OBJECTIVES, CHALLENGES AND SOLUTIONS FOR DIGITAL PAVEMENT MANAGEMENT OF TRANSPORT INFRASTRUCTURE

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Abstract: *The sustainable preservation of road infrastructure requires a consistent, data-driven pavement management approach integrating technical, economic, and organizational aspects. This paper discusses key objectives, challenges, and solutions for digital pavement management at network level. Major challenges include heterogeneous data sources, long-term data availability, evolving regulations, and the demand for transparent and reproducible decision-making. The presented approach combines high-resolution pavement condition data, standardized referencing systems, comprehensive quality assurance, and performance-based prediction models within a unified digital framework. By systematically transforming raw measurement data into validated condition indicators and maintenance strategies, digital pavement management enables preventive maintenance, optimized allocation of financial resources, and improved acceptance among decision-makers and road users. Modern web-based pavement management systems support strategic, tactical, and operational planning while ensuring data consistency and adaptability over the full lifecycle of pavement assets.*

Keywords: *Digital Asset Management, Pavement Management Systems, Infrastructure Preservation, Condition Assessment, Maintenance Planning*

1. INTRODUCTION

The sustainable management of transport infrastructure is a major challenge for public authorities worldwide. Aging road networks, increasing traffic loads, and limited financial resources require a transition from reactive maintenance towards data-driven, preventive strategies. At the same time, expectations regarding transparency, accountability, and sustainability are continuously increasing.

Digital pavement management systems (PMS) provide a framework to address these challenges by integrating condition data, performance models, and decision-support mechanisms. However, the implementation of such systems is often hindered by heterogeneous data sources, inconsistent data quality, and limited institutional capacities.

This paper presents a comprehensive approach to digital pavement management that integrates advanced data acquisition, standardized evaluation methods, and learning-based system concepts. It combines methodological, technical, and organizational perspectives to support strategic, tactical, and operational decision-making across different infrastructure contexts.

2. Background and Conceptual Framework

Pavement management is not an isolated technical task but part of a broader asset management framework that aims to ensure the long-term performance, value retention, and functionality of infrastructure assets. Road infrastructure represents one of the most valuable public assets in many countries, and its management requires systematic and transparent decision-making processes that consider technical, economic, and organizational aspects over the entire lifecycle.

Modern infrastructure management is therefore increasingly based on asset management principles as defined in the ISO 55000 series. ISO 55001 specifies requirements for asset management systems and emphasizes a structured management approach that links organizational objectives with asset-related decisions. The standard highlights the importance of lifecycle thinking, risk management, performance monitoring, and continuous improvement. In this context, pavement management can be understood as a technical core component within a broader asset management system, providing the data, models, and decision-support tools necessary to manage pavement assets in a systematic and objective manner.

