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Digital Product Passport for Machine Tools as an Information Core of Sustainable Manufacturing Engineering

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Abstract

INTRODUCTION: The transition toward Industry 5.0, sustainable manufacturing, and the European Digital Product Passport (DPP) concept creates new requirements for machine-building enterprises and engineering education. Modern machine tools are no longer considered isolated manufacturing units but complex cyber-physical systems generating continuous technological, operational, and diagnostic information throughout their lifecycle. In this context, the integration of Digital Product Passports into manufacturing systems becomes a key factor in ensuring traceability, sustainability, adaptability, and efficient lifecycle management.
OBJECTIVES: The objective of this paper is to develop a conceptual and practical framework for a Digital Product Passport of machine tools as an integrated information core for sustainable manufacturing engineering, lifecycle-oriented traceability, and technological decision-making within Industry 5.0 environments.
METHODS: The study is based on system analysis, lifecycle-oriented engineering approaches, digital manufacturing concepts, and information-flow modeling. A structured mathematical representation of technological information exchange between machine tool modules, technological parameters, monitoring systems, and decision-making units is proposed. The framework integrates CAD/CAM/CAE environments, QR-based identification, sensor data acquisition, cloud-oriented information support, and Alicona-based surface metrology according to ISO 25178.
RESULTS: A hierarchical Digital Product Passport architecture for machine tools was developed and experimentally validated using QR-linked engineering information structures and high-resolution surface metrology. The proposed model enables continuous synchronization of geometric, technological, operational, and diagnostic information throughout the machine lifecycle. Alicona InfiniteFocus G5 measurements confirmed the formation of stable microrelief structures suitable for reliable QR-code readability and engineering traceability. The developed framework additionally integrates Digital Twin structures, lifecycle-oriented monitoring, and educational engineering datasets within the Erasmus+ MechDiTS project, supporting Industry 5.0-oriented engineering education.
CONCLUSION: The proposed Digital Product Passport framework transforms machine tools into information-centric cyber-physical systems capable of supporting sustainable manufacturing, lifecycle traceability, predictive maintenance, and adaptive technological management. The integration of industrial engineering datasets, Digital Twins, and lifecycle-oriented information environments into engineering education creates new opportunities for preparing specialists capable of operating within data-driven Industry 5.0 manufacturing ecosystems.

Keywords: Digital Product Passport, Industry 5.0, sustainable manufacturing, machine tools, cyber-physical systems, digital engineering, lifecycle management, technological sustainability

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1. Introduction

The rapid transformation of modern manufacturing systems under the concepts of Industry 4.0 and Industry 5.0 has significantly changed the role of information within mechanical engineering [1]. Contemporary machine-building enterprises are increasingly transitioning from isolated production environments toward interconnected cyber-physical ecosystems integrating digital design, intelligent monitoring, data analytics, and lifecycle-oriented management approaches [2-4]. Within this transformation, information becomes not only an auxiliary production resource but one of the key factors determining technological sustainability, adaptability, and competitiveness of manufacturing systems [5,6].

At the European level, these processes are reinforced by sustainability-oriented regulatory initiatives and strategic frameworks, including the European Green Deal, Circular Economy Action Plan, Ecodesign for Sustainable Products Regulation (ESPR), and Digital Product Passport (DPP) concepts. These initiatives establish new requirements regarding product traceability, transparency of technological data, lifecycle monitoring, environmental impact assessment, and resource efficiency [7,8]. As a result, manufacturing systems must ensure continuous generation, synchronization, and management of engineering information throughout the entire product lifecycle [9].

Machine tools occupy a special position within this paradigm because they simultaneously act as manufacturing equipment, sources of technological data, and elements of integrated cyber-physical production systems [10,11]. Modern machine tools generate large volumes of heterogeneous information associated with geometry, operational parameters, diagnostics, maintenance history, tooling configuration, energy consumption, process deviations, and product quality [12,13]. However, in many industrial environments this information remains fragmented between CAD/CAM systems, monitoring modules, enterprise databases, and maintenance documentation. Such fragmentation reduces technological flexibility, complicates predictive maintenance [14], increases adaptation time, and negatively affects the sustainability of manufacturing systems [15,16].

The concept of the Digital Product Passport creates new opportunities for solving these problems by transforming engineering products into information-centric digital entities. In contrast to traditional technical documentation, the DPP approach enables dynamic integration of technological, operational, environmental, and lifecycle-related information within a unified digital environment [17-19]. For machine tools, such an approach allows the formation of a continuously updated information core capable of supporting technological decision-making, adaptive manufacturing, traceability, and lifecycle optimization [20,21].

Simultaneously, the transition toward digital manufacturing significantly influences engineering education. Modern engineers are expected to operate not only with physical equipment but also with information flows, digital twins, sensor systems, cloud platforms, and data-driven manufacturing architectures [22,23]. Therefore, Digital Product Passports can also be considered educational instruments for training specialists capable of working within sustainable digital manufacturing ecosystems [24,25]. In this context, the integration of DPP concepts into engineering curricula aligns with the objectives of the Erasmus+ project "Digital Transformation of Mechanical Engineering for Technological Sustainability" (MechDiTS), aimed at developing modern educational approaches for sustainable manufacturing engineering.

Recent studies demonstrate increasing scientific interest in digital lifecycle management, cyber-physical systems, Digital Twins, and intelligent manufacturing environments [2,10,24]. Nevertheless, the majority of existing research focuses primarily on product-level traceability, additive manufacturing [26,27], or smart logistics applications, while insufficient attention is devoted to Digital Product Passports for machine tools as integrated technological systems. Furthermore, the relationship between machine tool information structures, technological sustainability, and engineering education remains insufficiently explored.

