The Fundamental Modeling Practices and Specifications to support the Preservation and Reuse of Analytical Simulations

Mark Williams[1] Hubertus Tummescheit[2] Ajaykumar MST[3]
Jose María Alvarez-Rodríguez[4]

[1]International Council of System Engineering, USA,
mark.williams@incose.net

[2]Model Based Innovation LLC, USA,
hubertus.tummescheit@modelbased.cloud

[3]Boeing India Private Limited, India,
ajaykumar.mst@boeing.com

[4]Carlos III University of Madrid, Spain
josemaria.alvarez@uc3m.es

Abstract

Significant opportunities exist to preserve and reuse simulation and analytical models and data. Based on the capabilities developed by the Modelica Association (MA), LOTAR International, and other contributing tool developers, multiple engineering and manufacturing industries can compile extensive archives of reusable and interoperable performance, behavior and integrated product information. Through the development and implementation of a preservation plan, the use of compliant off-the shelf software applications, and packaging using compatible data standards, a repository of analytical interactions, simulations and functional prototypes can be archived, maintained, and resourced by future users. The scope of this paper is the exploration of alternative data standards that might support LOTAR requirements. This paper identifies progress made since the publication of (Coïc 2021, Coïc 2023) with respect to maturity of the "Long Term Archiving and Retrieval" (LOTAR) draft standards – ASD-STAN 9300 series, (ASD-STAN, 2025) and accompanying prototype implementations. There has also been significant progress by the Modelica Association with the introduction of layered standards in new versions of the FMI and SSP standards (Modelica Association 2024-11., Modelica Association 2024-12). The soon to be released layered standard SSP Traceability (Modelica Association 2025-04) provides mechanisms to document and preserve relevant metadata for model archiving in support of LOTAR. The FMI layered standard FMI-LS-Ref standardizes parameter sets and reference results, which are an important subset of the LOTAR International requirements.

Keywords: Model reuse, SSP, FMI, LOTAR, Traceability, Modelica

1. Introduction

Model-Based Systems Engineering (MBSE) has become the de facto standard for developing complex systems, where models are first-class members of the engineering process. Rather than relying on documents, MBSE encourages the use of descriptive and analytical models to support key lifecycle activities such as requirements definition, design, analysis, and verification. This model-centric approach is critical to enabling the Digital Thread—a connected and consistent flow of engineering information that supports collaboration across disciplines and lifecycle phases.

As digital engineering practices mature, simulations are essential to representing, verifying and validating complex Cyber-Physical Systems (CPSs). Analytical simulations capture domain-specific behaviors and performance characteristics. However, while these simulations are widely used during a product's development and manufacture, they are not commonly preserved in a reusable or interoperable format. Traditional Product Lifecycle Management (PLM) tools focus on managing static artifacts, configurations, and project milestones. However, they usually lack the features needed to manage alternative formats, expose and supplement metadata or maintain contextual links and dependencies needed for reuse across different lifecycle stages and related projects.

Recently, engineering has seen the definition of different metamodels that express the configuration and relevant information needed to share, exchange and execute analytical models. The Digital Data Package, DDP (Prostep ivip 2024) provides a structured container to bundle models, input/output data, documentation, and related metadata. This packaging approach enables traceability, validation, and long-term reuse across lifecycle phases. The analytical models contained in a DDP are further enhanced by using the Model Identify

Card, MIC-Core**,** (IRT SystemX 2020). The relationships with other models can be further elaborated by the ISO 1030-243 standard, known as AP 243, (ISO 2021) which serves as a formal metadata structure to capture the key characteristics of a model; such as its purpose, inputs, outputs, assumptions, limitations, and applicable domains. The AP 243 - MOSSEC standard defines a metamodel "*enabling the sharing and exchange of Modelling and Simulation contextual metadata"*. It acts as a technical "passport" for models, supporting collaboration and enhanced content identification, empowering engineers to assess a model's fitness for use without deep inspection of its internals. Note that the SRMD metadata format (Modelica Association 2025-3), defined in the SSP Traceability draft standard (Modelica Association 2025-1), can efficiently store metadata information from MIC-Core, MOSSEC, or any of the various other model metadata specifications currently in use.

1.1 LOTAR MBSE Standards - Overview

All forthcoming LOTAR MBSE standards are still in a draft format or under review for approval. It is, however, useful to present their overall structure here.

- **Part 500**: Fundamentals and Concepts for long term archiving and retrieval of Model-Based Systems Engineering information.
- **Part 510**: Long term archiving and retrieval of Requirements, and their management schema, as text, graphics, tables, models, or "parameter based" information.
- **Part 515**: Long term archiving and retrieval of Validation and Verification "text based" and "parameter based" information (expanding Part 510).
- **Part 520**: Long term archiving and retrieval of system or component level analytical behavior models described by specification or executable code, containing differential, algebraic and discrete equations. Includes causal or acausal models not addressed by the Part 600 series.
- **Part 530**: Long term archiving and retrieval of models that use system architecture descriptions and architecture description languages (ADLs) specified by ISO 42010/SAE AS5506 [9].
- **Part 540:** Long term archiving and retrieval of data and models specifying the Logical Bill of Materials (LBOM) (Design implementation requirements).
- **Part 550**: Long term archiving and retrieval of models or features describing digital or relational links. Methods for specifying highly integrated and interrelated models and elements across numerous software tool applications.

