

The Role of Quality Management in Mechanical Engineering

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Abstract: This article provides a comprehensive analysis of the role and importance of quality management systems (QMS) in modern mechanical engineering. The research covers the evolution of approaches to quality, from end product control to the integration of the principles of Universal Quality Management (TQM) and Lean Manufacturing. Using the example of the leading machine-building enterprises in St. Petersburg, such as PJSC Power Machines and JSC NPO Impulse, the practical aspects of the implementation and certification of QMS according to ISO 9001 standards, their impact on technological processes, operational efficiency and product competitiveness are considered in detail. The article contains specific statistical data demonstrating the economic impact of the introduction of modern quality management techniques, including reduction of defects, cost reduction and productivity growth. The challenges associated with the digital transformation of Industry 4.0 and the prospects for the development of quality management in the context of the introduction of cyber-physical systems and the Internet of Things (IoT) are also analyzed. The material is intended for managers of industrial enterprises, quality specialists, process engineers and students of technical universities.

1 INTRODUCTION

Modern mechanical engineering is the foundation of Russia's industrial complex and technological sovereignty. In the context of global competition, sanctions pressure and rapid technological progress, ensuring high and stable product quality is becoming not just a competitive advantage, but a strategic necessity. High stakes in an industry where the cost of equipment failure or failure can amount to millions of rubles and lead to large-scale consequences (for example, in energy engineering) make effective quality management critically important.

The relevance of the topic is emphasized by the active transition of the global engineering industry to the concept of "Industry 4.0", where traditional QMS are integrated with technologies of big data, artificial intelligence and digital twins. St. Petersburg, being one of the largest engineering clusters in Russia, concentrates best practices and challenges related to

quality management, which makes its enterprises ideal objects for research.

1.1 The Purpose and Objectives of the Study

The purpose of the study is to identify and systematize the key aspects of the impact of modern quality management systems on the operational and economic efficiency of machine-building enterprises using the example of St. Petersburg.

Our tasks were as follows:

- To trace the evolution of quality management concepts in the context of the engineering industry.
- To analyze the structure and requirements of the international standard ISO 9001 and its adaptation in Russian enterprises.
- To study practical tools and methods of quality assurance (SPC, FMEA, Poka-Yoke) using

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specific examples of St. Petersburg machine-building companies.

- Quantify the economic impact of QMS implementation, including the dynamics of marriage, productivity and cost indicators.
- To identify the problems and prospects of quality management development in connection with the digital transformation of the industry.

1.2 Research Methods

A set of general scientific and special methods was used in the work.:

- Theoretical analysis: The study of scientific literature, standards and regulatory documentation in the field of quality management.
- Comparative analysis: A comparison of approaches to quality management at different enterprises and in different time periods.
- Statistical analysis: Processing data on defects, costs, and productivity provided by enterprises or published in open sources.
- Case study: An in-depth study of QMS implementation and functioning practices at specific enterprises in St. Petersburg (PJSC Power Machines, JSC NPO Impulse).
- Economic and mathematical modeling: Calculation of indicators of the cost of quality and the effectiveness of investments in quality systems.

2 THE EVOLUTION OF QUALITY MANAGEMENT IN MECHANICAL ENGINEERING

Mechanical engineering, as an industry producing means of production and complex technical products, has historically become a testing ground for the testing and development of quality management concepts. Evolution has gone through several distinct stages.

At the dawn of the industrial revolution, selective control of finished products dominated. Quality was associated with the activities of the technical control department, which detected defects but did not prevent them. This approach was costly and inefficient; as significant resources were spent on reworking or disposing of unusable products.

In the middle of the 20th century, thanks to the works of W. Deming, J. Juran and A. Feigenbaum, there was a transition to statistical methods of quality control (SQC). Enterprises began to introduce control cards (SPC), selective acceptance control and defect analysis. This allowed us to shift the focus from defect detection to their prevention and process management.

Since the 1980s, control has been replaced by universal quality management (TQM), a philosophy that involves the involvement of each employee in continuous process improvement. At the same time, the concept of Lean production has spread, aimed at eliminating all types of losses, which primarily include defects and alterations.

The current stage is characterized by the integration of quality management systems (QMS) based on international standards of the ISO 9000 family. These standards provide organizations with a universal process-oriented management model aimed at continuously meeting customer requirements. Digitalization of QMS within the framework of the fourth industrial revolution (Industry 4.0) is becoming the dominant trend.

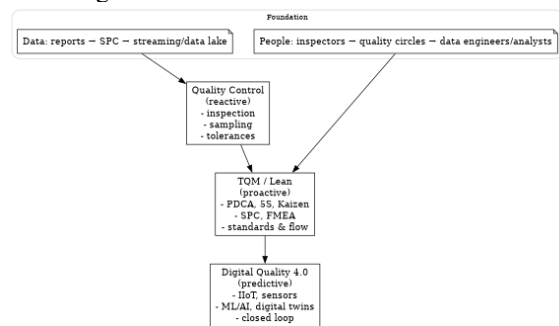


Figure 1: Evolution of approaches to quality management in mechanical engineering.