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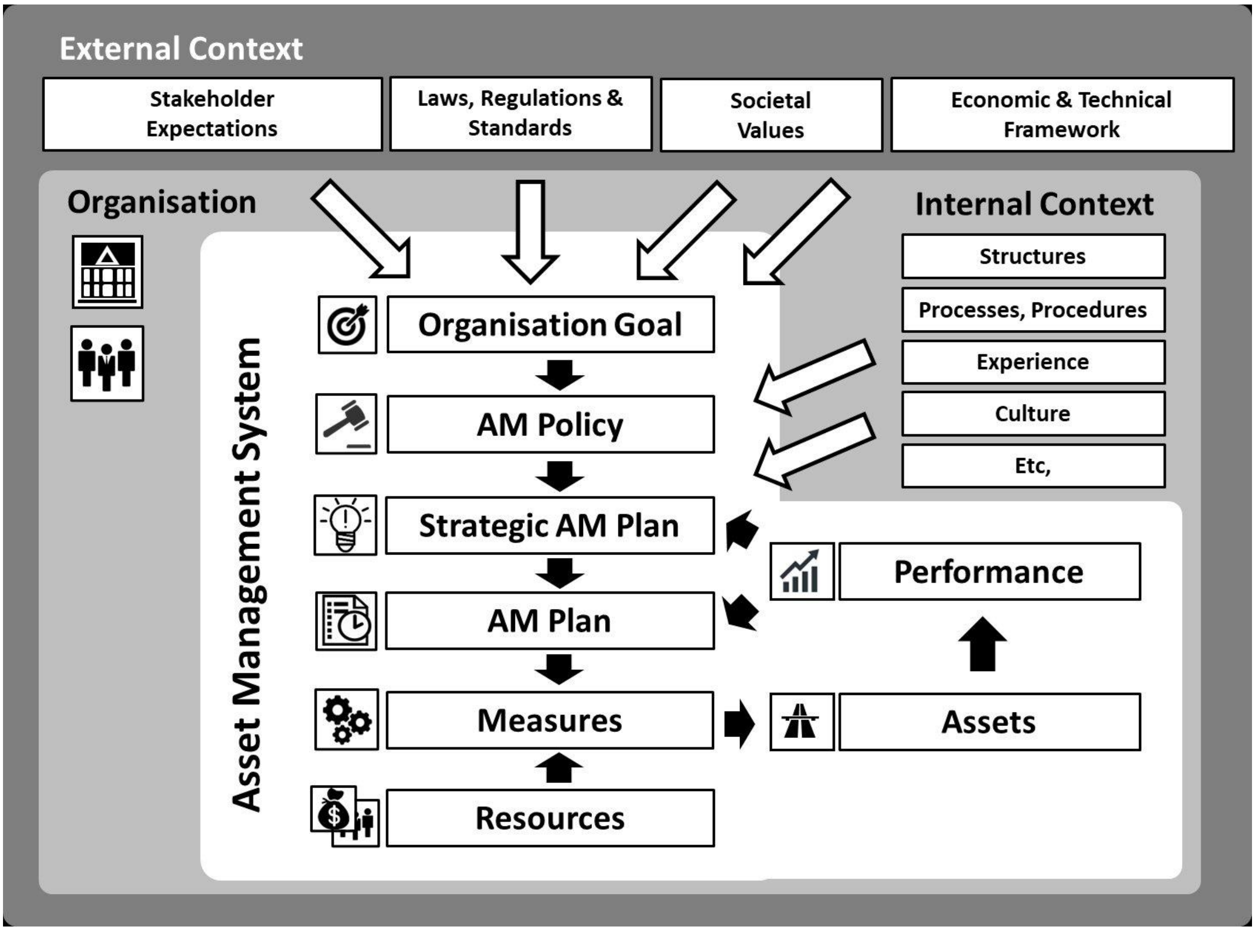

Figure 1: Organisation, context and asset management system (Source: BALCK, adapted from ISO 55001)

A key principle of asset management according to ISO 55001 is the alignment between organizational objectives, asset performance, and financial planning. This requires a clear understanding of how maintenance decisions influence long-term asset performance, lifecycle costs, and service levels. Pavement management systems play a central role in this process, as they provide the analytical basis for predicting pavement performance, identifying maintenance needs, and evaluating different intervention strategies.
The conceptual framework of modern pavement management can be described as a transformation process from data to decision support. This process begins with data acquisition and continues through condition assessment, performance modelling, and the evaluation of maintenance strategies. The objective is not only to describe the current condition of infrastructure but also to support informed decisions regarding future investments and maintenance strategies. In this context, pavement management serves as a decision-support system that connects technical condition data with economic and strategic considerations.

From a system perspective, pavement management operates at the interface between engineering and management. On the one hand, it relies on engineering methods for condition assessment, performance modelling, and maintenance design. On the other hand, it supports management processes such as budget planning, prioritization, and performance monitoring. This interdisciplinary nature makes pavement management a key element of infrastructure asset management systems.

Another important aspect is the relationship between costs and benefits over the lifecycle of infrastructure assets. Maintenance decisions taken today have long-term consequences for future costs and network performance. Delayed maintenance may reduce short-term expenditures but often leads to significantly higher lifecycle costs due to accelerated deterioration. Asset management therefore aims to optimize maintenance strategies not only from a technical perspective but also from an economic and societal perspective.
In recent years, digitalization has significantly expanded the possibilities of pavement and asset management. Large volumes of condition data can now be collected, stored, and analyzed over long periods. This enables a more detailed understanding of pavement performance and supports the development of data-driven decision models. As a result, pavement management systems are evolving from simple data repositories to

comprehensive decision-support platforms that integrate technical data, financial information, and strategic planning processes.

