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Knowledge-Driven Framework for Maintenance Error Prevention Design

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Maintenance errors often originate from early design decisions, such as ambiguous interface specifications, unclear assembly sequences, or improper component interactions, which can significantly reduce maintenance efficiency, increase operational costs, and compromise overall system reliability. Existing approaches to maintenance error prevention primarily rely on expert knowledge and past experience, lacking a systematic, formalized, and reusable mechanism for representing, reasoning, and managing maintenance-related knowledge throughout the design process. To address this limitation, this paper proposes a comprehensive knowledge-driven framework for maintenance error prevention design. The framework integrates systematic domain knowledge modeling, ontology-based representation, and a hybrid reasoning mechanism to support the proactive identification of potential errors at the early design stage. Concurrently, Model-Based Definition (MBD) annotations within 3D CAD models are semantically enriched and linked to ontology entities. By employing a hybrid semantic reasoning approach that integrates Description Logic (DL) subsumption for implicit structural classification with Semantic Web Rule Language (SWRL) for unstructured constraint validation, the framework establishes logical connections between design intent and maintenance requirements. This enables the automated detection of multidimensional risks, such as assembly sequence omissions and spatial clearance conflicts, while providing actionable design improvement recommendations. Furthermore, maintenance feedback, historical failure data, and operational observations are aligned with the ontology to iteratively refine rules and expand the knowledge repository. This approach creates an effective semantic bridge between design knowledge and practical maintenance experience, facilitating knowledge-based error prevention and supporting enhanced product reliability and maintainability throughout the entire lifecycle.

Keywords: Maintenance error prevention,Ontology-based reasoning, Model-Based Definition (MBD), Knowledge driven design.

1. Introduction

With the increasing complexity of industrial systems and the paradigm shift towards Industry

5.0, knowledge-driven engineering has emerged as a critical enabler for enhancing system dependability and lifecycle efficiency (Polenghi et al. 2022)(Fan et al. 2022). Unlike traditional data-driven approaches that focus on operational monitoring, knowledge-driven methods aim to formalize expert intent and engineering constraints into reusable representations to support intelligent decision-making (Reinpold et al. 2025). In this context, maintenance error prevention is of paramount importance. Studies indicate that a significant proportion of maintenance errors originate from early design decisions rather than operational mistakes. Therefore, addressing maintenance requirements proactively during the design stage has become a consensus in the field.

However, integrating maintenance knowledge into the design process remains challenging. Traditional practices rely on scattered expert experience, lacking systematic verification. To address this, ontology-based knowledge modeling has been widely investigated. Recent studies have successfully applied ontologies to support data quality improvement (Woods et al. 2024), knowledge reuse (Guo et al. 2024), maintenance strategy selection (Montero Jiménez et al. 2023), and production workflow representation (Yang et al. 2023). Furthermore, semantic technologies have been utilized to enhance interoperability among lifecycle management systems (Fraga et al. 2020). While some researchers have explored Natural Language Processing (NLP) and Knowledge Graphs to extract maintenance insights from unstructured data (Hossayni et al. 2020), these approaches predominately focus on post-design operational support, with limited integration into the geometric design environment where early errors are generated.

A critical barrier to this integration is the disconnection between knowledge models and design models. Model-Based Definition (MBD) has become the standard for digital engineering, embedding geometry and Product Manufacturing Information (PMI) directly into 3D CAD systems (Pokojski et al. 2022)(Xiao et al. 2025). Although standards for asset information models are evolving (Miny et al. 2023), current MBD models often lack the explicit process semantics required for automated reasoning. Existing research typically addresses ontology modeling and MBD design in isolation or struggles with managing inconsistencies arising from model changes (Ji et al. 2024). Consequently, potential maintenance risks caused by ambiguous design specifications are rarely identified systematically before physical prototyping.

To overcome these limitations, this paper proposes a knowledge-driven semantic reasoning framework for proactive maintenance error prevention. This approach connects unstructured maintenance experience with structured design models through three key steps. First, instead of relying on implicit experience, a Maintenance Error Prevention Ontology is built through systematic domain analysis to define core concepts and constraints. Second, an MBD semantic enrichment strategy is introduced, using user parameters and annotation sets to explicitly add non-geometric maintenance information into CAD models. Finally, a hybrid reasoning mechanism, integrating DL-based implicit classification and SWRL-assisted constraint validation, is developed to automatically deduce design-induced vulnerabilities. By coupling these two logical layers, this approach establishes a semantic link between design intent and maintenance knowledge , enabling the detection of multidimensional risks.

2. Methodology

This chapter details the proposed knowledge-driven framework, systematically outlining the methodologies for maintenance knowledge acquisition, ontology construction, MBD semantic enrichment, and the hybrid reasoning mechanisms employed for proactive error prevention.

2.1. *Overall framework*

This paper proposes a knowledge-driven framework for maintenance error prevention at the early design stage by semantically integrating reusable maintenance knowledge with Model-Based Definition (MBD) representations. The primary objective of the framework is to proactively identify potential design-induced maintenance error risks by evaluating whether design information explicitly and consistently supports maintenance error prevention requirements.