Recent studies have investigated Digital Twins, cyber-physical systems, sustainable manufacturing, and lifecycle-oriented engineering environments [4,11,14]. Particular attention has been devoted to intelligent manufacturing systems, digital lifecycle management, predictive maintenance, and information integration within Industry 5.0 production ecosystems [1,11,28]. Simultaneously, researchers increasingly emphasize the importance of digitalization and 3D information in the technological preparation of manufacturing, especially for SMEs [29]. Nevertheless, existing studies primarily focus on product-level traceability or isolated digital manufacturing solutions, while insufficient attention is devoted to Digital Product Passports for machine tools as integrated engineering-information ecosystems combining technological traceability, lifecycle management, surface metrology, and educational interaction. In contrast to existing Digital Product Passport approaches [30-35] primarily focused on product traceability and logistics-oriented lifecycle documentation, the proposed framework integrates machine-tool monitoring, engineering metrology, Digital Twin structures, lifecycle-oriented diagnostics, and educational interaction within a unified manufacturing-information ecosystem.

Therefore, this paper aims to develop a conceptual framework for a Digital Product Passport of machine tools as an integrated information core supporting sustainable manufacturing engineering, technological adaptability, and digital engineering education within Industry 5.0 environments.

2. Materials and Methods

2.1. General concept of the digital product passport for machine tools

Within sustainable manufacturing systems, a machine tool can no longer be considered only as a mechanical unit performing material processing operations. In Industry 5.0 environments, machine tools operate as information-generating cyber-physical systems continuously interacting with digital design platforms, technological databases, monitoring systems, and decision-making modules. Therefore, the proposed Digital Product Passport (DPP) is considered as an integrated information environment combining geometric, technological, operational, diagnostic, and lifecycle-related data into a unified digital structure.

The proposed DPP architecture is based on the principle of continuous information synchronization throughout the machine lifecycle. The information core includes:

- geometric and design data;
- technological process parameters;
- machine operational states;
- monitoring and diagnostic information;
- maintenance and repair history;
- energy and sustainability indicators;
- technological adaptation data;
- educational and training modules.

Unlike traditional documentation systems, the proposed framework supports dynamic updating of technological information and enables integration with external digital manufacturing environments, including CAD/CAM/CAE systems, ERP platforms, Digital Twins, cloud databases, and intelligent monitoring systems.

The conceptual structure of the proposed information flow is presented in Fig. 1.

2.2. Information flow model

The Digital Product Passport is modeled as a closed information-feedback system integrating machine states, technological parameters, and adaptive control actions.

The generalized information state of the machine tool can be represented as:

$$I(t) = \{G(t), P(t), S(t), D(t), E(t), M(t)\}, \quad (1)$$

where: *G(t)* – geometric and structural information; *P(t)* – technological process parameters; *S(t)* – operational state variables; *D(t)* – diagnostic and monitoring data; *E(t)* – energy and sustainability indicators; *M(t)* – maintenance and lifecycle information.

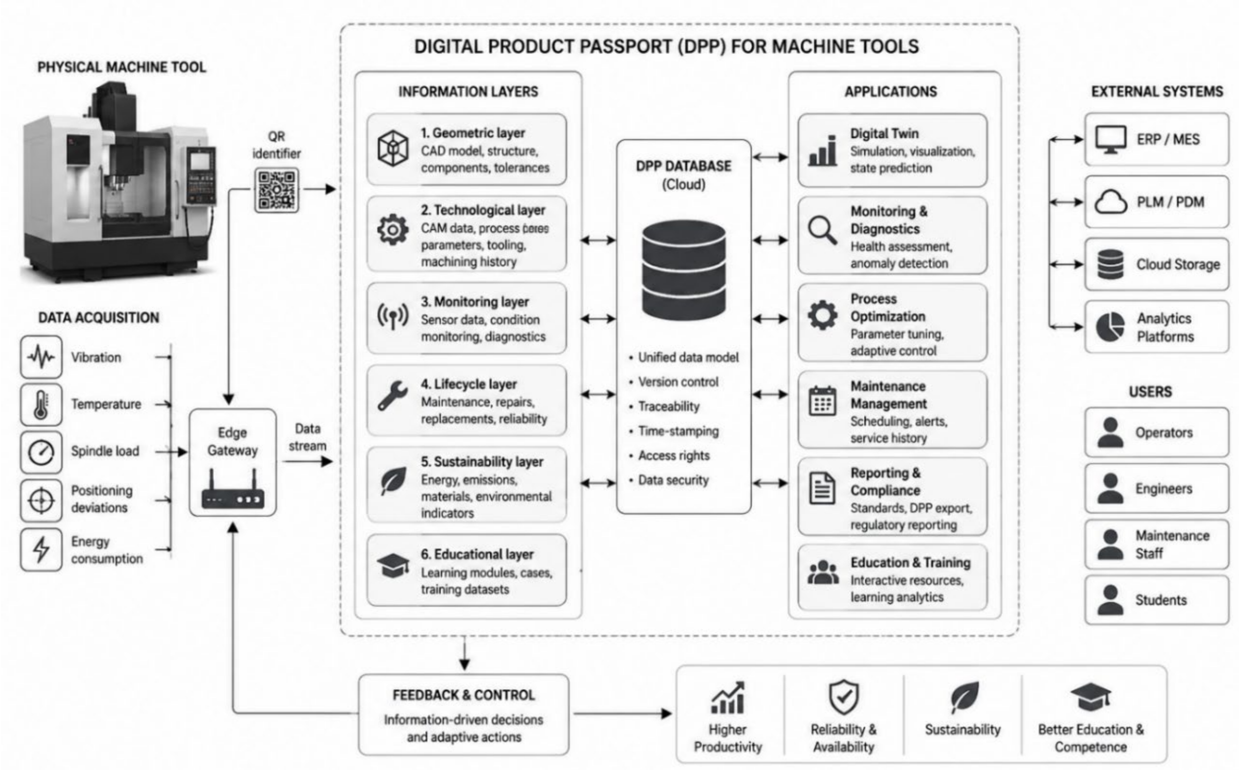

Figure 1. Conceptual structure of the Digital Product Passport for machine tools

The machine tool operates as an information-transforming system in which the technological state evolves depending on external process conditions and internal degradation mechanisms:

$$\frac{dS(t)}{dt} = F\big(P(t), L(t), W(t), U(t)\big), \qquad (2)$$

where: *L(t)* – operational loading conditions; *W(t)* – wear and degradation parameters; *U(t)* – control and adaptation actions.