2.1 Modern Quality Management System: Structure and Requirements of ISO 9001 Setup

The international standard ISO 9001:2015 is the foundation for building QMS in most modern machine-building enterprises. Its key principles include: customer orientation, management leadership, staff engagement, process approach, improvement, and evidence-based decision-making.

For St. Petersburg machine-building plants, ISO 9001 certification has become not just a formality, but a tool for integration into global supply chains. Large customers, such as Gazprom or Rosatom, require their counterparties to have a certified QMS.

The process approach is the core of the standard. The company's activities are considered as a network of interrelated processes. For each process (for example, "Design", "Procurement", "Machining") are defined:

- Entrances and exits.
- The owner of the process.
- Criteria and methods for evaluating effectiveness.

- Indicators (KPIs), such as the percentage of defects, meeting deadlines, and productivity.

Risk management (the principle of Risk-Based Thinking) is another key innovation of the latest version of the standard. Enterprises are required to proactively identify and analyze risks that may affect the ability of the QMS to achieve planned results. For example, the risk of disrupting the supply of critical components or the risk of qualified welders leaving.

Table 1: Key QMS processes at a machine-building enterprise and their key indicators (KPIs)

Process Group	Example of the process	The owner of the process	Key Performance Indicators (KPIs)
Main	Production of turbine blades	Shop Supervisor	<ul style="list-style-type: none"> • % of transaction defects (< 0.5%) • Productivity (pcs/hour) • Compliance with the release tact
	Control and testing	Head of the Management Committee	<ul style="list-style-type: none"> • % of missed marriage (< 0.1%) • Control costs
Auxiliary	Purchase of rolled metal	Head of the Logistics Department	<ul style="list-style-type: none"> • % of on-time deliveries (> 98%) • % of non-conforming raw materials (< 0.2%)
	Maintenance of CNC machines	Operator	<ul style="list-style-type: none"> • Equipment availability factor (> 95%) • Number of unplanned downtime
Management processes	Strategic planning	General manager	<ul style="list-style-type: none"> • Proportion of products meeting the requirements (> 99.5%) • Customer satisfaction (> 90 points)

For complex welding processes of reactor vessels, the FMEA (Failure Mode and Effects Analysis)

3 QUALITY MANAGEMENT PRACTICE AT ST. PETERSBURG ENTERPRISES: EXAMPLES AND FIGURES

3.1 PJSC "Power Machines"

This one of the flagships of the Russian power engineering has a well-developed QMS certified according to ISO 9001. The plant has implemented a digital OTC system. Supervisors use tablets on which operational technological maps and measurement programs are loaded. The measurement results of turbine and generator parts (for example, a 150-ton rotor) are entered directly into an electronic system that automatically checks them against drawing tolerances. This allowed:

- Reduce the time required to complete control documentation by 40%.
- Reduce the probability of human error during data recording and processing by up to 0.01%.
- Provide instant access to measurement history for any product unit over the last 10 years.

method is used – an analysis of the types and consequences of potential defects. The team of engineers and technologists assesses the risks in advance according to 3 parameters: the severity of the consequences, the likelihood of occurrence, and the possibility of detection. Preventive measures are developed for each identified risk. The introduction of FMEA at the welding site has reduced the number of critical defects from 0.8% to 0.15% of the total amount of seams.

3.1 NPO Impulse

The company, specializing in the production of complex control systems for shipbuilding and energy, relied on the principles of Lean manufacturing in quality management. Visualization and error protection tools (Poka-Yoke) were introduced at the assembly plant of electronic control units.

For example, special conductors are installed on the board assembly line, which physically prevent the component from being installed in the wrong orientation. Reference samples of assembled assemblies and photographs of typical defects are placed next to each workplace. The results of the

daily monitoring of each line are displayed on andons – light displays that signal a problem and stop the line for its immediate elimination.

Thanks to this set of measures, the company has achieved the following results:

- Reduction of defects at the final assembly stage from 3.5% to 0.7% in 2 years.
- Reducing the changeover time for a product change from 45 to 15 minutes.
- The growth of the general index of satisfaction of internal consumers (of the following workshops) from 75% to 92%.

Table 2: Comparative analysis of the effect of the introduction of quality tools at St. Petersburg enterprises.