In preparation of defining, demonstrating, and publishing future preservation process standards, the LOTAR Model Based Systems Engineering Workgroup (LOTAR MBSE 2025) has introduced the application of the P510 and P515 metamodel (see above). Draft schemata are also available for P520 and P550, as well as a common core schema. The current state of Systems Engineering in virtual environments emphasizes the increasing need for early verification and validation of system specifications, often described as the stakeholder, functional, and technical requirements, and the necessity for configuration management and traceability of all related design data. The preservation of this information will be described in the P515 process standard and will be supported by preserving the data traceability features utilizing the P550 standard for linking information. As systems become more complex and interconnected, ensuring that specifications align with both system behavior and stakeholder needs throughout the development lifecycle represents a cornerstone of the MBSE process. This paradigm shift highlights the importance of good practices for model-based approaches that can facilitate the continuous tracking and validation of requirements, their allocation to design features, and model specific test results, ensuring that every decision and change is captured and verifiable at all stages of the system's lifecycle. Note that the ISO 26262-Standard (ISO 2028) for automotive functional safety has very similar traceability requirements and often needs the same type of behavioral models for verification and validation.

In this paper, we introduce the modeling practices and specifications needed to preserve and reuse analytical simulations effectively. This includes defining standard ways to document simulation intent, manage contextual metadata, and ensure consistency across tools and formats. By formalizing these aspects, we can move toward an executable and dynamic engineering environment, where simulations are not isolated efforts but integrated assets within a sustainable and reusable digital ecosystem.

Note the significant overlap of these purposes with finished and ongoing standardization efforts and process practices within the Modelica Association:

- **Part 515**: Part 515 aims at formalizing the informal process that is currently used by the Modelica Library project of verification and validation of the Modelica Standard Library. Similar methods are also used by commercial Modelica vendors. The ongoing effort of standardizing the capture of modeling results and parameter sets in FMI-LS-REF covers the same end user needs. In the ongoing prototype work, the proposed P515 schema was merged with the draft FMI-LS-REF schema for demonstration purposes, but developing the framework for a common schema would be preferable.
- **Part 520**: Part 520 addresses the core topics of Modelica Association standards, notably the behavior and simulation models. Both Modelica and

FMI generally cover the P520 model type referenced here. However, the potential future role of the SSP-standard will need to be evaluated. Until recently, the P520 has focused on FMI mostly due to the much broader adoption of FMI by the software tool vendors. Also note, to avoid repeated translations, that the long-term preservation benefits represented by the LOTAR process are potentially easier to achieve with native Modelica models than with proprietary code repackaged into reusable FMUs. Nevertheless, using FMI as a preservation format will still accommodate many of the models developed using software applications that are alternatives to Modelica.

- **Part 530**: Through the use of Modelica components and acausal connectors, the SSP-standard utilizes a different philosophy than the ISO/SAE ADLs and is potentially useful as a substitute representation of a logical or functional design architecture. An execution oriented SSP system model would be easier to verify. Taking this view, the combination of Part 530 and Part 520 form a similar hierarchical and practical relationship as the SSP and FMI standards.
- **Part 550**: Combining the functionality of the SSP container format with the features of SSP Traceability exposes many of the characteristics defined by the P550 process. Together, they establish and specify the need for relational links between the models and their internal artefacts. They are both successful at formalizing the model integration results and providing auditable evidence of design traceability.

It therefore seems obvious that the Modelica Association and the LOTAR MBSE working group would recognize the significant benefits of developing a closer collaboration relationship. With the Modelica Association's focus on data standards, and LOTAR MBSE's focus on process standards, there is an obvious synergy and mutual benefits.

2. The Benefits of Preservation

Data preservation should be a leading consideration for all engineering models, and preservation planning should be a leading activity in all modeling endeavors. While the specific advantages of digital data preservation vary by industry, maintaining an engineering data archive offers broad benefits to any engineering enterprise or effort. The obvious renumerations include: the documentation of design decisions, permitting flexibility in the contributions of future personnel, historical evidence of process management, and sustaining the traceability of interrelated data from all applicable domains. Other practical but important factors include facilitating warranty investigations, product maintenance planning, a design history to address potential part obsolescence, and support for future modifications and enhancements.

A concise preservation plan typically includes the following elements: a repository with configuration management and robust data search capabilities; use of modeling techniques that promote data interoperability and integration; tools or processes to expose and capture model metadata; generation of summary model reports for future results verification; and the establishment of traceable links to source the original technical requirements and any reference data.

2.1 Preservation Process

Preservation begins with the formulation of a data preservation plan that identifies the model types, dependencies, applicable standards, and intended future uses. Archiving is performed at defined maturity milestones—such as design reviews or configuration releases—capturing fully verified and consistent data packages known as configured baselines.

Each archived package targeted for preservation includes a Model Manifest, which documents the model's structure, purpose, and metadata; and a Model Report, which records the model's execution, results, and verification and validation (V&V) evidence. Verification ensures the technical completeness and integrity of the archived data, while validation confirms that the model meets its intended purpose, and viability after storage and subsequent retrieval. To facilitate interoperability and futureproofing, data is translated into a standardized neutral format, such as those defined by STEP protocols.