The information update mechanism of the DPP is represented as:

$$I_{k+1} = I_k + \Delta I_k, \qquad (3)$$

where: I_k – current information state of the passport; ΔI_k – newly acquired technological or diagnostic information.
This approach enables continuous synchronization between the physical machine tool and its digital representation.

2.3. Digital integration structure

The proposed Digital Product Passport framework is based on the integration of several interconnected digital layers forming a unified information ecosystem for machine tools. The general structure of the proposed integration model is presented in Fig. 2.

At the geometric level, the system incorporates CAD models, assembly structures, tolerance information, and machine configuration parameters. This layer forms the primary digital representation of the machine tool and provides the basis for further technological and operational data integration. The technological layer includes CAM strategies, cutting parameters, tooling configurations, machining history, and process optimization data associated with manufacturing operations and adaptive technological control.

The monitoring layer is responsible for continuous acquisition and processing of operational information generated during machine functioning. This includes sensor signals, vibration behavior, thermal field distribution, spindle condition, positioning deviations, and energy consumption indicators. The integration of monitoring data into the Digital Product Passport enables continuous synchronization between the physical machine state and its digital representation.

An additional information layer is associated with lifecycle management. This layer accumulates maintenance history, repair documentation, component replacement records, operational reliability indicators, and service-related information. Such integration allows the Digital Product Passport to support predictive maintenance strategies and improve technological sustainability of manufacturing systems.

A separate educational layer is introduced within the proposed framework to support engineering training under Industry 5.0 conditions. This layer integrates interactive engineering datasets, Digital Twin technologies, technological case studies, and educational scenarios for engineering students. Within the MechDiTS project framework, the Digital Product Passport is therefore considered not only as an industrial information environment but also as a digital educational platform for training future engineers.

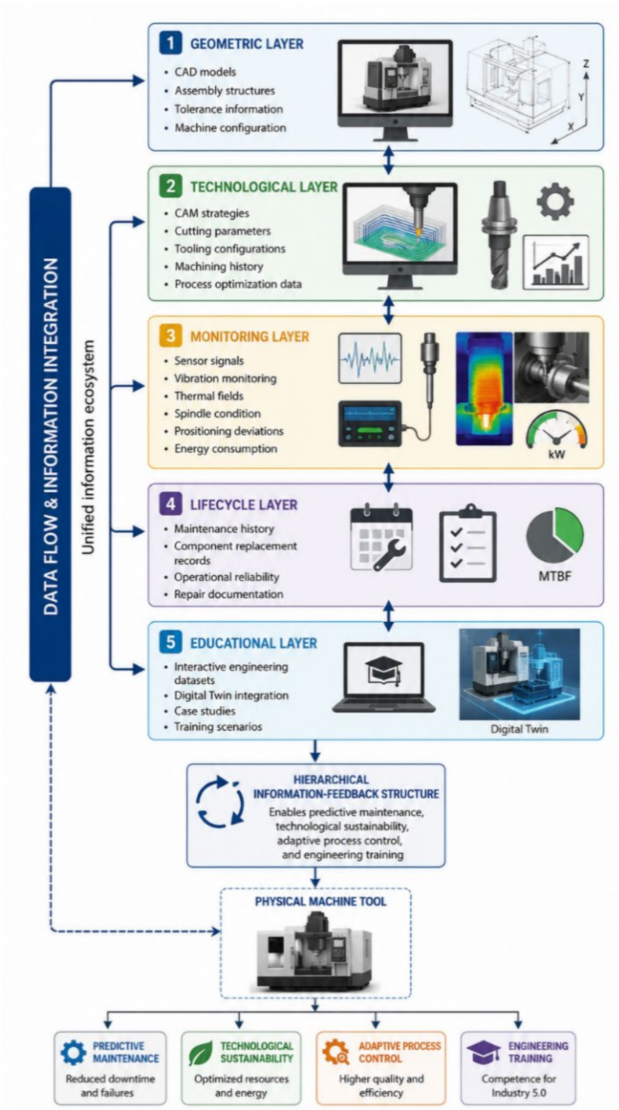

Figure 2. Digital integration structure of the Digital Product Passport for machine tools

The interaction between all digital layers forms a hierarchical information-feedback structure capable of supporting adaptive process control, predictive diagnostics, lifecycle optimization, technological sustainability, and data-driven engineering decision-making. The proposed integration structure also simplifies interaction between machine tools, cloud-oriented information systems, enterprise platforms, and educational digital environments.

2.4. QR-Based identification and information accessibility

To simplify interaction between physical equipment and digital information environments, the framework incorporates QR-based identification linked to cloud-oriented databases. Each machine tool module receives a unique digital identifier associated with the corresponding DPP dataset.

The QR-linked information environment provides access to (Fig.3):

- operational documentation;
- Digital Twin models;
- maintenance schedules;
- sensor monitoring dashboards;
- technological process history;
- sustainability indicators;
- engineering educational materials.

