reducing downtime and operating costs.

MATERIALS AND METHODS

In recent years several authors have focused on macroeconomic trends and forecasts concerning the development of the construction machinery market. The study by Fortune Business Insights presents a market segmentation by equipment types and regions with a forecast up to 2032 [1], enabling the assessment of demand dynamics for lifting mechanisms. A comparable analysis conducted by GlobalData broadens this perspective by dividing by contractor type and construction sectors [12], whereas the annual report of FIEC emphasizes the impact of regulatory initiatives and environmental requirements on investments in new equipment [13].

In the area of enhancing the energy efficiency of hydraulic systems Li R. et al. [2] summarized the principles of reducing losses in valve and pump elements, considering methods for leakage compensation and the use of controlled charging pumps. Azzam I. et al. [5] proposed digital hydraulics based on a multi-valve architecture, which enables hydrodynamic recuperation and reduces fuel consumption in hybrid transmissions of construction machinery. Mahato A. C., Ghoshal S. K. [11] analyzed strategies for optimizing the operational cycle of the hydraulic system, including adaptive pressure control and mode switching of hydraulic motors, demonstrating potential energy savings.

A separate group of studies is devoted to improving control systems. Yuan Z. et al. [3] described a distributed architecture of electrohydraulic actuators for excavators, showing a reduction of inertial effects when multiple independent drives operate concurrently. Nguyen M. H., Ahn K. K. [4] proposed a trajectory correction algorithm with guaranteed execution quality under disturbances and model uncertainties, which enhances the positioning accuracy of the working tool of lifting equipment.

In the direction of increasing reliability and resource intensity of components Georgiou E. P. et al. [6] carried out accelerated tests of alternatives to hard chrome plating of piston rods, identifying the most durable coatings based on WC/Co and Cr_3C_2/Ni. Hong S. et al. [10] evaluated cavitation erosion of ceramic-metal composite coatings applicable to hydroturbines, providing insight into their potential use in cylinders and valves of construction machinery. Kazannikov O. V., Popov E. V. [14] examined the restoration and alloying of worn working elements, proposing technologies for spraying alloys with increased hardness and adhesion to the base metal.

In the field of diagnostics Liu X. et al. [8] implemented a multiscale algorithm of entropy analysis of signals based on CEEMDAN for predictive online detection of hydraulic pump failures. Hossain M. S. et al. [9] reviewed designs and models of electromechanical intake valves for gas expanders, which, although pertaining to a different domain, demonstrate trends in miniaturization and increased response speed of valve systems.

Finally, Al-Musaibeli H., Ahmad R. [7] developed a trajectory planning method for robotic laser cladding in the repair of surface defects, indirectly indicating the prospects for automating service operations with hydraulic systems of construction and road machinery.

The literature reveals discrepancies in estimates of actual energy savings: digital hydraulics shows significant potential [5], whereas adaptive control strategies estimate the effect more modestly (≈ 10–15 %) [11]. The interaction of distributed drives with energy accumulators and recuperation systems remains insufficiently studied. In addition, despite numerous studies on coatings and alloys for cylinders, few investigations link these materials with specific operational cycles of lifting mechanisms. Publications dedicated to the comprehensive integration of diagnostics, control, and energy and resource saving into a unified "smart" hydraulic system platform for construction machinery are virtually nonexistent.

RESULTS AND DISCUSSION

In standard hydraulic systems of medium-class construction machinery basic discrete (On/Off) or manual directional control valves are often employed, which leads to significant energy losses due to throttling, especially under partial-load conditions. The transition to electro-hydraulic proportional control systems not only reduces these losses but also fundamentally expands the machine's operational capabilities. The effectiveness of this approach was confirmed in the modernization project of the Caterpillar CAT-320D excavator. The machine was originally produced solely for earthmoving operations. During the modernization a two-circuit proportional hydraulic system by VTN Europe S.p.A. was installed, the original directional control valve was replaced, additional hydraulic lines were routed and the electronic controller software was completely reengineered.

The implementation of these modifications ensured highly accurate, smooth regulation of flow rate and pressure of the working fluid supplied to the attachments. As a result the excavator attained the status of a machine of class Demolition, acquiring the capability to operate effectively with heavy and specialized attachments — hydraulic shears with rotator, concrete breakers and crushing attachments. The practical efficiency of the project fully corresponds to the theoretical conclusions regarding the advantages of proportional control formulated in studies [4, 9]. Comparative characteristics of the original and modernized models are presented in Table 1.