Within this framework, pavement management can be understood as a structured process consisting of several core elements:

- Asset inventory and referencing
- Condition assessment
- Performance prediction
- Maintenance planning and prioritization
- Budget allocation and program development
- Monitoring and feedback

These elements form a continuous management cycle in which decisions are regularly reviewed and adjusted based on observed performance. This feedback loop is a central component of modern asset management systems and supports continuous improvement and long-term optimization of infrastructure management strategies.

In summary, pavement management is a key technical component of infrastructure asset management and provides the analytical and methodological foundation for sustainable and transparent decision-making. By integrating engineering data, economic considerations, and organizational objectives, modern pavement management systems support the implementation of asset management principles as defined in international standards such as ISO 55001.

3. Challenges in Digital Pavement Management

The implementation of digital pavement management must be understood not only as a technical task but as part of a broader asset management framework. The main challenges therefore arise at the interface between data, engineering methods, organizational processes, and decision-making structures. Digital pavement management systems are expected to transform large volumes of heterogeneous data into reliable decision support, while ensuring transparency, long-term consistency, and adaptability to changing requirements.

One of the fundamental challenges is the integration of heterogeneous data sources. Pavement management relies on various types of data, including condition measurements, traffic information, construction history, maintenance records, and environmental data. These datasets differ in structure, spatial reference, temporal resolution, and accuracy. Integrating such data into a consistent and usable system environment requires standardized referencing systems, data models, and interfaces. Without a consistent data structure, the transformation of data into information and knowledge becomes difficult, limiting the effectiveness of decision-support processes.

Another major challenge is long-term data management. Pavement management is inherently a long-term process, as infrastructure assets have lifecycles spanning several decades. Decision-making therefore depends on the availability of historical data and the ability to analyze long-term performance trends. This requires reliable data storage, historization, and data governance strategies to ensure that information remains accessible and interpretable over long periods. The long-term usability of data is particularly important in asset management, where decisions must be evaluated not only based on current conditions but also on expected future performance.

A further challenge arises from changing standards, regulations, and evaluation methods. Condition assessment procedures and threshold values are not static but evolve over time due to technological progress and changing requirements. For this reason, it is essential to store raw data in addition to aggregated condition indicators. Only the availability of raw data allows the recalculation of condition indices and ensures the long-term comparability of condition data. This aspect is particularly important in asset management systems, where consistency and comparability over long time periods are essential for strategic decision-making.

Data quality and reproducibility represent another critical challenge. Reliable predictions of pavement performance depend on accurate and consistent input data. Variations in data collection methods, evaluation procedures, or data processing can lead to inconsistent results and reduce the reliability of performance models. Standardized procedures for data collection, processing, and evaluation are therefore essential to ensure reproducibility and comparability of results. In the context of asset management, data quality directly influences the quality of decisions and therefore the long-term performance of infrastructure assets.

Finally, transparency and acceptance of decision-making processes represent an important organizational challenge. Maintenance decisions in infrastructure management often involve significant financial resources and must therefore be transparent and justifiable. Digital pavement management systems must provide traceable and reproducible decision processes that allow decision-makers to understand how priorities and maintenance programs are derived. Transparent procedures increase trust in the system and improve communication between technical experts, financial planners, and political decision-makers.

In summary, the challenges of digital pavement management are not limited to data collection or software implementation. They arise from the need to integrate data, models, and organizational decision processes into a consistent and long-term asset management framework. Addressing these challenges requires not only technological solutions but also standardized procedures, clear data governance strategies, and transparent decision-making processes.

4. Methodology: From Data to Decision

The methodological framework of digital pavement management can be described as a structured transformation process in which raw data is systematically converted into information, knowledge, and decision support. This process forms the analytical core of pavement management within the broader asset management framework and connects engineering data with strategic and financial decision-making.

The process begins with the acquisition of infrastructure and condition data using modern measurement and data collection technologies. These technologies provide detailed information about pavement condition, including surface characteristics, evenness, and functional properties. However, the acquisition of data alone does not create value. The primary objective is the transformation of raw data into decision-relevant information. A consistent spatial and temporal referencing system is therefore essential to ensure that different datasets can be integrated and analyzed over time. Referencing systems form the backbone of pavement management, as they enable the linkage of condition data, construction history, traffic data, and maintenance measures within a unified asset framework.

