Extending a Material Master System by Multi CAE material information.

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Abstract

The development and application of advanced materials are critical to innovation in CAE-driven product and process development. Managing material data for CAE poses several challenges, including data harmonization across diverse simulation tools, ensuring accuracy in material models, and maintaining regulatory compliance while meeting the dynamic needs of multiple brands. To address these challenges, an extended Material Master System was implemented for the Volkswagen Group, offering a unified, scalable framework that integrates material card management with laboratory test data across brands such as Volkswagen, Porsche, and Audi.

This system fosters cross-brand collaboration by harmonizing workflows and accommodating individual brand requirements, creating synergies while maintaining flexibility. Through JSON-based CAE-neutral data structures, material cards can be imported, modified, and exported across CAE platforms like LS-DYNA, PAMCRASH, Abaqus. Direct integration with test data ensures full traceability, while constitutive models and Python-based tools enable advanced evaluations such as curve fitting and fatigue analysis. Built-in visualization tools streamline comparison of material properties, enhancing the reliability and accuracy of simulations. By leveraging open standards and electronic workflows based on BPMN 2.0, the system reduces errors, strengthens traceability, and supports seamless integration across brands. The incorporation of open-source components ensures scalability, adaptability, and vendor independence, supporting sustainable long-term data management. The extended Material Master System accelerates the applicability of new materials, enhances operational efficiency, and improves the reliability of simulations.

1. Introduction and Objectives

Product innovations and market success are closely linked to the use of advanced materials. Their processing technologies are crucial for lightweight design, performance, and sustainability. Traditionally, product development has focused heavily on geometric technologies like CAD, PDM, and FEM, where product structures, configurations, and drawings were central, while materials were often treated as simple textual identifiers in bills of materials.

For product and process development using CAE methods, these textual identifiers are converted into material-specific parameters as so-called material cards, which are typically stored as simple ASCII files. However, different CAE systems use proprietary formats to model thermophysical properties, plasticity, failure, fatigue, etc. As a result, material cards for the same material and discipline are often created independently across various applications, failing to exploit potential synergies and efficiency gains.
In the context of interdisciplinary collaboration required for automotive development, media disruptions inevitably lead to errors, increased effort, and higher costs. This applies both to the application and creation of material-related information.

The goal of cross-brand collaboration between Volkswagen AG, Porsche AG, and Audi AG is to overcome these media disruptions, increasing efficiency in the generation and application of material data across brand and departmental boundaries. This encompasses areas such as material standardization, design, simulation, material testing, and sustainability.

An important aspect of the implementation is the use of open standards and FOSS (Free and Open Source Software) technologies to minimize dependency on proprietary systems, while ensuring global availability through a SaaS solution that integrates with interfaces to existing system components and tools.

2. Concept and Implementation

2.1 Material Master System and Data Model

A “Material Master” data system for material designations with links and basic properties was developed as a web application accessible to all group employees. At its core, the solution is built on a document-based approach utilizing JSON [1]. The data model is based on the VDA guidelines VDA-231-106 [2] for the primary categorization of materials, as well as VDA 231-200 [3] for basic attribution and classification.

In addition to assigning names based on class-specific schemas, materials are identified across common system environment using a system-generated 6-

digit alphanumeric code followed by a revision number. This unique identifier is consistent across the group and designed to be compact, user-friendly, and free from easily confusable characters.

The resulting master data system serves as a foundation for expanding brand-specific data systems and laboratory integrations. It also facilitates the creation of interfaces with overarching system components, such as standard libraries and PLM systems.

2.2 Extended Material Data System

The material master data of “Material Master" has been extended in the “Material Data” system to include the following components:

- Reference databases:

Reference databases for steel, aluminum, copper and plastics, which are created and maintained in collaboration of Matplus with industrial associations VDEh, AA, EAA, Copper alliance [4]. This serves as a knowledge base for material managers, supporting the editing process by automatically supplying substance information and characteristic values to the workflow.