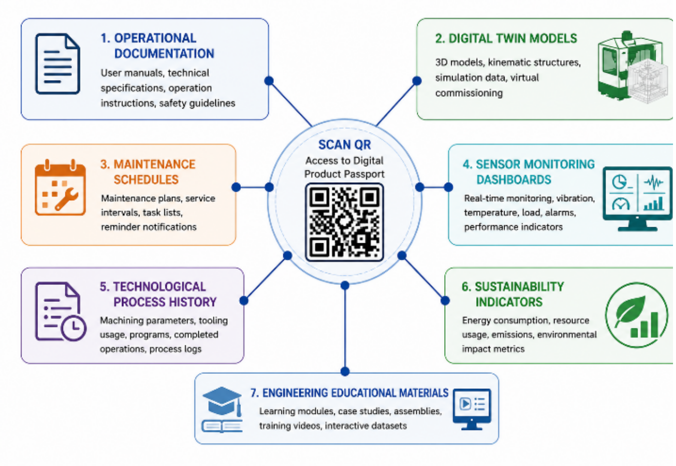

Figure 3. QR-linked information environment of the Digital Product Passport for machine tools

Such an approach significantly simplifies information accessibility for operators, engineers, maintenance personnel, and students within educational and industrial environments.

2.5. Educational Implementation within MechDiTS

Within the Erasmus+ project "Digital Transformation of Mechanical Engineering for Technological Sustainability" (MechDiTS) (Grant Agreement No: 101241157), the proposed Digital Product Passport architecture is additionally considered as an educational platform for training future mechanical engineers under Industry 5.0 conditions. The conceptual structure of the educational implementation is presented in Fig. 4.

The proposed approach integrates industrial engineering data, Digital Twin technologies, lifecycle-oriented information, monitoring systems, and cloud-based digital environments into the educational process.

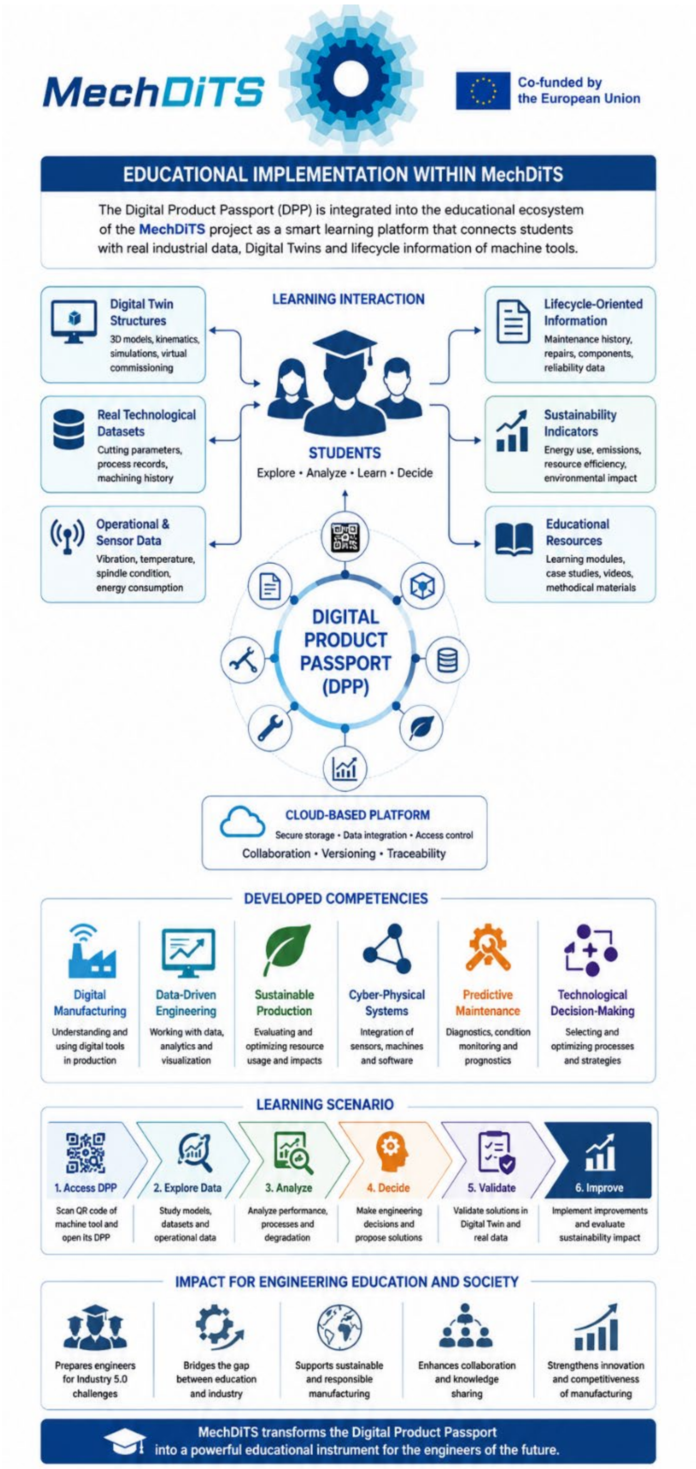

Figure 4. Educational implementation of the Digital Product Passport within the MechDiTS framework

Unlike traditional engineering training methods focused primarily on theoretical knowledge and isolated technological operations, the proposed framework enables students to interact with real manufacturing information generated during the operation of machine tools and digital manufacturing systems.

Within the educational environment, students obtain access to Digital Product Passport datasets associated with machine configuration, technological process parameters, operational conditions, maintenance history, sensor monitoring information, and sustainability indicators. Such integration creates conditions for developing practical competencies in data-driven engineering, digital manufacturing, predictive maintenance, cyber-physical systems, and adaptive technological decision-making.

The proposed educational model also supports interaction with Digital Twin structures, simulation environments, and technological case studies based on real industrial scenarios. Students can analyze operational data, investigate machine degradation processes, evaluate technological efficiency, and participate in engineering optimization tasks using integrated digital information environments.