Following data acquisition, raw data is processed and transformed into condition indicators that describe the structural and functional state of the pavement. These indicators are typically aggregated into section-based condition values that provide a standardized representation of network condition. The aggregation process is necessary to transform highly detailed measurement data into manageable information for network-level decision-making. At the same time, the storage of raw data remains essential, as it ensures the long-term usability of the data and allows recalculation of condition indicators when assessment methods or standards change.

Based on condition assessment, performance models are applied to describe and predict the future development of pavement condition. Pavement deterioration is influenced by multiple interacting factors, including traffic loading, environmental conditions, material properties, and construction quality. Due to this complexity, pavement performance cannot be described by purely deterministic models alone. Instead, empirical and data-driven approaches based on observed condition development across the network provide a robust basis for large-scale applications. Performance modelling therefore represents a central element of pavement management, as it enables the evaluation of long-term consequences of maintenance decisions.

The next step in the methodological framework is the determination of maintenance needs. This step combines current condition information with predicted performance development to identify sections where intervention is required. Intervention thresholds and performance indicators are used to determine the optimal timing of maintenance measures. The objective is to identify the point in time at which maintenance interventions are technically effective and economically efficient.

Once maintenance needs have been identified, prioritization and program development are carried out under budget constraints. Since available financial resources are typically limited, not all technically necessary measures can be implemented immediately. Pavement management therefore includes prioritization methods that consider technical condition, deterioration rate, traffic importance, and economic efficiency. Decision-support tools are used to analyze different budget scenarios and to determine optimized maintenance programs.

From a methodological perspective, this entire process can be described as a continuous management cycle rather than a linear workflow. The results of implemented maintenance measures influence future pavement performance and therefore provide new data for performance modelling and decision-making. This feedback loop transforms pavement management from a purely descriptive system into a learning system that continuously improves based on observed infrastructure performance.

In summary, the methodology of digital pavement management consists of a structured process that includes data acquisition, condition assessment, performance modelling, maintenance planning, and decision support. The main objective of this process is not only to describe the current condition of infrastructure but to support transparent, reproducible, and economically efficient decision-making within an asset management framework.

5. Digital Implementation and Web-Based Application

The implementation of pavement management within an asset management framework according to ISO 55001 requires not only methodological procedures but also an appropriate digital system environment. Asset management systems must ensure that data, models, decision processes, and organizational workflows are consistently linked and accessible to different stakeholders. Digital pavement management systems therefore represent not only data storage tools but integrated decision-support platforms within an infrastructure asset management system.

From the perspective of ISO 55001, several functional requirements can be derived for digital systems used in infrastructure asset management. These include the management of asset inventory and condition data, lifecycle planning, performance monitoring, financial planning support, documentation of interventions, and the provision of information for decision-makers at different organizational levels. A digital system must therefore be capable of linking technical data with management processes and strategic objectives.

A fundamental requirement is the consistent referencing of all data to the infrastructure network. By linking condition data, maintenance measures, construction history, and structural information to a common network reference system, the infrastructure can be analyzed as a coherent asset system. This enables the evaluation of network condition, the analysis of condition development over time, the prediction of future performance, and the determination of maintenance demand. Furthermore, such a data structure allows the evaluation of whether financial resources are used efficiently and whether defined performance targets can be achieved.

Based on this integrated data environment, digital systems must support decision-making processes at different management levels. At the strategic level, the system must provide key performance indicators and scenario analyses that allow decision-makers to evaluate the long-term development of network condition, maintenance demand, and financial requirements. Typical strategic questions include the current condition of the network, its development over time, future condition scenarios, required budgets to achieve defined performance targets, and the age structure of infrastructure assets. The provision of dashboards and standardized reports is essential to support communication between technical departments, financial planning units, and political decision-makers.

At the tactical level, digital pavement management systems must support the development of maintenance programs. This includes the identification of homogeneous sections, the calculation of condition indicators, the application of deterioration models, the definition of maintenance measures, and the prioritization of interventions under budget constraints. Scenario analyses and optimization procedures allow the development of multi-year maintenance programs and the evaluation of different budget strategies.