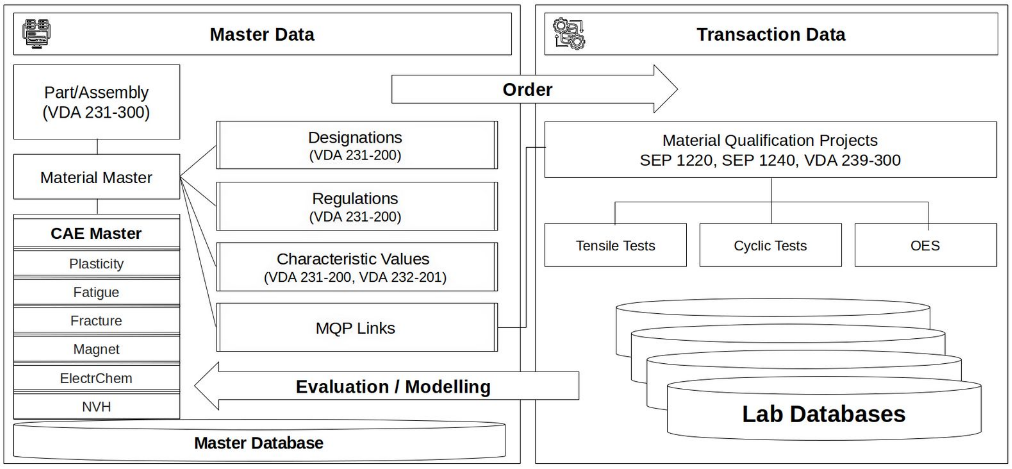

Figure 1: Integration of Material Qualification Projects

- Transaction Data for Material Qualification Projects:

Transaction data generated for material qualification projects is stored in specific databases linked to the “Material Master”. Figure 1 illustrates the interaction between master data and transaction data. Material qualification projects are recorded within laboratory databases and connected to the master data system. On the laboratory side, import functions are available for various testing machines (e.g., Zwick) and for standardized data exchange formats such as SEP 1240 [5] and VDA239-300 [6]. This implementation builds on results from funded projects in this domain, cf. [7].

The solution provides the following advantages:

1. Unlike traditional LIMS systems, raw test data is stored as parametric data fields digitized into JSON objects, enabling seamless use for system modelling.

2. Through the "Material Master", all qualification projects are visible across laboratories. This transparency allows for data consolidation and helps avoid costly duplicate testing.

- Serialization of Data using JSON:

The previously mentioned data exchange formats are structured ASCII datasets with inherent limitations. By adopting JSON as a data exchange format combined with JSON Schema [8] for data validation, many of these limitations can be addressed, which also ensures robust data integrity and consistency.

The VDA project group "Material Data Management in the Sampling Process" recognized this advantage and developed a new JSON schema for data exchange, formalized as VDA231-301 [9]. This schema is scheduled for release as a free resource on GitHub in the first half of 2025. Once adopted, it will enable the replacement of legacy ASCII data formats in this domain with type-safe subschemas based on the JSON data model defined by the VDA guideline. Additionally, reports from sampling processes and external laboratory tests, which have previously been challenging to digitize, can now be effectively integrated into the system.

To enable integration and analysis of test results**,** knowledge graphs are constructed that capture the relationships between material states, processing steps, laboratory orders, test series, and individual tests. These graphs are serialized using JSON, where each entity is represented as a document with references to its logical "parents" (pgraph structure). This model supports efficient traversal using MongoDB's "graphLookup", enabling seamless linkage of test data with the corresponding process history.

Material states and processing steps are thus connected through a directed graph of JSON documents. Time series process data can be attached to processing steps, allowing test results to be contextualized within the complete processing chain and correlated with preceding conditions.

To support test planning and visualization, a graphical editor has been developed (see Figure 2). The editor provides an intuitive interface for constructing and navigating knowledge graphs: ellipses represent material conditions (e.g., states before or after processing), **s**quare**s** denote processing steps enriched with time series data, and rectangle**s** are used for test data, structured hierarchically into test orders, test batches, and individual tests. This visual abstraction aids users in designing and managing complex test campaigns, making the tool especially valuable in R&D settings such as the development of SIBORA [10].

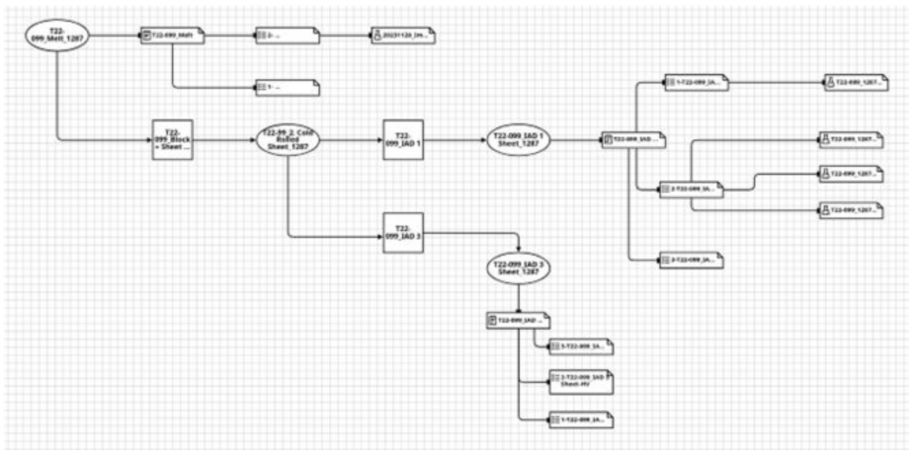

Figure 2: Graph Editor for linking Material Property Evolution and Testing

<u>2.3 Material Card Management and System Integration</u>

Traditionally, material cards are provided as ASCII files for respective target systems. While the “Material Data” system continues to support this type of file management, it enhances it with classic document management capabilities, including metadata, formal releases, and revisions.