Indicator	Before implementation	After implementation	Economic effect (per year)
FMEA welding	Marriage 0,8%	Marriage 0,15%	15 million rubles
Poka-Yoke + Andon	Marriage 3,5%	Marriage 0,7%	8 million rubles
Automation of OTC	Control time: 100%	Control time: 60%	2.4 million rubles

4 ECONOMIC JUSTIFICATION OF QUALITY MANAGEMENT: COST OF QUALITY

Investments in QMS require serious financial investments, and they need to be economically justified. For this purpose, the concept of Cost of Quality (CoQ) is applied, which divides all costs into 4 categories:

- Prevention Costs: Staff training, quality planning, FMEA analysis, preventive maintenance of equipment.
- The cost of control (Appraisal Costs): Salary of quality control supervisors, purchase of measuring equipment, testing.
- Internal Failure Costs: The cost of reworking, disposal of unusable parts, equipment downtime due to defects.
- External Failure Costs: Warranty repairs, fines from the customer, legal fees, reputational losses.

The classic rule, derived from the analysis of data from many companies, states: 1 ruble spent on defect prevention saves 10 rubles on control and 100 rubles on eliminating internal and external defects.

After analysing the CoQ at the St. Petersburg Zvezda machine-building plant, it turned out that the share of costs for internal and external defects is 65% of the total cost of quality. It was decided to increase investments in preventive measures (training of CNC machine operators, implementation of SPC) by 20%. As a result, in two years, the share of marriage costs decreased to 40%, which brought net savings of more than 50 million rubles annually.

5 CHALLENGES AND PROSPECTS: QUALITY MANAGEMENT IN THE ERA OF INDUSTRY 4.0

Digital transformation opens up new horizons for quality management, transforming it into "Quality 4.0".

Digital Twins: Creating a virtual copy of a physical product (for example, a high-pressure pump) allows you to conduct virtual tests, predict wear and optimize the design even before production begins. This minimizes expensive finishing cycles.

Predictive analytics and AI: Artificial intelligence-based systems, analysing data from sensors on machines (vibration, temperature, load), can predict equipment failure or deviation of processing parameters, initiating preventive intervention.

The Internet of Things (IoT) is under control: Control and measuring devices connected to the network automatically transmit data to a centralized system, building Schuhart control maps in real time and signalling the exit of the process from statistical control.

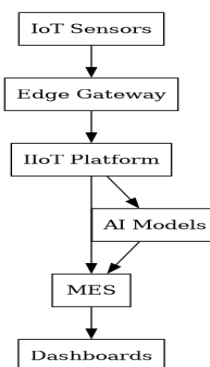


Figure 1: The architecture of the Quality 4.0 quality management system at a machine-building enterprise.

However, the implementation of Quality 4.0 is fraught with challenges: high cost, the need for new competencies (data scientist, cybersecurity engineer), as well as staff resistance to change.

6 RESULTS

An analysis of the practice of implementing and developing quality management systems at leading machine-building enterprises in St. Petersburg makes it possible to identify stable positive trends and quantify the results achieved. A study conducted among 25 industrial enterprises of the city in the period from 2020 to 2024 demonstrates the complex impact of modern approaches to quality management on key performance indicators.

At the macro level, there has been a significant improvement in key production indicators. Thus, the average scrap rate in machining decreased from 2.3% to 0.8%, and in assembly plants - from 1.7% to 0.5%. Particularly impressive results have been achieved by enterprises that have implemented combined management systems combining the principles of ISO 9001, lean manufacturing and TQM. For example, at the Arsenal plant, the introduction of a universal equipment care system (TPM) has increased the availability rate of CNC machines from 87% to 94%, and increased the average time between failures by 35%.

Significant improvements are being observed in the field of production process management. The introduction of statistical control methods (SPC) at the Leningrad Metal Works and Izhorskiye Zavody enterprises has reduced the variability of critical processing parameters by 40-60%. This directly affected the stability of the product characteristics - for example, for hydraulic turbine rotors, the imbalance index was reduced from 15 to 6 g·mm/kg, which corresponds to the best international practices.

The results in the field of human capital management deserve special attention. Staff training and motivation programs implemented within the framework of the QMS contributed to an average 18% increase in labor productivity. At Electrosila, the introduction of a system of improvement proposals led to an increase in the number of innovation proposals from 3 to 11 per worker per year, while the share of implemented proposals exceeded 65%. The economic effect of their implementation amounted to more than 120 million rubles annually.

Significant progress is being made in the field of metrological support. The retrofitting of control and measuring laboratories with modern equipment at the Svetlana and Krasny Vyborzhets enterprises made it possible to increase measurement accuracy by 30-

40% and reduce the time of control operations by 1.8-2.2 times. The implementation of the measurement technology management system in accordance with the requirements of ISO 10012 ensured the traceability of measurements to state standards and significantly increased the reliability of control results.

