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Research and Application of Digitalization in Basic Metrological Inspection Institutions

Yajun Zhang, Guangcheng Jia, Peng Wang

Xinjiang Uygur Autonomous Region Institute of Metrology and Testing, Urumqi 830000, Xinjiang, China

**Author to whom correspondence should be addressed.*

Abstract: Metrological testing is an indispensable link supporting the high-quality development of various industries, and basic metrological inspection institutions are a key force serving the national economy and people's livelihood, technological innovation, and industrial development. In the digital age, promoting the digital transformation of metrology is an inevitable trend for the development of metrological inspection institutions. The application value of digitalization in metrological inspection institutions is reflected in four aspects: ensuring data quality, optimizing business processes, strengthening risk prevention and control, and innovating service models. Combined with the problems in the informatization construction of metrological inspection, this paper puts forward strategies for the digital transformation and application of basic metrological inspection institutions, focusing on platform construction, system improvement, tool empowerment, facility guarantee, and team building, aiming to provide a reference for the development of metrology towards efficiency and precision.

Keywords: Metrological inspection institutions; Digitalization; Application

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1. Introduction

With the emergence of the digital age, the integrated application and collaborative iteration of new-generation information technologies such as network technology, digital technology, and intelligent technology have injected new momentum into social and economic development. Digital technology has shown strong advantages in the field of metrology. Relying on key technologies such as ultra-dense heterogeneous networks, self-organizing networks, and content delivery networks, 5G communication technology supports remote calibration and automated data collection in metrological testing, realizes intelligent logistics in sample management, and supports remote project review in scientific research [1]. Big data technology, virtual instrument technology, cloud computing technology, etc., are promoting the upgrading of metrological services, with advantages in optimizing metrological processes, improving data processing efficiency, and strengthening quality control [2,3]. At present, basic metrological inspection institutions are facing new challenges such as the application of appointment business processes and the complexity and diversity of testing projects. Traditional business processes and control processes have been difficult to meet the needs of the times [4]. Therefore, it is imperative to deepen digital transformation and development, and improve the efficiency and service quality of metrological work.

2. Application value of digitalization in basic metrological inspection institutions

2.1. Ensure the quality of metrological data and lay a foundation for industry credibility

The accuracy and traceability of data are the lifeline of metrological testing, which directly determines the credibility of institutions. Digitalization guarantees data quality through full-chain management and control, specifically reflected in as follows:

(1) Realize structured collection of key data, convert sample information, testing basis, and judgment standards into a standardized dictionary database, and avoid the randomness and errors of manual entry;

(2) With the help of data verification technology and automatic verification rules, conduct real-time verification of data types, source legality, and logical consistency to ensure that test data is true and traceable;

(3) Promote the replacement of paper documents with electronic files, store original records and reports in an unalterable format, meet the requirements of relevant specifications, and strengthen the legal validity of data [5].

2.2. Optimize business process efficiency and improve institutional operation effectiveness

Traditional metrological business is limited by offline operations and departmental barriers, with prominent inefficiency problems. Digitalization realizes full-chain collaboration through process reconstruction as outlined:

(1) Business acceptance link: Through functions such as online appointment and electronic form submission, reduce customers' offline trips and realize one-stop services of "online application, progress query, and certificate download";

(2) Internal collaboration link: Realize the online flow of sample reception, task assignment, test implementation, and report generation, support mobile on-site entry and cross-department real-time review, and solve the problems of delayed task tracking and high communication costs [6];

(3) Resource allocation link: Provide a scientific basis for equipment scheduling and personnel allocation through automatic data statistics and analysis, improve equipment utilization rate, and reduce operating costs.