However, this traditional approach falls short of delivering the benefits of value-adding digitization. It lacks traceability, efficiency, and data security: test data is exported from the protected system environment, processed using non-standardized manual scripts, and material cards are typically not linked to the underlying test data.

The new system addresses these challenges by supporting the entire workflow —from the evaluation of test data to system-neutral CAE material cards— through a fully integrated solution. This approach is built on three key pillars:

a. Harmonized Data Structure for Material Models

- A unified data structure for material models is created in JSON format, linking models to the “Material Master” master data and experimental results from laboratories.
- Extensions are provided for various target systems to ensure compatibility and adaptability

b. Infrastructure for Scientific and Technical Tasks

- Constitutive equations (e.g., Ramberg-Osgood, Johnson-Cook, Zerilli-Armstrong) can be stored and parameterized within the system, with support for curve fitting and advanced mathematical evaluations. Automated tools can be used to generate piecewise input data for CAE applications, reducing manual intervention and improving integration efficiency.
- Python-based tools, including libraries like SciPy, NumPy, and Pandas, are integrated, enabling users to create flexible plugins and extend system functionality.
- The system is expandable with external FOSS (Free and Open Source Software) libraries, enabling advanced functionalities while ensuring proper system authorizations and adherence to quality assurance measures. For example, PyLife [11] has been integrated as a core component for the evaluation of fatigue test data [12], leveraging its robust statistical and material fatigue analysis capabilities.

As illustrated in Figure 3, the system supports automatic generation and visualization of fatigue evaluation results. The figure displays a **stress–**number of cycles (S/N) plot, where each point represents the outcome of an individual fatigue test. The blue curve indicates the calculated mean S/N curve, while the red and green curves correspond to survival probabilities (e.g., 10% and 90%) derived using PyLife's maximum likelihood estimation method. This visualization enables quick and statistically sound interpretation of fatigue behavior, supporting both material characterization and design validation processes.

Furthermore, the representation allows direct comparison of multiple S/N curve**s**, enabling users to contrast different materials, R-values, heat treatments, or surface conditions within a unified view. This comparative capability enhances insight generation and facilitates decision-making in material selection and process optimization.

c. Import and Export Functions

- JSON-based mapping structures for property names and units enable flexible import/export of material cards, supporting round-tripping between systems. For example, a LS-DYNA card can be imported system-neutrally and exported as a PAMCRASH card.
- Material cards from various departments and systems (e.g., Ansys, Abaqus, StarCCM, NX, and Catia) can now be consolidated.
- System-internal visualizations facilitate comparisons of curves and scalar properties across different material cards.

This integrated approach ensures improved traceability, efficiency, and data security while streamlining workflows across diverse CAE environments.

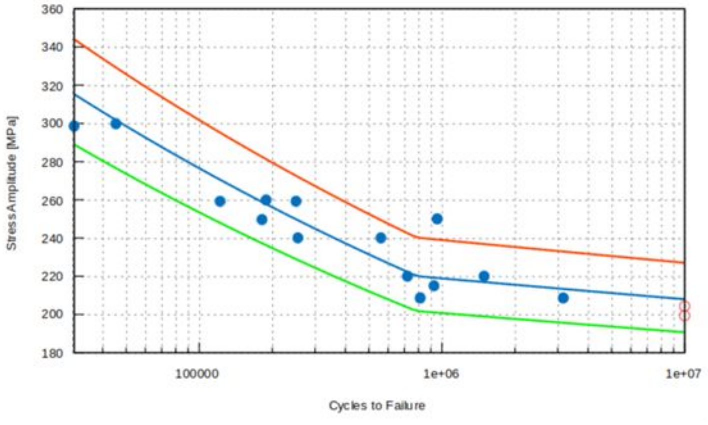

Figure 3: Exemplary System integrated Fatigue Evaluation

2.4 Electronic Workflow

The primary objective of electronic workflows is to automate processes, eliminate media discontinuities, enhance efficiency, minimize errors, and ensure transparent tracking and seamless documentation of conventional workflows. In the context of material data, this includes key processes such as the release and revision of master data, as well as maintaining full traceability when creating and managing material cards.