As prescribed by formal Systems Engineering standards, all archived models must maintain clear traceability to their source requirements, design rationales, and validation artifacts. The preservation infrastructure itself must support robust search functions, metadata management, and integrity checks to ensure that the data remains unaltered and usable. This paper has already identified the key metadata standards, MIC-Core and

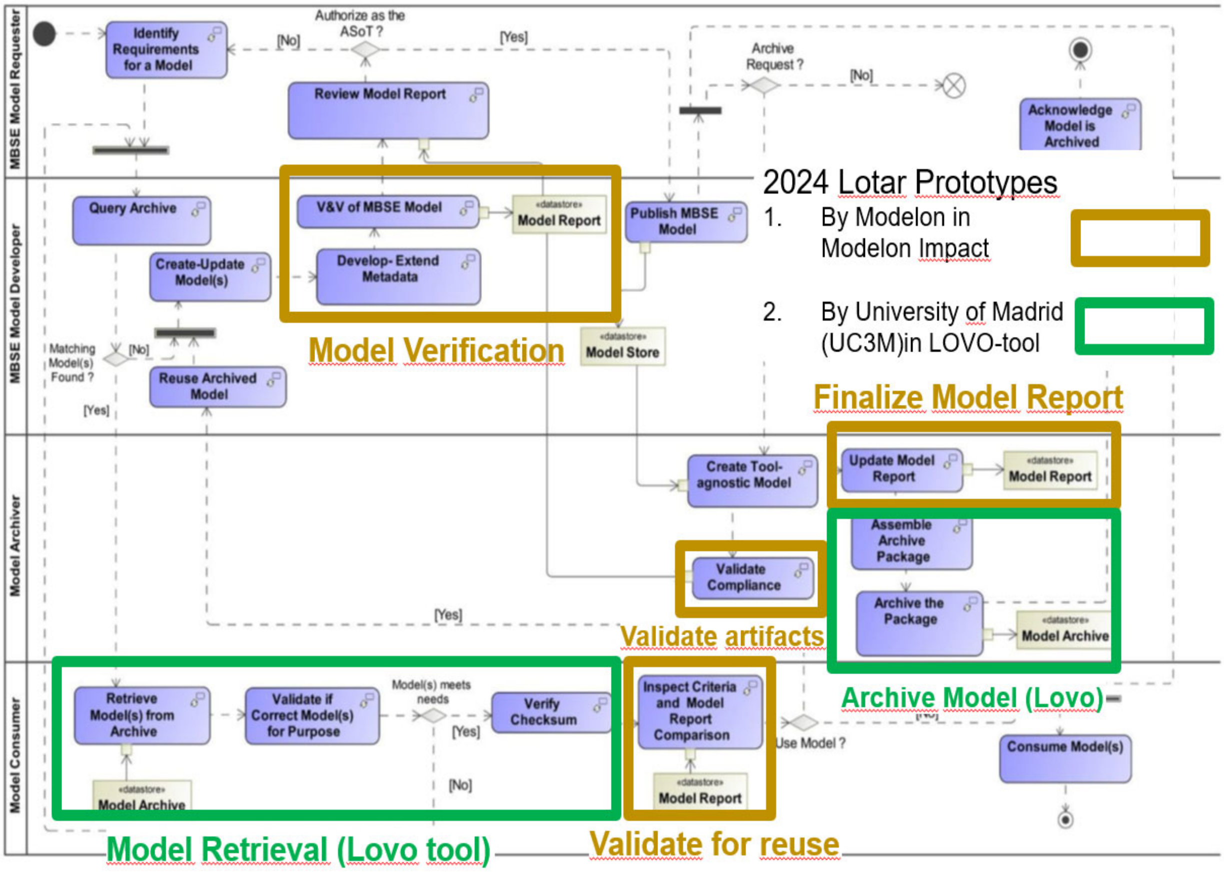

Figure 1: The LOTAR MBSE process flow with role-based swim lanes (Coïc et al, 2023).

MoSSEC, and the DDP as a packaging mechanism. The LOTAR standards identify a packaging framework, as described by the OAIS standard (ISO 2012), that compliments and formalizes the DDP.

The LOTAR preservation process, showing swim lanes for different enterprise roles for both the archival and retrieval process is depicted in Figure 1.

3. Types of Standards

The LOTAR domain specific Parts, previously defined as the P510, P515, P520, and P550 standards, are process standards that rely on widely available and robust data modeling standards. Data modeling standards support data interoperability between multiple brands of tools and users. They can also support translations into neutral or alternative formats. Data Modeling standards support model preservation if subsequent versions maintain compatibility through future software tool revision cycles. Some of the best examples of modeling standards are produced and maintained by the Modelica Association. Other notable modeling process standards for modeling and simulation are by NASA, (NASA 2024, NASA 2019).

3.1 Data Modeling Standards

The Functional Mock-up Interface (FMI) facilitates the exchange of simulation and analytical models, while System Structure and Parameterization (SSP) supports system assembly. Recent updates made them more appropriate for LOTAR purposes than they were originally, and the introduction of "Layered Standards" supports the concept and implementation of LOTAR even better. Two layered standards under development by their respective FMI and SSP projects stand out in how much they align with LOTAR needs:

- The SSP Traceability standard (to be released shortly) supporting model and process traceability; and the
- FMI-LS-REF standard that aims to add a standardized way to include simulation experiment definitions, multiple parameters sets and simulation result files to an FMU.