An important feature of the proposed framework is the integration of QR-linked access mechanisms simplifying interaction between physical machine tools and educational digital platforms. Through QR-based identification, students can obtain direct access to technological documentation, monitoring dashboards, engineering datasets, and Digital Twin models within a unified cloud-oriented information ecosystem.

The interaction between educational modules, industrial information flows, and digital manufacturing technologies forms a hierarchical educational-information structure supporting competency-oriented engineering education. In this context, the Digital Product Passport becomes not only a technological information system but also a practical educational instrument bridging the gap between engineering training and modern industrial requirements.

The proposed approach corresponds to current European educational strategies aimed at integrating sustainability, digitalization, and Industry 5.0 principles into engineering curricula. Therefore, the MechDiTS framework demonstrates the potential of Digital Product Passports as a foundation for developing modern educational ecosystems for sustainable manufacturing engineering.

3. Results and Discussion

3.1. Formation of the digital product passport structure for machine tools

The conducted research demonstrated that the Digital Product Passport for machine tools should be considered not as a static repository of technical documentation, but as a dynamically evolving information environment integrating technological, operational, diagnostic, and educational data throughout the entire machine lifecycle. The proposed framework transforms the machine tool into an information-centric cyber-physical system capable of continuous interaction with digital manufacturing ecosystems.

The developed DPP structure integrates several interconnected information domains. At the geometric level, the system accumulates digital engineering data associated with CAD assemblies, machine configuration, tolerance structures, and kinematic schemes. This information forms the basis for synchronization with technological and operational layers of the passport.

A practical implementation example of the proposed DPP-linked engineering ecosystem for machine tools is presented in Fig. 5. At the technological level, the Digital Product Passport continuously stores and updates machining parameters, CAM strategies, tooling configurations, machining history, adaptive process corrections, and optimization results. The integration of such information enables the creation of traceable technological chains connecting machine configuration, processing conditions, and product quality indicators.

An important feature of the proposed framework is the integration of monitoring and diagnostic information generated directly during machine operation. Real-time sensor data, spindle loading, thermal conditions, vibration behavior, energy consumption, and positioning deviations become part of the continuously updated digital information structure. Such integration allows the Digital Product Passport to operate as a dynamic monitoring environment supporting predictive maintenance and adaptive technological decision-making.

The proposed approach also introduces lifecycle-oriented information integration. Maintenance schedules, repair history, component replacement records, operational reliability indicators, and service documentation are accumulated within a unified digital structure. As a result, the DPP supports not only operational control but also long-term technological sustainability of manufacturing systems.

As shown in Fig. 5, the proposed Digital Product Passport integrates several engineering information domains, including CAD models of the machine tool and its functional components, Digital Twin structures, operational monitoring dashboards, Alicona-based surface characterization, cloud-oriented data management, and QR-linked access to engineering information. Such integration enables continuous synchronization between physical manufacturing equipment and digital lifecycle environments.

The interaction between the integrated information layers forms a hierarchical information-feedback structure connecting physical machine states with digital engineering environments. This interaction can be represented as a closed information cycle:

$$G(t) \to P(t) \to S(t) \to D(t) \to U(t) \to G(t+1), \quad (4)$$

where geometric information $G(t)$ influences technological parameters $P(t)$, which determine operational machine states $S(t)$. Monitoring and diagnostic information $D(t)$ forms the basis for adaptive control actions $U(t)$, leading to updated engineering and technological configurations $G(t+1)$.