The integration of BPMN 2.0 (Business Process Model and Notation) [13] enables the system to leverage an industry-standard approach for designing and executing flexible workflows. This allows users to model workflows tailored to specific requirements, including decision-making processes supported by DMN (Decision Model and Notation). Additionally, system extensions, such as the above-mentioned custom plugins, can be integrated as executable process steps, providing enhanced functionality and adaptability.

Upon workflow execution, tasks are automatically assigned to the appropriate users or teams based on predefined rules, ensuring efficiency and accountability. Every event in the process chain is meticulously recorded, creating a fully traceable audit trail. This not only strengthens compliance and quality assurance but also provides valuable insights for further process optimization.

Figure 4 shows the graphical workflow editor based on bpmn.io, illustrating an example of a structured test data processing workflow. The top lane, associated with the laboratory, models the processing and evaluation of test results. The middle lane represents the review process, which includes verification and quality control steps. In the bottom lane, a grouped activity performed by CAE experts is shown, focusing on the generation of a material card from the validated test data. This layered representation clarifies responsibilities across roles and supports traceable, collaborative workflows in material data management

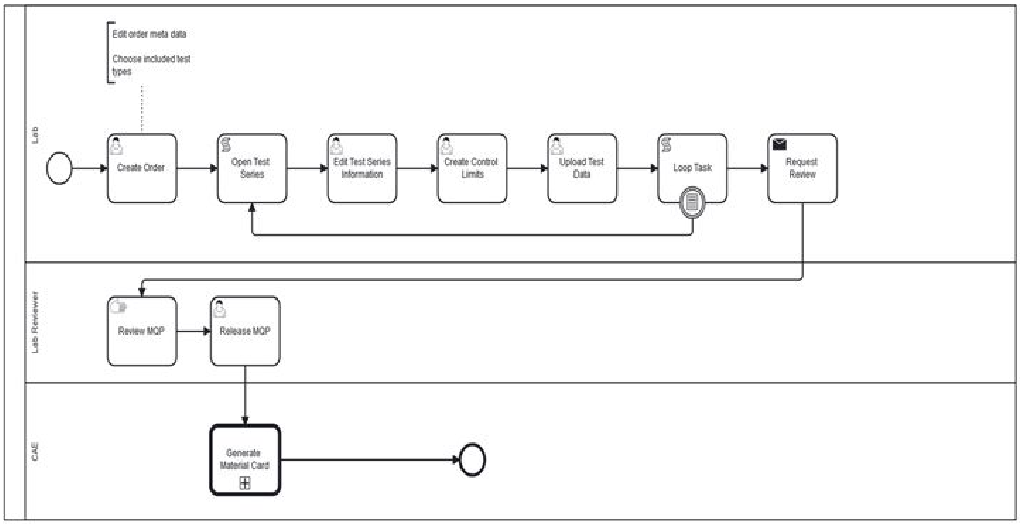

Figure 4: Design of Process Automation using the integrated BPMN2 editor

3. Summary and Conclusion

In CAE-driven product and process development, material cards are essential for accurately modeling properties such as plasticity, failure, and fatigue. Traditional workflows based on proprietary ASCII formats have long limited traceability, automation, and interoperability. The Material Data system overcomes these challenges by integrating test data, process history, and material card management into a unified, JSON-based platform now in use across multiple brands within the Volkswagen Group.

A key enabler is the use of JSON in combination with JSON Schema for structured, type-safe data exchange. This approach supports robust validation and platform-neutral interoperability. It also aligns with the newly defined VDA231-301 **s**tandard for material data exchange, developed by the VDA project group “Material Data Management in the Sampling Process.” The release of this schema in 2025 will mark a strategic shift from legacy ASCII formats to modern, schema-based data exchange in the automotive industry—supporting digital integration of sampling reports and external lab results.

Methodologically, the system employs a parent–child graph structure (pgraph) stored in MongoDB, enabling efficient traversal of processing histories and test data using native “graphLookup” queries. As an example of seamless integration of FOSS components, the fatigue analysis library PyLife has been embedded to perform automated S/N curve fitting and survival probability estimation using maximum likelihood methods. This supports robust material characterization directly linked to test results.

Together with a BPMN-based workflow editor for traceable, role-specific planning and approval, “Material Data” provides a future-ready, scalable solution that enhances data quality, accelerates development, and enables consistent CAE-driven material workflows across the automotive sector.

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