Together they will further enable the identification and management of metadata and traceability features in both FMUs and SSP containers.

3.2 The Behavioral Model Results Report

During 2024, major progress was made to implement and test a prototype that enhances the Part 515 verification and validation process. The deliverables developed by Modelon AB included python code and a draft xsd-schema. This expanded earlier efforts to prototype the Part 520 process and integrate the Part 550 linking mechanisms directly into a Modelica model (Coïc et al. 2021, Coïc et al. 2023). The 2024 prototype added detailed checks on the completeness and correctness of all available FMU and SSP assets, as well as the model verification capability. The process break-through evolved by formalizing the existing infrastructure, used by the Modelica Association and modeling community, that automates the regression testing of behavioral models. Unfortunately, even with more than a decade of experience in automated model verification, the Modelica Association has never agreed on formalizing the definition of solver types and terminology, which are necessary for quantitative verification of simulation models. In addition to other features, the Part 515 xsd-schema formalizes the following elements of model verification:

- The link to the model to which it applies
- The required test cases
- The context of the test case
- The actual scenarios used
- The experiment definition, such as solver type, tolerances, start and stop times, and number of result points that should be stored
- The referenced variables
- Verification tolerances in the x and y direction
- Boundary conditions
- Modified parameters
- Links to the reference result files

This is a superset of the information currently envisioned for the FMI-ls-ref layered standard. The intention of the FMI-ls-ref standard was to enable a so called “smoke test” for exchanging FMUs, whereas the needs for verifying archived models for design reuse requires precisely quantified tolerances. Nevertheless, the development, agreement and utilization of a basic verification infrastructure as a layered standard to FMI would simplify future adoption.

The SSP Traceability standard by the MA provides a modular data standard that enables an in-depth and customized metadata definition. It does, without additions, not provide the precise definitions that are needed for long term archival.

4. Encoding Metadata

The LOTAR Working group’s standards include encoding the processes steps and defining the necessary metadata to enable reuse of models after potentially long periods of archive storage. In parallel to the LOTAR developments, the German national research project SET level (Otter et al. 2022, Setlevel 2023) initially developed what has become the SSP Traceability standard. As enhancements to the product development process, SET Level starts with defining the “Credible Decision Process” and the “Credible Simulation Process” (CSP). It also established a metadata format in support of SSP Traceability. It evaluates the credibility of the process by documenting the steps and linking and integrating all required artifacts. While the purpose for collecting and integrating the metadata is different, there are a lot of commonalities. SSP Traceability (MA 2025-1) has been defined as a feature that facilitates a large degree of process variation. An observer’s ability to understand the model’s purpose and then generate identical results at different times is common to both efforts. SSP Traceability is designed to capture metadata throughout the entire design process, whereas for LOTAR only the final maturity status must be set before an archiving decision is considered. However, model preservation for a longer period likely requires additional metadata that might not be needed for a shorter lifecycle. In any case, with the recently added ability to add “layered standards” in a compatible way to MA standards, the LOTAR MBSE standards could be built as a layered standard on top of SSP Traceability. The integration of this additional capability could simplify the implementation and future adoption.

The SSP Traceability standard contains several separate namespaces and parts, which don’t map 1:1 to the LOTAR specification, but would still make it possible to cover LOTAR’s intended results. The main elements of SSP Traceability are (MA 2025-1):

- **Decision Task Meta Data (DTMD)** is an XML format representing process-relevant information, as defined by the Credible Decision Process, with a file extension ending in dtmd.
- **Simulation Task Meta Data (STMD)** is an XML format representing process-relevant information, as defined by the Credible Simulation Process, with a file extension ending in stmd.
- **Simulation Resource Meta Data (SRMD)** is an XML format representing metadata for resources, with file extension ending in srmd.

Note that according to the SSP standard these metadata files can also be embedded in FMU files, not only in the SSP packaged files.

To use recurring description elements consistently, they must be defined separately from the three XML Schemas above. As a result, these description elements are also available in the DTMD, STMD and SRMD XML Schema. The XML Schema for common content is named **Simulation Traceability Common (STC)** XML Schema representing recurring description elements of the other three XML Schemas. An important concept of SSP Traceability is the Glue Particle approach:

- The **Glue Particle Approach** is a concept for packaging data and the file-based transfer of process-relevant information and resources from a Credible Decision Process or a Credible Simulation Process.
- A **Glue Particle** is a package of process-relevant information and resources from a Credible Decision Process or a Credible Simulation Process. The form in which this bundle exists, e.g. whether it is stored as a file or in a database or a specific data format, is not specified.
- A **Glue Particle file** is a Glue Particle that is in a file-based representation and can therefore be transferred between tools or organizational units such as people, departments, or companies.
- File-based resources linked by or to a Glue Particle file should be exchanged with the Glue Particle file itself to take full advantage of the Glue Particle transfer.

SSP Traceability reuses the W3C XLink language (XLink 2012) for data element linking, whereas the P550 draft schema uses a simple URI schema that differentiates between local and global links. Both linking schemata have the same goal: to provide the “Authoritative Source of Truth” (ASoT) by creating traceable links between requirements, needs, and the artifacts to be verified or validated.