2.3. Strengthen quality risk prevention and control to meet compliance management requirements

Metrological testing faces multiple risks such as personnel qualifications and equipment status, and compliance requirements are becoming increasingly strict. Digitalization builds a full-cycle risk prevention and control system, with specific directions as follows:

(1) Automatic risk early warning: Convert quality control points into digital thresholds, embed them into key nodes of business processes, and automatically remind of expired personnel qualifications, expired equipment calibration, standard updates, etc., to avoid illegal operations [7];

(2) Full traceability of operations: Record operational behaviors through hierarchical permissions, digital signatures, timestamps and other technologies. When quality problems occur, quickly locate the responsible links and personnel to support closed-loop rectification;
(3) Policy compliance guarantee: Meet the requirements of laws and regulations related to network security and data security, and national cybersecurity grade protection. Prevent data leakage and unauthorized access through data backup, encrypted storage and other measures.

2.4. Empower service model innovation and expand institutional development space

Traditional service models are difficult to adapt to customers' personalized needs and industry collaboration needs. Digitalization provides technical support for service innovation, with main innovation directions as listed:

(1) Customer service innovation: Establish a customer credit information management system, connect to the national enterprise credit information public disclosure platform, and provide differentiated services according to customers' credit status to achieve precise services and risk prediction [8];
(2) Industry collaboration innovation: Support cross-institutional data sharing and credit information interaction, promote the integration of regional metrological services, and realize the mutual recognition of test results and resource complementarity;
(3) Expansion of service value: With the help of big data analysis technology, tap the industry quality trends in test data, provide decision support for government supervision, and extend the service boundary [9].

3. Strategies for digital transformation and application of basic metrological inspection institutions

3.1. Build a full-process digital management platform to consolidate the foundation of informatization

In response to the common industry pain points of "data silos" and system fragmentation, and in line with the trend of full-link intelligent management and control, building an integrated platform is the primary task of digital transformation.

3.1.1. Plan the platform function architecture

The platform is designed to support the complete workflow encompassing sample reception, task allocation, test execution, data recording, report generation, and quality supervision. Its functional architecture is composed of the following core modules:

(1) Business management, enabling online appointment scheduling, real-time progress tracking, and electronic approval;
(2) Quality management, incorporating risk early-warning mechanisms, compliance verification, and internal audit management;
(3) Resource management, covering the management of equipment, personnel, and reference materials;
(4) Customer service, providing online inquiry services, certificate downloading, and complaint handling.

This modular design ensures comprehensive process coverage and operational efficiency.

3.1.2. Ensure platform technical performance

To meet the demands of scalable computing power and data storage, the platform adopts a cloud computing or hybrid cloud architecture, thereby enhancing system flexibility and access stability. Priority is given to the deployment of secure and controllable domestic operating systems and database technologies to comply with national cybersecurity graded protection requirements. These measures collectively ensure adequate system response speed, high availability, and secure operation [10].

3.1.3. Promote system integration and data interoperability

The platform is designed to achieve seamless integration with testing instruments, laboratory information management systems (LIMS), and customer relationship management (CRM) systems. This integration enables automatic acquisition of instrument-generated data, effectively reducing manual input and minimizing the risk of data entry errors [11]. In addition, connectivity with government regulatory platforms supports automated reporting of testing data. Participation in industry-level data-sharing platforms further promotes the harmonization of cross-institutional data standards and enhances data interoperability.

3.2. Improve digital management systems and standardize process execution

Facing the pain points of disconnection between systems and digital processes and inconsistent operating standards, combined with the trend of "system-technology" collaboration, improving the standard system is the key to process implementation.

3.2.1. Formulate list-based management specifications

List-based management specifications were formulated around core business processes through the compilation of a "Digital Management Work System" and a "System Operation Guide". These documents clearly define data collection requirements, operational procedures, and the division of responsibilities at each stage of the workflow. A dynamic update mechanism was established to ensure timely revision of management specifications in response to policy adjustments and evolving business needs. In addition, explicit rules were defined for critical processes, including the management of electronic original records and report generation, to enhance traceability and regulatory compliance.

3.2.2. Strengthen process standardization constraints

Testing workflows were digitized to enable standardized process management, with standard operating procedures (SOPs) embedded directly within the system to ensure consistent execution. The platform enforces compliance by validating sample information, testing standards, and operational steps throughout the workflow. A process compliance verification mechanism was implemented to automatically identify inconsistencies between test items and applicable standards, as well as unapproved critical steps, thereby ensuring strict adherence to prescribed procedures.