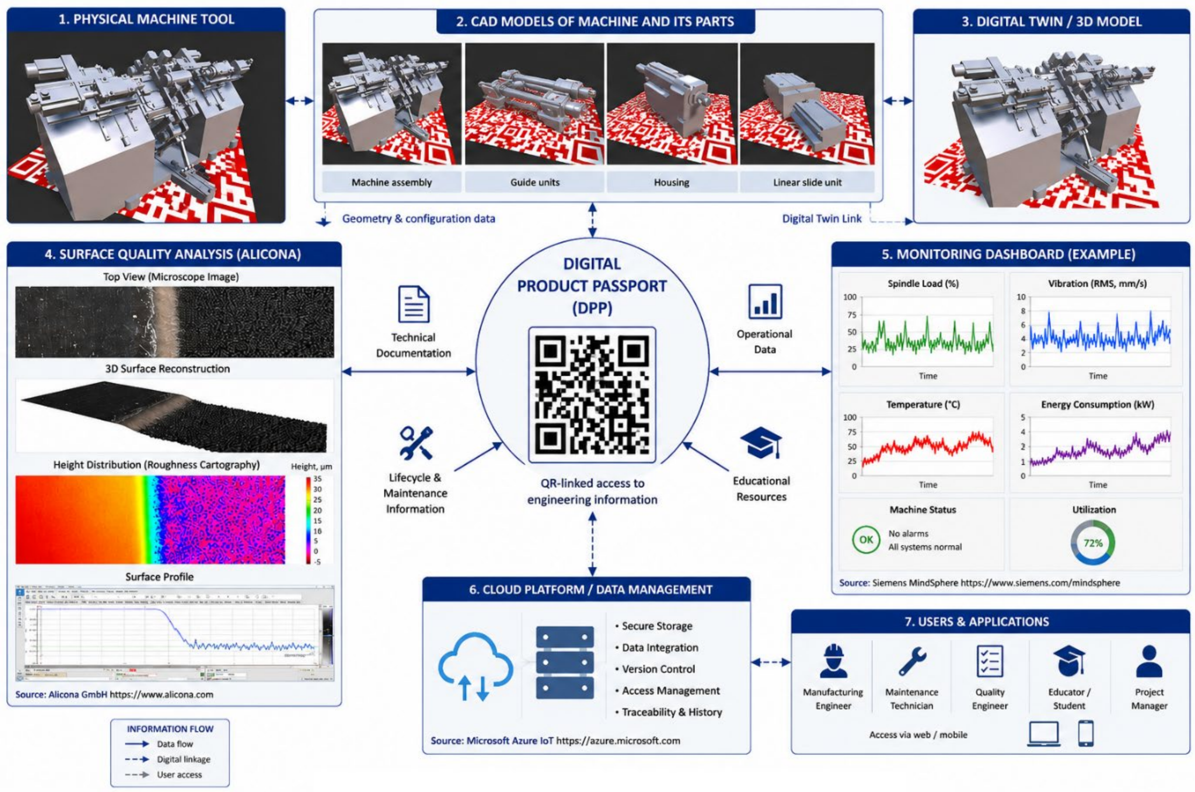

Figure 5. DPP-linked engineering information ecosystem for machine tools

The obtained results demonstrate that the proposed Digital Product Passport structure enables continuous synchronization between physical manufacturing systems and digital engineering environments. In contrast to conventional documentation approaches, the developed framework supports adaptive information updating, predictive diagnostics, and lifecycle-oriented manufacturing management. Furthermore, the proposed DPP architecture demonstrates significant educational potential within Industry 5.0 engineering training environments. The integration of real technological datasets, monitoring information, Digital Twin structures, and lifecycle-oriented engineering data allows students to interact with realistic manufacturing scenarios and develop competencies associated with sustainable digital manufacturing systems.

The obtained results confirm that the Digital Product Passport can be considered a key information component of future sustainable manufacturing systems integrating production, diagnostics, lifecycle management, and engineering education into a unified digital ecosystem.

3.2. Practical implementation and educational integration

The practical implementation of the proposed Digital Product Passport (DPP) architecture was performed using an integrated machine-tool-oriented engineering ecosystem combining QR-linked identification, CAD structures, Digital Twin elements, technological monitoring, and high-resolution surface metrology. A practical realization of the proposed information environment is presented in Fig. 5. Unlike conventional documentation systems, the developed approach establishes continuous synchronization between the physical machine tool, technological process data, operational monitoring information, and digital lifecycle environments. The developed DPP ecosystem integrates several interconnected engineering domains, including geometric models of the machine tool and its functional modules, operational dashboards, cloud-oriented data exchange, surface characterization results, and educational engineering datasets. Special attention was devoted to maintaining traceability between the physical object and its digital representation during all stages of the machine lifecycle. In this case, engineering information becomes continuously accessible, dynamically updated, and interconnected within a unified digital manufacturing environment. QR technologies within the proposed framework perform not only identification functions but also operate as interactive gateways to distributed engineering information systems. The QR-linked information interaction structure used within the proposed DPP ecosystem is illustrated in Fig. 6. Through QR-based access mechanisms, engineers, operators, and students can obtain real-time access to technological documentation, machine configuration parameters, maintenance history, Digital Twin structures, operational monitoring dashboards, and lifecycle-oriented datasets.

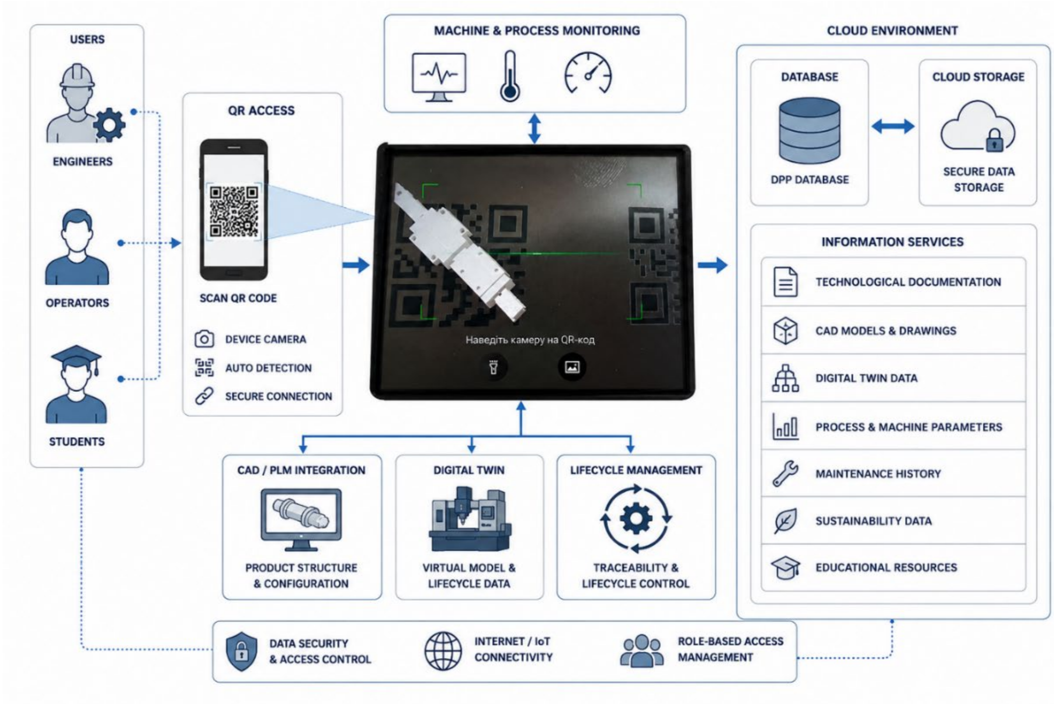

Figure 6. QR-linked access architecture of the Digital Product Passport environment for machine tools integrating lifecycle management, Digital Twin data, monitoring systems, and educational engineering resources

Such integration significantly reduces information fragmentation inside manufacturing systems and simplifies interaction between physical equipment and cloud-based engineering environments.