Part 520 metadata provide a set of classifications describing the model’s pedigree and usage. The same classifications could equally be expressed with the ClassificationEntry elements in the STC schema. Some of the Part 520 data elements map more clearly with elements in the STMD schema, such as the Integration_Process_Type.

The Part 515 schema focusses on the data needed to verify the model results after retrieval from an archive. The data may be different than what was used to verify the original analysis requirements and results. As mentioned earlier, this is similar to the current draft fmi-ls-ref specification but with additional considerations. STMD on the other hand focuses on the entire verification process of the original model. Undoubtedly, STMD data would be of great use for an engineer trying to reuse a model after it spent a decade or more being buried in an evolving archive.

Prototypes for creating and validating the P515 and P520 LOTAR MBSE archiving process were implemented in the Modelon Impact software application to demonstrate that they can easily be accomplished and repeated using Modelica-based tools.

5. Representing Analytical Models

Utilization of the Modelica language satisfies many of the needs of the P520 process, but in today’s environment the majority of models are developed using proprietary tools. However, most of these tools now support the export of models as Functional Mock-up Units (FMUs). In principle, text-based language models have fewer intricate implicit dependencies on details of the execution environment such as Application Binary Interfaces (ABIs) and dynamically linked libraries (sometimes referred to as “dll-hell”), which doesn’t go to the full depth of the second problem, major revisions of the underlying operating system. The volume of metadata needed to define, let alone guarantee, a compatible execution environment is quite high. However, the containerization of computational resources has at least made it easier to recreate the original settings, but preservation planners must still account for open-source or proprietary operating systems, plus any additional system libraries and software platforms. A partial remedy to the execution environment lifecycle is to use “source-code FMUs”, but they are not supported by many tools. The detailed “Build Configurations” available in FMI 3.0 will improve portability, ease of use, and expand the archiving alternatives. There are further improvements in FMI 3.0 that “sharpen” the semantic precision of models and therefore accommodate the packaging of more sophisticated simulations of integrated systems and controls. The most relevant features here are:

- Clocks
- Transition events in co-simulation FMUs
- Interface provisions for scheduled executions
- New data types, including binary data
- Methods to manage the build configuration
- A new implementer’s guide to improve the user’s interpretation of the standard.

In earlier work prototyping the P550 concepts (Coïc et al 2023), Modelica records were used to embed interactive traceability links to elements (e.g., requirements parts, attributes) directly in the Modelica code. They were modelled as Strings in a traceability record. Now that the Modelica Association has exposed the SSP Traceability standard (current status - release candidate, but several commercial tools appear to be early adopters), it seems reasonable to tag elements with a Modelica Resource, enabling a standardized annotation link to point to the required resources. Such resources can even be embedded in the SSP.

6. Model archive and retrieval: verification and traceability

As discussed previously, preservation of engineering artifacts is a critical capability for organizations seeking to enable long-term traceability, reuse, and maintain compliance in complex system development. The preservation process is not limited to mere storage. As illustrated in Figure 1, data preservation requires a robust workflow for model identification, verification, archival, and retrieval. Combining these steps ensures the integrity and accessibility of engineering data over time. In this section, we briefly describe significant process enhancements to the archive and retrieval of engineering artifacts by leveraging metadata verification, packaging standards, and knowledge graphs for queries and model identification.

1) The archival process starts with the verification of a **metapackage** described through an instance of the P550 schema. This metapackage-information serves as the entry point for validating the consistency of the engineering artifacts to be preserved. Each metapackage comprises references to one or more subpackages (e.g., P510, P515, P520), each associated with a manifest and a corresponding engineering artifact. Before indexing any package into an archive, two levels of verification are required:
   - **Traceability level**: the archival process must ensure that all traceability links between the engineering artifacts actually exist and are all accessible. This includes validating cross-references between requirements, models (logical and physical), and model elements.
   - **Artifact level**: the content of each artifact must also be correct in terms of data formats. For instance, artifacts of type **P510** (e.g., requirements) must comply with the ReqIF standard. Artifacts of type **P520** (e.g., physical/analytical models) must be executable with the associated FMI components and produce the results specified in the manifest and model report. In general, each manifest must declare a valid checksum and timestamp to verify content immutability.

   Once these two aspects are verified, packages can be stored in the archive. The process supports updating the manifest metadata as necessary to reflect any corrective or clarification changes. This guarantees the long-term preservation of both the engineering artifact and its descriptive. context
2) The retrieval process for preserved engineering artifacts follows a similar set of checking actions. Given a package is contained in an archive, the system starts from a P550 instance and traverses all associated subpackages recursively. Each subpackage is unpacked, and its manifest is opened and validated using the same rules as in the archival phase. If the type of artifact is known (P510, P515, P520, etc.), the appropriate toolchain is invoked to:
   - Parse the manifest and validate schema conformance.
   - Check that the artifact's format (e.g. ReqIF, FMI) is as expected.
   - Run simulations or syntax checks as needed to validate behavior or structure with an external tool.

Once verified, both metadata and artifact data can be exposed for further processing, modification, search, or visualization.