3.2.3. Improve the data quality management system

A comprehensive data quality management framework was established across the stages of data collection, processing, storage, and utilization. During data collection, dictionary-based input was applied to key fields, linking manually entered data to a standardized reference dictionary to ensure consistency. During data processing, automated validation techniques, including data type matching and source verification, were employed to reduce human error. For data storage, a dual-layer strategy combining local backup with remote disaster recovery was adopted, supported by regular data recovery drills. At the data utilization stage, data quality evaluation metrics, such as accuracy, completeness, timeliness, and consistency, were defined, and routine data quality audits were conducted to support continuous improvement [12].

3.3. Strengthen Technical Tool Empowerment and Improve the Level of Management Intelligence

Facing the pain points of low efficiency of traditional tools and passive risk prevention and control, and in line with the trend of AI and mobile Internet applications, the upgrading of technical tools is the core path of intelligent transformation.

3.3.1. Optimize process management tools

A mobile application for on-site testing was developed to support real-time data entry, photographic documentation, and electronic signature confirmation, enabling effective collaboration between on-site operations and back-end management systems [13]. Furthermore, a task progress tracking module was implemented to allow managers to monitor the status of each workflow stage in real time and to automatically issue alerts for overdue tasks. An intelligent test report generation tool was further developed, which populates standardized report templates using structured data and supports clause-based matching between test results and evaluation criteria, thereby reducing manual compilation errors.

3.3.2. Build an intelligent quality risk management and control system

Key quality risk factors, including personnel qualifications, equipment status, environmental conditions, and updates to testing standards, were transformed into digital control rules and embedded within the operational workflow. A personnel competence matrix database was established to automatically match task assignments with qualified personnel. Equipment management functions include early warning thresholds and automated reminders for calibration and maintenance prior to expiration. Furthermore, an intelligent abnormal data identification mechanism was introduced, employing algorithm-based comparison of real-time data with historical trends and standard reference ranges to flag anomalies and trigger mandatory review procedures.

3.3.3. Promote the full-process application of electronic files

In compliance with relevant regulatory and technical specifications, electronic archiving was implemented for original records, test reports, and quality management documents, using tamper-resistant file formats to ensure data integrity and security. An electronic document management system was established to support classified retrieval, access control, and full audit trails, as well as online viewing and compliant data export. This system facilitates the gradual replacement of paper-based documentation and enhances the efficiency and traceability of document management across the entire testing process.

3.4. Strengthen infrastructure and data security construction to build a guarantee line

Facing the pain points of low digitalization of equipment and prominent data security risks, and in line with the trend of safety compliance and infrastructure upgrading, building a solid guarantee line is a prerequisite for the implementation of digitalization.

3.4.1. Upgrade digital infrastructure

Testing instruments were upgraded to support automated data acquisition, enabling real-time interconnection with centralized information platforms. A stable and secure network environment was established, incorporating firewalls, intrusion detection systems, and other security devices to ensure logical isolation between internal networks and the external Internet. In addition, high-performance servers and scalable storage systems were deployed to accommodate large-volume data storage requirements and to support efficient data access, backup, and recovery processes [14].

3.4.2. Improve the data security guarantee mechanism

A comprehensive data security management framework was formulated, defining data classification and grading standards and implementing encrypted storage and access control for sensitive information. Digital signatures, timestamps, and related technologies were employed to ensure end-to-end traceability of data processing and to mitigate the risk of unauthorized modification. Furthermore, a data security incident response plan was established, supported by regular cybersecurity drills to enhance emergency handling capabilities. Strict controls were also implemented for data export and external data sharing.

3.4.3. Standardize electronic authentication and permission management

A unified user identity authentication system was established, incorporating multi-factor authentication based on a combination of username, password, and dynamic verification codes, with biometric verification required for critical operations. System access rights were assigned in accordance with the principle of least privilege, clearly defining operational scopes for different user roles, including administrators, inspectors, auditors, and customers. Dynamic permission adjustment and comprehensive audit logging were implemented to enhance accountability. In addition, electronic reports were secured using legally recognized electronic seals and digital signatures to ensure their legal validity, integrity, and non-repudiation.