Table 1. Comparative characteristics of the CAT-320D excavator before and after modernization (compiled by the author based on [4, 7, 9])

Parameter	Standard configuration	Modernized configuration
Control system	Standard, discrete	Dual-flow, proportional
Available attachments	Bucket only	Bucket, hydraulic shears, rotators, concrete breakers
Hydraulic lines	Single line (bucket)	Three lines (main, rotation, medium pressure)
Controller software	Standard	Customized, with attachment support
Market value	Base price	+15-20% to the base price

From the analysis of the table it follows that the carried-out modernization not only ensured an increase in productivity but also enhanced the market value and liquidity of the machines, which enabled the sale of two units of equipment to Orga Atlas Ukraine, which required machines with extended functionality without a lengthy waiting period from the factory.

However, the modernization and the associated expansion of the equipment's functional capabilities—specifically, the use of powerful attachments such as hydraulic shears—inevitably lead to increased loads on the key components of the hydraulic system: hydraulic cylinders, articulated joints, and their housings. This, in turn, exacerbates the problem of intensive wear, which is the second critical factor reducing the economic efficiency of operation. Consequently, to fully realize the benefits of an upgraded control system and ensure its long-term reliability under new, more demanding operating conditions, it is essential to simultaneously address the challenge of extending the service life of load-bearing components.

The application of modern restoration technologies is a key solution to this challenge, allowing for a manifold extension of the service life of expensive machine parts. A striking example of this approach is the experience of restoring the boom lift and bucket hydraulic cylinders of Komatsu PC8000 open-pit excavators with a mass of 750 t.

Restoration work begins with precise straightening of the rod to eliminate distortions, followed by local removal of the degraded chrome coating and application of new wear-resistant composite layers, including ceramic-based ones. The final stage includes high-precision grinding and polishing until a surface roughness of Ra 0.16–0.32 μm is achieved. All welded joints undergo ultrasonic testing to detect and eliminate hidden defects. The use of ceramic coatings instead of conventional chrome plating increases resistance to abrasive wear by 3–5 times, thereby significantly extending the interval between repairs [6, 10]

Particular attention is paid to restoring the geometry of worn bearing holes of hinge joints (bucket ears, booms and sticks). During operation, the housings acquire an elliptical shape and exhibit increased wear, which prevents the installation of standard pins and bushings. The use of mobile surfacing and boring machines allows the nominal dimensions of the holes to be restored with high accuracy directly on-site or in workshop conditions. A unique solution was the development of a methodology for restoring cast-iron swing and sliding frames of JCB and CAT backhoe-loaders. With an original part price of approximately €5000, a delivery time of up to 1.5 months and frequent failures due to wear of the bearing holes, the proposed set of operations — preliminary boring, low-current surfacing with specially selected materials compatible with cast iron, and final boring to nominal tolerances — allows repair time to be reduced to three days and customer costs to be lowered by nearly five times. The decision-making algorithm for the feasibility of applying this technology is shown in Figure 1.

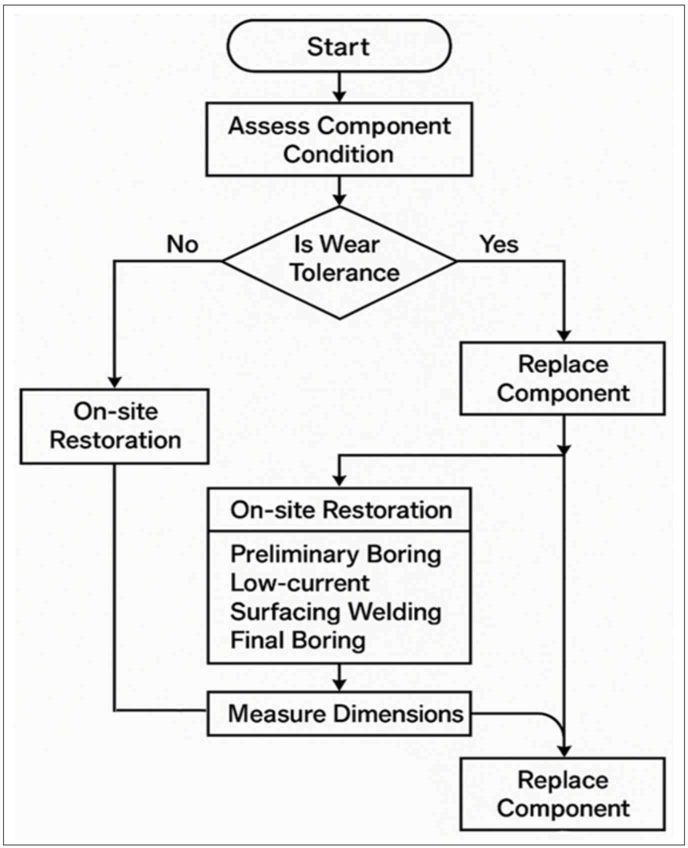

Fig. 1. Flow chart of the decision-making process "Repair or Replace" for a critical component (compiled by the author based on [4, 5, 8, 14]).