6.1 Knowledge Graphs and Search Queries

While the verification process ensures and maintains model integrity, precision identification, suitability and selection of engineering artifacts requires more powerful query and exploration capabilities. To address this, we implemented a semantic layer on top of the archive based on knowledge graph representations. Two strategies were implemented: 1) a Label Property Graph (LPG) using Neo4j Desktop 1.5.9 and 2) an RDF Graph using Apache Fuseki 5.2.0**.** These representations were derived directly from the XML-based manifests using the following transformation rules:

1) XML to Label Property Graph transformation.
   - Each XML element becomes a **node** with a unique identifier and a type-classification derived from the element's type in the XML Schema.
   - Attributes of elements are mapped to their respective node properties (e.g. attribute_name:attribute_value).
   - Hierarchical relationships are transformed into directed edges between nodes, named as `has_<element_name>`. For simple (literal) child elements, values can also be modelled as node *properties* of the parent node rather than separate nodes to avoid too many edges.
2) XML to RDF. The second approach makes a representation of the XML content in RDF (an OWL/RDFS ontology was previously created to derive all XML Schema definitions as classes and properties):
   - Each XML element is an instance of an RDF resource, where the resource type corresponds to an XML Schema Complex Type represented as a class.
   - For each element, a triple is created linking it to its parent using a property named `has_<element_name>`, and then typed either as

an ObjectProperty, AnnotationProperty or DatatypeProperty depending on its origination and whether the value is complex or literal (user defined or from a pre-defined dictionary of terms).

- Every resource is annotated with a rdfs:label to ensure a human-readable identifier.

3) As illustrated in Figure 2, a graph structure enables the integration of the model manifests and the opportunity to perform traversal-based queries using languages such as SPARQL or Cypher. Through the use of queries engineers can explore model features, data relationships, or perform consistency checks. A sample of query results is depicted in Figure 3. A query example, "***Find all scenarios that have a verification credibility level 'Low'***" is defined using SPARQL in Figure 4.