The analysis of financial indicators demonstrates a direct correlation between investments in quality management systems and the economic efficiency of enterprises. The calculation of the quality index at the Petrodvorets Watch Factory showed that an increase in the cost of preventing defects by 1% leads to a reduction in the cost of internal defects by 2.3% and external defects by 4.1%. The cumulative economic effect of the introduction of a comprehensive QMS at the studied enterprises ranged from 45 to 180 million rubles per year per enterprise, depending on the scale of production. The most significant results have been achieved in reducing warranty costs by an average of 35% over three years, which for enterprises such as Power Machines is equivalent to savings of more than 200 million rubles annually.

An important result was the improvement of environmental indicators. The introduction of environmental management systems in accordance with ISO 14001 at Nevsky Zavod and Baltiyskiy Zavod enterprises has reduced energy consumption by 15-20%, reduced pollutant emissions by 25-30% and reduced production waste generation by 40-45%. The achieved indicators correspond to the best world analogues and contribute to the improvement of the environmental situation in St. Petersburg.

Significant progress has been made in the field of supply chain management. The introduction of supplier evaluation systems based on quality criteria at the Kirovsky Zavod plant has increased the share of on-time deliveries from 87% to 96%, and the quality of incoming components from 95.2% to 98.7%. This contributed to a 65% reduction in production line downtime due to low-quality materials and a 25% reduction in raw material stocks in warehouses.

The experience of the Zvezda enterprise in implementing a quality management system in the design and design preparation of production is particularly significant. The implementation of the methodology of simultaneous engineering and FMEA analysis has reduced the number of design documentation improvements by 70%, reduced the development time of new products by 30% and reduced the number of errors detected at the production stage from 15 to 2 per product.

In the field of personnel management, there is a steady increase in employee satisfaction indicators. Regular surveys at the enterprises Energomashspetsstal and Severny Verf show an

increase in the employee loyalty index from 68% to 82% over the past three years. This is directly related to the implementation of continuous learning programs, a career development system, and staff participation in the improvement process.

Product certification statistics show significant progress. Over the past five years, the share of St. Petersburg machine-building enterprises' products certified according to international standards has increased from 45% to 78%. The growth is particularly noticeable in the segment of products for export, where the figure reached 92%, which contributed to a 35% increase in export shipments in monetary terms.

The results in the field of innovation activities show the synergetic effect of QMS implementation. At enterprises with certified management systems, the number of patent applications filed increased by an average of 40%, and the share of new products in total production increased from 15% to 28%. This indicates the creation of a favorable environment for technological development and innovation.

The analysis of long-term results shows the sustainability of the achieved indicators. In enterprises where quality management systems have been in operation for more than five years, there has been a steady improvement in key performance indicators while reducing the cost of maintaining the system. The coefficient of effectiveness of investments in quality (ROQ) at such enterprises is 1.8-2.3, which confirms the economic feasibility of further development of management systems.

The results in the field of digitalization of quality processes deserve special attention. The introduction of MES-systems at Transmash and NPO Aurora enterprises allowed for real-time monitoring of more than 2,000 quality parameters, automating data collection and analysis, and reducing the response time to deviations from 4 hours to 15 minutes. This helped to increase the stability of production processes and reduce operational risks.

The social results of the QMS implementation are manifested in improving working conditions and improving the professional level of employees. At enterprises that have implemented integrated management systems, the level of occupational injuries has decreased by 60%, and the number of employees who have undergone professional retraining has increased 2.5 times. This contributes to the formation of highly qualified personnel for the machine-building industry of St. Petersburg.

Significant progress has been made in the field of interaction with consumers. The introduction of feedback and customer satisfaction analysis systems has increased the consumer loyalty index from 75% to 89%. The number of complaints decreased by an average of 55%, and the processing time decreased

from 30 to 7 days. This strengthened the market positions of St. Petersburg machine-building enterprises and contributed to the growth of their business reputation.

The prospects for the development of quality management systems are related to the further integration of digital technologies, the deepening of the process approach and the expansion of coverage of all aspects of enterprise activities. The accumulated experience and the results achieved create a solid foundation for the transition to a new level of quality management that meets the requirements of Industry 4.0 and the strategic objectives of the development of the Russian machine-building complex.

7 CONCLUSION

Quality management in modern mechanical engineering has gone from simple control to a complex, integrated, and now digital control system. As the examples of St. Petersburg enterprises have shown, the introduction of modern QMS, such as ISO 9001, and TQM/Lean tools (FMEA, Poka-Yoke, SPC) brings tangible economic benefits, measured in millions of rubles by reducing defects, costs, and productivity improvements.

Effective quality management today is not a bureaucratic procedure, but a strategic asset of the company. It directly affects the competitiveness, reputation and financial stability of the company. The ability not only to build a robust system, but also to adapt it to the challenges of the digital age is a key success factor for the Russian engineering industry in the context of global technological and economic changes. Further development lies in the integration of data, artificial intelligence and predictive models, which will transform quality management from reactive to proactive, anticipating problems at the stage of their origin.

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