3.5. Strengthen talent team building and improve digital application capabilities

Facing the pain points of lack of compound talents and insufficient digital skills of employees, and in line with the trend of talent adaptation to digital transformation, team building is the core support for technology implementation.

3.5.1. Establish a compound talent team

A multidisciplinary talent team integrating expertise in metrological testing and digital technologies was established to support system development, maintenance, and continuous optimization [15]. In parallel, existing personnel were encouraged to participate in digital skills training to enhance competencies in system operation, data analysis, and cybersecurity. To strengthen strategic coordination, a dedicated digital management role was created at the managerial level to oversee the formulation and implementation of digital transformation strategies.

3.5.2. Establish a hierarchical training mechanism

A hierarchical training framework was implemented to address the distinct competency requirements of different roles. Inspectors received targeted training in data acquisition, mobile terminal operation, and abnormal event handling. Managers were trained in process optimization, data analysis, and risk management and control. Technical personnel focused on system maintenance, security protection, and functional upgrades. Training activities adopted a blended approach combining theoretical instruction, practical exercises, and case-based learning, with contributions from industry experts and system developers.

3.5.3. Improve the incentive and assessment mechanism

Digital competency and application effectiveness were incorporated into employee performance evaluation systems, with assessment indicators including standardized system operation, data quality improvement, and contributions to process optimization. Outstanding performance was recognized through commendation and incentive mechanisms. Employees were further encouraged to engage in digital innovation initiatives, with dedicated rewards for teams or individuals who proposed effective optimization strategies or developed practical digital tools, thereby fostering a culture of broad participation and continuous improvement.

3.6. Promote digital upgrading in phases to ensure implementation effectiveness

Facing the pain points of blind informatization promotion and lack of systematicness, and in line with the trend of gradual digital transformation, phased implementation is a scientific method to ensure effectiveness:

3.6.1. Pilot phase

Departments with high operational volume and well-standardized workflows were selected for pilot implementation. Core functional modules, including sample acceptance, task assignment, data recording, and report generation, were deployed during this phase. Operational issues and optimization recommendations identified during pilot use were systematically collected, and iterative system refinements were conducted to improve functionality and user experience. In parallel, foundational data were organized and standardized, leading to the establishment of a core data dictionary to support subsequent system expansion.

3.6.2. Full promotion phase

Building on the outcomes of the pilot phase, the digital system was progressively extended across the entire institution, enabling full digital migration of all business processes. Comprehensive system operation training was provided to all staff to facilitate adoption and to support the complete transition from paper-based documentation to electronic original records and reports. A system operation monitoring mechanism was established, with dedicated personnel assigned responsibility for routine maintenance and the timely resolution of technical issues and operational challenges.

3.6.3. Optimization and upgrading phase

System operation data were leveraged to identify workflow bottlenecks and management weaknesses, providing an evidence base for ongoing functional optimization. Advanced technologies, including big data analytics and artificial intelligence, were introduced to develop higher-level applications such as data mining, intelligent early warning, and trend analysis. Moreover, integration with industry data-sharing platforms and government regulatory systems was pursued to enhance data utilization and support the development of an "intelligent metrology" management model.

4. Conclusion

In summary, as a core part of the national quality infrastructure, metrological inspection's management level is directly related to industrial quality improvement, fair market order, and people's livelihood security. Digital reform is the key engine driving metrological testing institutions to achieve high-quality development. Digital management can not only consolidate the operational foundation of institutions in terms of data quality, process efficiency, and risk prevention and control, but also help institutions build core competitiveness in the wave of digital transformation through service model innovation and technology empowerment. This is not only a practical need to cope with industry competition, but also an inevitable choice to respond to the national quality power strategy. In future practice, institutions need to avoid the misunderstandings of "valuing system construction over process adaptation" and "valuing function development over safety management". They should always be guided by business needs and take compliance requirements as the bottom line. Through phased promotion and pilot optimization strategies, ensure the effective implementation of digital construction and application.

Disclosure statement

The author declares no conflict of interest.

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