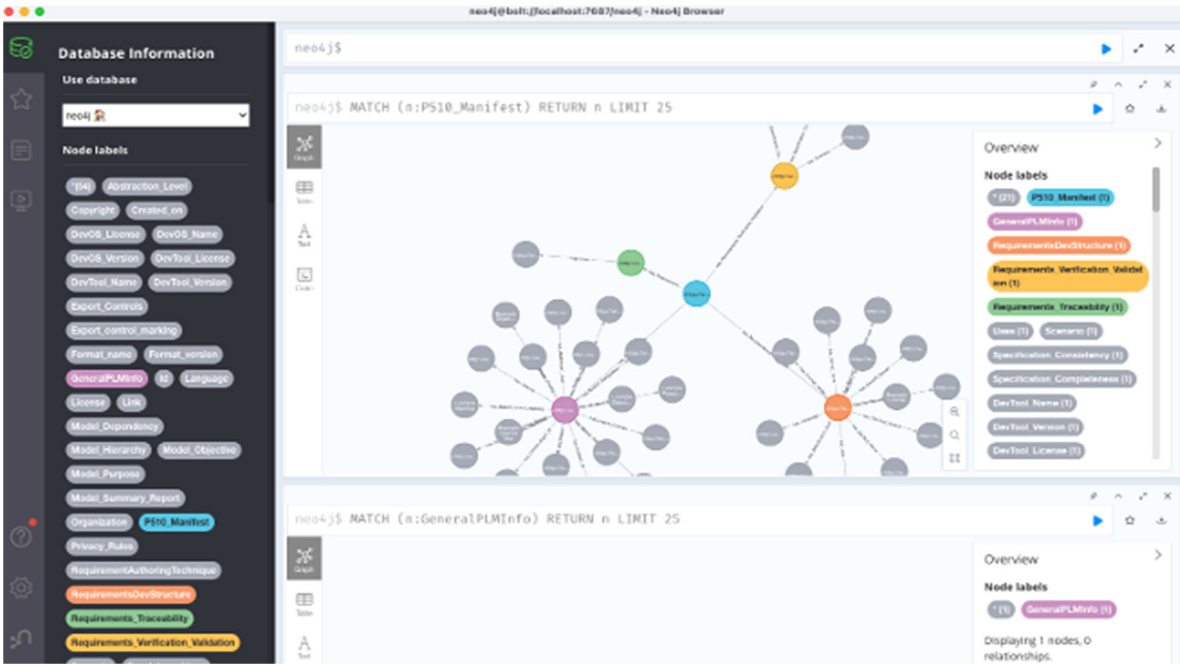

Figure 2: Visualizing a Manifest in Neo4J

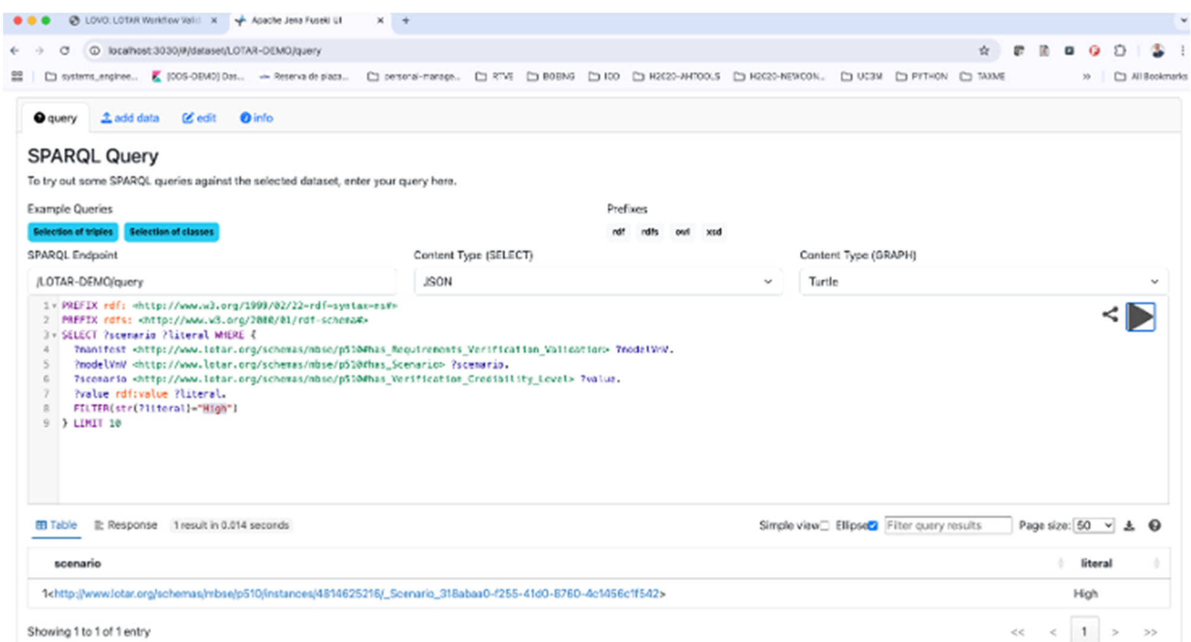

Figure 3: Results of the SPARQL Query

```
PREFIX rd.:
http://www.w3.org/1999/02/22-rdf-syntax-ns#
PREFIX rdfs: http://www.w3.org/2000/01/rdf-schema#
PREFIX 510: http://www.lotar.org/schemas/mbse/p510#
SELECT ?scenario ?literal WHERE {
?manifest
p510:has_Requirements_Verification_Validation ?modelVnV.
?modelVnV p510:has_Scenario ?scenario.
?scenario
p510:has_Verification_Credibility_Level
?value.
?value rdf:value ?literal. FILTER(str(?literal) =
"Low")
}
```

Figure 4: Sample SPARQL query

The engineering artifacts and sample data used for these examples are hosted in the Stratoliner Project (MBE-Demonstrator-RM 2024). The sample source models and manifests included a text-based technical requirements specification in a ReqIF model format, and two FMUs depicting the airplane's alerion actuators. All of the verification and traceability capabilities presented in this section are implemented within the LOVO (LOtar Validation tOols) framework, included in the Stratoliner Project. LOVO will be released under license in a common Python package repository by the authors in 2025.

7. Summary

Significant progress has been made in defining the fundamental parts of the LOTAR MBSE archiving process. This includes multiple tool prototypes to develop and demonstrate feasibility, code to automate many of the process steps, and to-be-released process documentation to standardize the procedures. Many of the techniques necessary for a proper archival and retrieval process are currently un-documented "best practices" developed by experienced simulation experts. But these process advances are usually implemented as an ad-hoc methodology, and with inconsistent technologies across different companies. The LOTAR MBSE schemata formalize these practices and thereby facilitates their eventual integration into familiar off-the-shelf tools.
The initiatives for the SSP Traceability standard, primarily motivated by the needs of the automotive industry, and the aerospace driven LOTAR MBSE standards, were developed in parallel at about the same time. Both industries have similar needs for data traceability and model interoperability. It is therefore assumed that increased coordination and dialog between the respective representative organizations will encourage and accelerate their adoption by the software tool vendors. Although the current Standards produced by the Modelica Association have significantly enhanced the LOTAR process options, multiple challenges remain. The Modelica Language should include the prescriptive identification of the common metadata elements. If the SSP Traceability standard could also apply to FMU containers, and the source analytical models, traceability would be significantly improved. The true advantage would be integration within the Modelica language.
The LOTAR MBSE standard originally was designed to use only the FMI standard, but the extension to SSP is a logical step. Unfortunately, industry's adoption of SSP is lagging behind FMI. The metadata that extends to the SSP container will be slightly different and needs its own unique set of system level classes. Many of the metadata elements could be captured automatically by the original modeling and simulation applications and automatically reproduced in the XML-files used for model integration and traceability. When exported and exposed to the repository, the model metadata would support queries across the LOTAR MBSE preservation archives.
Layered standards, such as SSP Traceability, are quite new in the Modelica community. They offer significant opportunities for LOTAR-type initiatives to satisfy their specific process needs on top of the well-established standards of the Modelica Association (MA) (e.g. FMI and SSP). However, basic instructions and knowledge of how to specify them are not generally available. A published guide about how to develop and coordinate layered standards by the MA would notably improve their adoption. Layered standards, if designed and used correctly, will make implementation of related data standards much easier and facilitate their widespread use.

8. Acknowledgements

This work has been supported by the yearly project prototypes (2022, 2023, and 2024) developed under the sponsorship of LOTAR International, a consortium of industry volunteers sponsored by PDES, Inc. In the United States, and prostep ivip in Europe, with publication services provided by the Aerospace Industries Association (AIA) in the U.S. and the Aerospace and Defense Industries Association of Europe for Standardization (ASD-STAN) both under the supervision of the International Aerospace Quality Group (IAQG).