A key component of the developed implementation is the integration of optical surface metrology into the DPP structure. High-resolution measurements obtained using the Alicona InfiniteFocus G5 system were incorporated into the digital information environment as engineering descriptors of processed surfaces and machine-readable structures. Representative examples of the generated microrelief structures and Alicona-based surface topography measurements integrated into the DPP environment are presented in Fig. 7. The performed femtosecond laser texturing experiments confirmed the possibility of forming stable micro- and submicrorelief structures with high optical absorbance and reliable QR-code readability under complex operational conditions.

The integration of surface metrology into the Digital Product Passport enables not only visualization of geometric characteristics but also quantitative engineering analysis of surface functionality, processing repeatability, and technological quality. The principal surface metrology parameters integrated into the DPP database for engineering-quality evaluation are summarized in Table 1. Parameters such as *Sa*, *Sq*, *Sz*, and *Sdr* provide additional information regarding surface morphology, effective interaction area, and stability of machine-readable structures. As a result, the DPP environment can support engineering verification procedures, technological traceability, predictive maintenance strategies, and adaptive manufacturing decision-making.

The obtained quantitative parameters confirm the possibility of integrating high-resolution surface metrology into the Digital Product Passport environment for engineering traceability, technological verification, and lifecycle-oriented quality assessment. An important feature of the proposed framework is the direct integration of industrial engineering datasets into the educational process within the Erasmus+ MechDiTS project. The educational implementation of the proposed approach is presented in Fig. 4. In contrast to traditional engineering education focused mainly on isolated CAD exercises or theoretical process descriptions, the developed methodology enables students to interact with real industrial information ecosystems integrating Digital Twins, technological monitoring, surface metrology, lifecycle management, and sustainability-oriented engineering analysis.

Within the proposed educational environment, students gain access to real machine-tool datasets, Digital Product Passport structures, technological process histories, and monitoring information generated during manufacturing operations. Such integration supports the development of competencies associated with Industry 5.0 manufacturing systems, including cyber-physical integration, data-driven engineering, sustainable manufacturing, predictive maintenance, and adaptive technological decision-making.

The proposed implementation demonstrates that the Digital Product Passport can simultaneously operate as a technological management instrument, a lifecycle-oriented traceability platform, and an educational engineering ecosystem supporting the preparation of specialists for modern digitally integrated manufacturing systems.

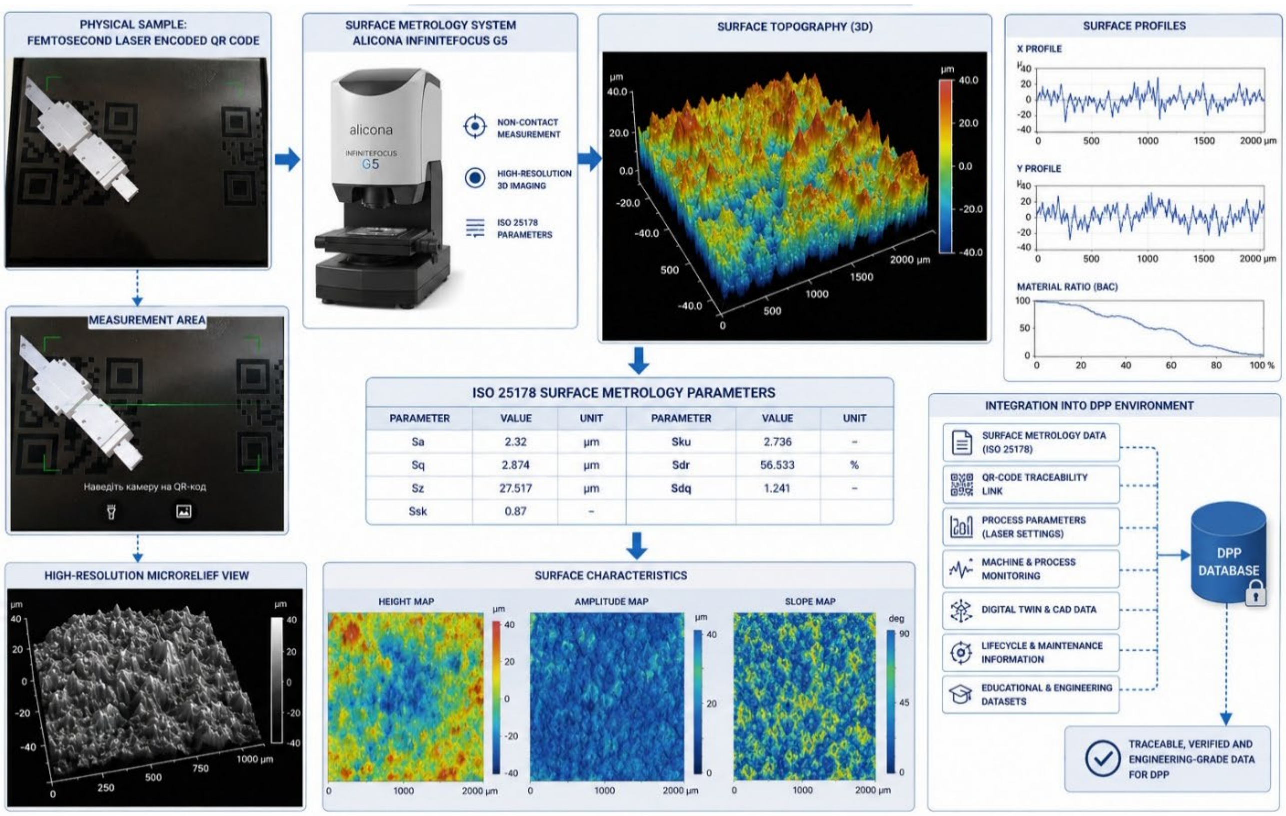

Figure 7. Physical validation of QR-linked surface structures and Digital Product Passport integration using Alicona InfiniteFocus G5 surface metrology and ISO 25178 parameters