At the operational level, the system must support the documentation and monitoring of implemented measures, the management of inspection data, and the continuous updating of the database. Mobile data collection, damage documentation, and quality control processes can be integrated into the system environment, ensuring that new information is directly available for analysis and decision-making. This creates a continuous data and management cycle in which planning, implementation, and monitoring are digitally connected.

From a technical perspective, web-based applications offer significant advantages for such integrated asset management systems. Web-based architectures enable centralized data management while allowing distributed access for different users and organizations. This facilitates collaboration between administrative levels and departments, as all stakeholders work with the same data basis. In addition, web-based systems reduce the need for local software installations and simplify system maintenance and updates. Modern system architectures typically separate data storage, application logic, and user interfaces, which improves scalability, flexibility, and long-term maintainability of the system.

Another important requirement for digital asset management systems is interoperability. Infrastructure management involves multiple IT systems, including geographic information systems, databases, and financial management systems. Digital pavement management systems must therefore provide standardized interfaces that allow data exchange with existing IT environments. Open system architectures ensure that the digital system can be integrated into existing organizational processes and can evolve over time as new requirements emerge.

The described requirements for digital systems are not limited to theoretical considerations but have been implemented in various infrastructure management environments. In large urban road networks, digital pavement management systems are used to manage condition data, perform automated maintenance planning based on defined algorithms, and generate financial and demand forecasts. In higher-level road administrations, the focus is often on network-wide condition monitoring, program planning, controlling, and the provision of standardized information across the organization. These examples demonstrate that digital pavement management systems can support different organizational objectives while operating on a common data and system architecture.

Project Example 1: Infrastructure Asset Management Guidelines for the State of Bavaria

A first concrete example of embedding pavement management within a formal asset management framework is provided by the Infrastructure Asset Management Guidelines developed for the Free State of Bavaria (Degelmann, Heller, Korn 2018). The Bavarian road network encompasses approximately 23,000 kilometres of federal and state roads, representing a fixed asset value of around 40 billion euros. The guidelines were developed by HELLER Ingenieurgesellschaft mbH and ALFEN Consult GmbH on behalf of the Bavarian Road Construction Administration, with the purpose of translating the requirements of the ISO 55000 series into concrete processes and instruments applicable to the specific organisational and operational context of a state road authority.

The guidelines establish the formal organisational framework for asset management in line with ISO 55001: they define how organisational objectives are to be translated into an AM policy, a strategic AM plan, and asset-level AM plans, and specify the responsibilities, processes and performance criteria at each level of the road authority. A central finding was that asset management must be anchored at all levels of the organisation - from strategic leadership to operational staff - and must be supported by a clear mandate from senior management. The project also addressed cross-asset resource allocation across pavements, structures, equipment and information assets, establishing a governance framework for integrated, performance-oriented investment decisions (Degelmann, Heller, Korn 2018).

Project Example 2: Systematic Pavement Management in Baden-Württemberg

Where the Bavarian guidelines establish the formal framework, the state of Baden-Württemberg illustrates how such a framework is put into operational practice. As a major economic and transit hub in central Europe, the state relies on a well-maintained road network comprising approximately 4,200 km of federal roads and 10,000 km of state roads. Preserving this infrastructure for current and future generations - under conditions of increasing traffic loads and limited budgetary resources - constitutes the central challenge driving the development of a systematic, data-based pavement management approach (Hilpert, Balck, Epp 2022).

Data foundation and condition survey. The pavement management system is built on the standardised condition survey and assessment procedure (ZEB - Zustandserfassung und -bewertung), which has been applied in Baden-Württemberg since 2007 on a regular four-year survey cycle. Each campaign generates substantial volumes of data: for every lane-kilometre surveyed, approximately 400 environment images, 100 high-resolution surface images and 36,000 measurement points for longitudinal and transverse evenness are recorded, amounting to roughly 1.2 GB per lane-kilometre. The resulting condition data are referenced to the central road network model (TT-SIB) using linear referencing, enabling systematic cross-referencing with inventory data, traffic data, structure inspection results and maintenance project records across the entire network.