A comprehensive combination of control system modernization and restoration technologies produces a pronounced synergistic effect: the improvement of control electronics and software increases the productivity and energy efficiency of both new and in-service equipment, whereas the restoration of components markedly reduces the costs of maintaining it in operable condition. Savings are generated in the following areas:

- reduction of direct expenditures on spare parts: restoration costs on average 20–30 % of the price of a new equivalent;

- decrease of downtime: repair work is completed within a few days, whereas delivery of original components may take weeks or even months;

- improvement of energy efficiency: restoration of precision pairs (e.g., hydraulic pumps) and the application of smooth, wear-resistant coatings reduce internal leakages and friction [11, 12].

In the operation of an enterprise with a fleet of 150 machine-technical units, the implementation of the methodology of systematic restoration exhibits an economic effect that accumulates over time. Empirical calculations based on actual operating and financial data show that the cumulative savings for customers over a multiyear period can amount to hundreds of thousands of dollars, which confirms the high return on investment in restoration technologies (Fig. 2).

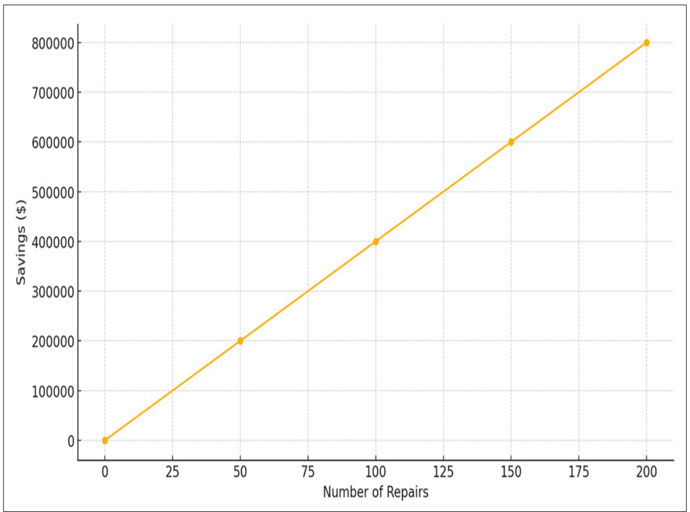

Fig. 2. Predicted cumulative savings from the implementation of the recovery program (compiled by the author based on [11, 12, 13, 15]).

For small and medium-sized enterprises, the following practical recommendations can be formulated:

- The priority direction is the acquisition of mobile units for buildup-boring operations, which opens access to the segment of high-precision maintenance and repair of machinery;

- It is necessary to organize targeted training of personnel in modern buildup methods (MIG/MAG, PTA), thermal spraying (HVOF) and nondestructive quality control procedures;

- The creation of an in-house production line for fast-wearing components (pin, bushing) with systematic hardness and surface roughness control makes it possible to reduce dependence on external supplies and shorten equipment downtime;

- The formation of unique restoration methodologies: the development of repair technologies for characteristic damages of common models (for example, JCB/CAT track rollers) provides the company with a differentiating competitive advantage.

As a result, the comprehensive approach is considered not as a set of disparate technical solutions but as a holistic business model for service enterprises, built on the principles of sustainable development and the circular economy, where the emphasis shifts from complete replacement to restoration and modernization.

CONCLUSION

As a result of the research, an integrated approach to improving the hydraulic systems of construction machinery was developed, grounded in the synergistic combination of control-system modernization and the implementation of advanced restorative technologies. It was established that replacing classical hydraulic circuits with proportional electrohydraulic loops not only increases the energy efficiency and accuracy of actuators but also expands the functional capabilities of machines, providing a rise in their market value by 15–20 %.

At the same time, the high effectiveness of modern surfacing-restoration methods—particularly ceramic-coating spraying and the use of mobile boring complexes—was demonstrated. The application of these technologies makes it possible to reduce repair costs and cut equipment downtime from multi-month intervals to several days.

The maximum return on operating a construction-equipment fleet is achieved not by choosing between modernization and restoration, but by their competent integration. Such a strategy enables small and medium-sized service enterprises to form unique competitive advantages, offering clients not merely repair, but a comprehensive solution for boosting productivity and lowering the total cost of ownership of machinery. Prospects for further research are associated with combining the approaches presented with predictive-diagnostics methods based on the Internet of Things (IoT) and machine learning in order to transition to proactive lifecycle management of hydraulic systems.

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