Table 1. Surface metrology parameters integrated into the DPP database for engineering-quality evaluation and QR-code traceability assessment based on Alicona InfiniteFocus G5 measurements according to ISO 25178

Parameter	Value	Unit	Engineering significance within the DPP environment
Sa	2.32	µm	Average surface roughness confirming the formation of a stable and uniform microtexture suitable for high-contrast QR structures
Sq	2.874	µm	Root mean square roughness indicating statistical stability of the generated microrelief
Sz	27.517	µm	Maximum surface height range ensuring efficient light scattering and optical contrast
Ssk	0.87	–	Positive skewness indicating predominance of peaks typical for femtosecond laser-modified surfaces
Sku	2.736	–	Kurtosis coefficient confirming relatively uniform height distribution without extreme sharp peaks
Sdr	56.533	%	Developed interfacial area ratio demonstrating significant increase in effective surface area responsible for enhanced optical absorption and QR readability
Sdq	1.241	–	Root mean square gradient confirming the presence of steep microrelief slopes contributing to light trapping effects
Laser wavelength (λ)	1030	nm	Infrared femtosecond laser radiation used for controlled surface modification
Pulse duration (τ)	270	fs	Ultrashort pulse duration minimizing thermal influence on surrounding material

Pulse repetition rate (f)	200	kHz	Stable operational regime ensuring homogeneous QR-code formation
Pulse energy (E_{pulse})	25–80	µJ	Controlled energy range providing stable surface darkening without local melting
Spot diameter (d)	≈20	µm	High spatial resolution enabling accurate contour formation of QR elements

3.3. Discussion

The obtained results demonstrate that the Digital Product Passport should not be considered merely as a digital identification mechanism or documentation repository. Within modern Industry 5.0 manufacturing systems, the DPP becomes a dynamic engineering-information environment integrating geometry, technological processes, operational monitoring, lifecycle management, and educational interaction into a unified digital ecosystem.

One of the principal advantages of the proposed framework lies in the establishment of continuous traceability between the physical object and its digital representation. The integration of QR-linked identification, Digital Twin technologies, cloud-oriented information systems, and high-resolution surface metrology enables real-time synchronization of engineering information during all lifecycle stages of the machine tool. In contrast to conventional static documentation approaches, the developed system supports adaptive information updating, technological verification, predictive diagnostics, and distributed engineering decision-making.

The performed Alicona-based validation confirmed the possibility of integrating engineering-grade surface metrology data into the Digital Product Passport environment. The obtained ISO 25178 parameters demonstrated the formation of stable microrelief structures suitable for reliable machine-readable marking and optical information reproduction. Such integration significantly extends the functionality of the DPP from simple product identification toward engineering-quality assessment and lifecycle-oriented technological control.

An important aspect of the proposed approach is its educational applicability within the Erasmus+ MechDiTS framework. The developed DPP architecture enables students to interact with real industrial datasets, Digital Twin structures, monitoring systems, and technological traceability environments. As a result, engineering education becomes directly connected with modern industrial information ecosystems rather than remaining limited to isolated theoretical or CAD-oriented training tasks.The proposed methodology also corresponds to current European digitalization strategies associated with sustainable manufacturing, cyber-physical systems, and data-driven engineering. In particular, the integration of lifecycle-oriented information management, predictive maintenance principles, and engineering traceability mechanisms supports the transition toward resilient and sustainable manufacturing environments required by future Industry 5.0 production systems.

Despite the advantages of the proposed framework, several challenges remain associated with standardization of DPP architectures, interoperability between industrial platforms, cybersecurity of distributed engineering data, and integration of heterogeneous monitoring systems. Future research should therefore focus on cloud-oriented interoperability standards, AI-assisted engineering analytics, adaptive Digital Twin synchronization, and automated lifecycle-oriented decision-support systems for machine tools and manufacturing equipment.

Particular attention should additionally be devoted to interoperability between heterogeneous industrial platforms and engineering software environments. The integration of Digital Product Passports into large-scale manufacturing ecosystems requires standardized information exchange mechanisms capable of supporting interaction between CAD/CAM/CAE systems, PLM platforms, monitoring infrastructures, and cloud-oriented Digital Twin environments.

An important challenge is also associated with cybersecurity and protection of distributed engineering data within cloud-based manufacturing systems. As Digital Product Passports increasingly integrate operational monitoring, lifecycle information, and predictive maintenance data, secure access management and engineering data protection become critical requirements for industrial implementation.

The scalability of the proposed framework for large manufacturing enterprises and distributed production systems also requires further investigation. Future developments should address adaptive cloud architectures and distributed information management strategies capable of supporting large volumes of engineering and monitoring data generated by complex manufacturing infrastructures.

4. Conclusions

A Digital Product Passport architecture for machine tools integrating QR-linked traceability, Digital Twin technologies, cloud-oriented engineering information systems, lifecycle management, and high-resolution surface metrology was developed. The proposed framework enables continuous synchronization between physical manufacturing equipment and digital engineering environments throughout the entire operational lifecycle.

The practical implementation demonstrated the possibility of integrating Alicona InfiniteFocus G5 surface metrology data and ISO 25178 parameters into the DPP environment for engineering-quality evaluation, technological verification, and machine-readable traceability. The obtained results confirmed the formation of stable microrelief structures suitable for reliable QR-code readability and lifecycle-oriented information integration.

The developed approach additionally demonstrated significant educational potential within the Erasmus+ MechDiTS project. The integration of Digital Product Passports into engineering education enables students to interact with real industrial datasets, Digital Twins, monitoring systems, and technological traceability environments, supporting the development of competencies associated with Industry 5.0 manufacturing systems.

The proposed framework can therefore be considered not only as a technological information system for sustainable manufacturing but also as a modern educational platform supporting the preparation of future engineers for digitally integrated industrial ecosystems.

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