From data to decision-making. A key principle applied in Baden-Württemberg is that raw condition data alone do not constitute actionable information. To move from data to decision-relevant knowledge, the condition survey results are processed through the Improved Maintenance Planning method (VEP - Verbesserte

Erhaltungsplanung), developed by HELLER Ingenieurgesellschaft in collaboration with the Bavarian road authority in the late 1990s. The VEP aggregates the relatively short condition-rated pavement sections into longer maintenance sections with defined urgency rankings. This structured aggregation allows the regional construction authorities (Regierungspräsidien) to compile annual maintenance programmes that are transparent, reproducible and directly linked to the condition evidence. The approach directly reflects the asset management principle - as described in ISO 55000 - that information only generates real value for an organisation once it is actively integrated into decision-making processes at all levels.

Digital management platform. To make this information accessible and usable across all levels of the road authority, Baden-Württemberg has since 2009 deployed the web-based online visualisation platform OnKo, developed by HELLER Ingenieurgesellschaft. Following a major extension in 2021, developed jointly by the Ministry of Transport and HELLER, OnKo now serves as a comprehensive pavement management system providing five integrated views: map, route band, route image, table and statistics. The system integrates condition data from successive ZEB campaigns with inventory data, structure inspection results, traffic loading (DTV/SV), cross-section data and - critically - the history of completed construction measures. This cross-referencing of condition and maintenance project data since the 2011 campaign has enabled new insights into the actual effectiveness of maintenance works on network condition development, supporting both programme controlling and the refinement of maintenance strategies.

Multi-level information use and KPIs. The system supports all three decision levels of the road authority simultaneously. At the strategic level, aggregated condition data and budget-oriented maintenance forecasts inform financial and programme planning at the state level. At the tactical level, Key Performance Indicators (KPIs) derived from condition, traffic and inventory data enable controlling across the state, the regional presidia and the highway maintenance districts. At the operational level, staff in the regional construction authorities access detailed route band views, pavement condition profiles and road imagery directly online, allowing planning decisions to be made efficiently without site visits. This multi-level data use directly embodies the information management principles of ISO 55000: data are collected once, referenced to a common network model, and made available in application-specific form to users at every organisational level.

The Baden-Württemberg example demonstrates that the transition to a systematic, digital pavement management system is not primarily a question of technology, but of organisational commitment and process integration. The consistent application of a top-down information requirements approach - defining data needs from the perspective of strategic and operational use cases, rather than from the bottom up - has enabled the state road authority to realise the full value of its condition data across the entire maintenance management cycle. The example confirms that digital pavement management systems, when embedded in a coherent asset management framework aligned with ISO 55001, can deliver measurable improvements in the efficiency, transparency and sustainability of infrastructure maintenance (Hilpert, Balck, Epp 2022).

In summary, web-based digital systems represent a key component for the implementation of pavement management within an asset management framework. They enable the integration of data, models, and decision processes and support strategic, tactical, and operational infrastructure management. By providing a consistent data basis, transparent decision processes, and scalable system architectures, digital applications form the technological foundation for modern infrastructure asset management systems in accordance with ISO 55001.

6. Summary

The management of road infrastructure is becoming increasingly complex due to aging assets, growing traffic loads, limited financial resources, and rising requirements for transparency and sustainability. In this context, digital pavement management plays a key role as a technical component of infrastructure asset management systems according to ISO 55001.
This paper describes a structured approach to digital pavement management, understood as a process that transforms raw infrastructure data into information, knowledge, and decision support. The methodological framework includes data acquisition, condition assessment, performance modelling, maintenance planning, and prioritization under budget constraints. This process forms the analytical core of pavement asset management and supports strategic, tactical, and operational decision-making.
A central challenge in digital pavement management is not only data collection but the integration of heterogeneous datasets, long-term data management, data quality assurance, and the transparency of decision-making processes. These challenges demonstrate that pavement management must be understood as part of a comprehensive asset management system rather than as a purely technical evaluation process.

The paper further shows that digital implementation in the form of web-based applications is a key enabler for modern asset management. Such systems integrate data, models, and management processes into a unified platform and provide decision-makers with reliable information on network condition, performance development, maintenance demand, and budget requirements. By linking condition data with maintenance and construction information, digital systems also enable feedback mechanisms that support continuous improvement and the transition from descriptive to learning pavement management systems.
In summary, digital pavement management systems represent the analytical and technological backbone of infrastructure asset management. They enable data-driven, transparent, and economically efficient decision-making and therefore contribute significantly to the sustainable management of transport infrastructure networks.

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