The authors would also like to thank:

- Jesse Gohl, Modelon AB, for his work in implementing the prototype archiving mechanism

using FMI and SSP in Python and integrated in Modelon Impact.
- Model Based Innovation LLC, Hartford CT, USA, a company dedicated to Modelica standards, supporting the investigation into analytical and simulation tools.

References

ASD-STAN, Aerospace and Defense Industries Association of Europe (2025), standards published at https://www.asd-stan.org/en

AIA, Aerospace Industries Association (2025), in partnership with the American National Standards Institute (ANSI) standards published at https://www.aia-aerospace.org/

Coïc, Clément Mark Williams, Juan Carlos Mendo, José María Alvarez-Rodríguez, Marcus Richardson (2023). "Linking Design Requirements to FMUs to create LOTAR compliant MBSE models". In: "2023 FMI User Meeting". URL: https://fmi-standard.org/assets/literature/FMI_User_Meeting_2023/04_Co%C3%AFc-Linking_Design_Requirements_to_FMUs_to_create_LOTAR_compliant_mBSE_models-168_a.pdf

Coïc Clément, Adrian Murton, Juan Carlos Mendo, Mark Williams, Hubertus Tummescheit, Kurt Woodham (2021-10). Modelica, FMI and SSP for LOTAR of Analytical mBSE models: First Implementation and Feedback. DOI: https://doi.org/10.3384/ecp2118149

IAQG, International Aerospace Quality Group, (2025) The certification and registration authority for commercial aerospace standards and suppliers, https://iaqg.org/

IRT SystemX (2020). Model Identity Card (MIC): Towards a standardization of the specification and description of simulation models. https://mic.irt-systemx.fr

ISO 2023, ISO/IEC/IEEE 15288:2023 Systems and software engineering — System life cycle processes. https://www.iso.org/standard/81702.html

ISO 2018, ISO 26262-1:2018, Road Vehicles – Functional Safety. https://www.iso.org/standard/68383.html

ISO 2021, ISO 10303-243:2021, Industrial automation systems and integration — Product data representation and exchange — Part 243: Application protocol: For modelling and simulation information in a collaborative systems engineering context (MoSSEC), https://www.iso.org/standard/72491.html

ISO 2012, ISO 14721:2012, Space data and information transfer systems – Open archival information system (OAIS)

LOTAR MBSE 2025, LOTAR Model Based Systems Engineering Workgroup, LOTAR Internation. URL: https://lotar-international.org/lotar-workgroups/model-based-systems-engineering/

MBE-Demonstrator-RM 2024, https://github.com/MBE-Demonstrators/MBE-Demonstrator-RM, a GitLab prototype and testing environment using a Stratoliner's structure and modern aerospace systems

Modelica Association (2023-03). Modelica – A Unified Object-Oriented Language for Systems Modeling. Language Specification Version 3.6. Tech. rep. Linköping: Modelica Association. URL: https://specification.modelica.org/maint/3.6/MLS.pdf.

Modelica Association (2024-12). SSP, System Structure and Parameterization Standard – Document version: 2.0 URL: https://ssp-standard.org/docs/2.0/

Modelica Association (2024-11). FMI Functional Mockup Interface Specification – Document version: 3.0.2. URL: https://fmi-standard.org/docs/3.0.2/

Modelica Association (2025-1). SSP Traceability Standard Specification, Document version 1.0.0 beta 2. https://modelica.github.io/ssp-ls-traceability/master/, accessed April 16, 2025

Modelica Association (2025-2). FMI Layered Standard REF draft standard, https://modelica.github.io/fmi-ls-ref/main/ accessed April 16, 2025

Modelica Association (2025-3). SRMD metadata format, part of the SSP Traceability Standard, version 1.0.0 beta 2, https://modelica.github.io/ssp-ls-traceability/master/#sec-srmd, accessed April 16, 2025

Modelon 2025, Modelon Impact Modelica platform, https://help.modelon.com/latest/, accessed April 29, 2025.

NASA 2019. NASA Handbook for Models and Simulation: An Implementation Guide for NASA-STD-7009. https://standards.nasa.gov/standard/NASA/NASA-HDBK-7009

NASA 2024. NASA STD 7009B. Standard for Models and Simulations. https://standards.nasa.gov/standard/NASA/NASA-STD-7009

Otter, Martin, Matthias Reiner, Jakub Tobolář, Leo Gall, Matthias Schäfer, 2022 Towards Modelica Models with Credibility Information, https://doi.org/10.3390/electronics11172728

Prostep ivip 2024, Digital Data Package (DDP), https://www.prostep.org/en/projects/digital-data-package, accessed April 16, 2025.

Radio Technical Commission for Aeronautics 2011, DO-331 - Model Based Development and Verification Supplement to DO-178C and DO-278A, https://my.rtca.org/productdetails?id=a1B36000001IcfjEAC

Radio Technical Commission for Aeronautics 2011-2, DO-333 - Formal Methods Supplement to DO-178C and DO-278A https://my.rtca.org/productdetails?id=a1B36000001IcffEAC

Setlevel 2023, Das SET Level Projekt, https://setlevel.de/

XLink (2012). World Wide Web Consortium, Inc. (W3C): XML Schema 1.1. April 2012. https://www.w3.org/XML/Schema