As illustrated in Fig.1, the proposed framework consists of four tightly coupled layers:

maintenance knowledge acquisition, maintenance error prevention ontology construction, ontology-MBD semantic integration, and knowledge-based reasoning and feedback.

First, reusable maintenance knowledge is acquired from heterogeneous textual sources, including industry maintenance standards, generic maintenance guidelines, and historical maintenance error reports. Through domain analysis, key maintenance-related entities, relationships, constraints, and error-prone patterns are identified and extracted from these documents. This process aims to structure generic maintenance experience that is independent of specific product designs.

Second, the extracted knowledge is formalized into a Maintenance Error Prevention Ontology. This ontology serves as a reusable knowledge schema that defines core concepts, such as product elements, maintenance resources, process constraints, and risk types-along with their semantic relationships and rule-based constraints. It provides a structured representation of error prevention principles to support logical inference.

Subsequently, the MBD data generated during the design stage are integrated with the ontology. To overcome the semantic limitations of pure geometric models, the MBD model is semantically enriched with non-geometric attributes. Through a semantic mapping mechanism, these design elements are instantiated into the ontology. This transformation converts static geometric data and manufacturing information into a semantically interpretable instance graph, enabling the framework to assess whether critical maintenance information required by the ontology is explicitly expressed in the design model.

Finally, ontology-based reasoning is performed on the mapped ontology instances. Two complementary mechanisms are supported:

- Completeness and consistency checking, which identifies missing, ambiguous, or inconsistent maintenance-related annotations in the design model;
- Error risk inference, which applies ontology rules to infer potential maintenance error risks arising from the combination of design characteristics and insufficient semantic specification.

The reasoning outcomes are presented as actionable design feedback, enabling designers to improve maintenance error prevention during early design iterations.

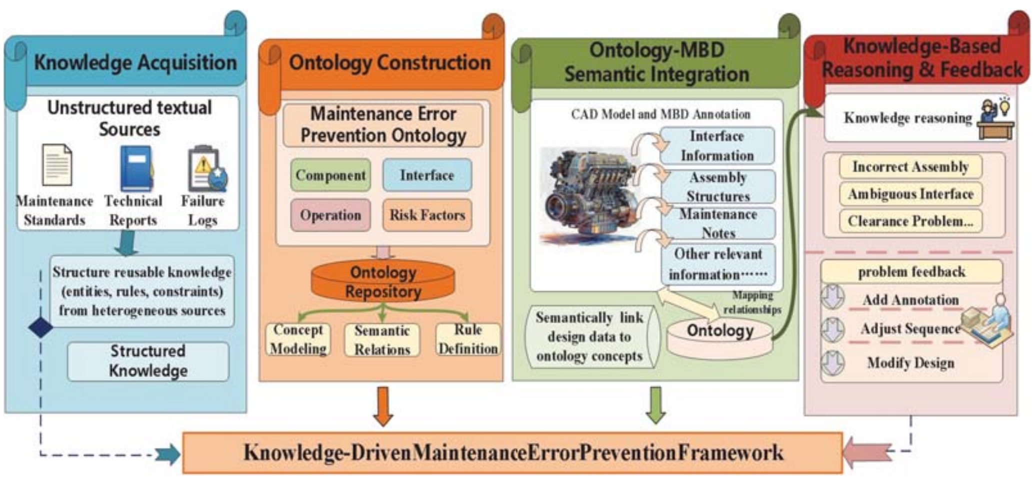

Fig. 1.Overall framework of the knowledge-driven maintenance error prevention approach

2.2.*Maintenance Knowledge Acquisition*

To ensure the ontology accurately reflects engineering reality, domain knowledge must be acquired from authoritative sources prior to formal modeling. Given the discrete and unstructured nature of maintenance data, this framework adopts a systematic domain analysis approach to distill and standardize key concepts from heterogeneous documents.

Primary knowledge sources include maintenance procedure manuals, design process standards, and historical FMEA records. These documents provide the foundational data regarding standard operating sequences, critical non-geometric constraints, and causal links between specific design deficiencies and operational consequences. Through a rigorous abstraction process, unstructured domain information is transformed into structured knowledge elements, primarily encompassing physical objects, process constraints, and risk patterns. These formalized elements constitute the direct inputs for the subsequent ontology construction, ensuring the model covers the essential entities and logic required for error prevention.

2.3.*Ontology Construction for Maintenance Error Prevention*

Based on the acquired knowledge elements, a Maintenance Error Prevention Ontology is constructed using OWL DL(Web Ontology Language Description Logic). This ontology serves as the Knowledge Schema, providing a formalized and computer-interpretable vocabulary for the domain.

The ontology establishes a comprehensive class hierarchy to categorize design and maintenance entities. Product_Element represents the physical constituents, distinguishing between general Mechanical_Components and critical Interface_Features to apply differentiated checking rules. Parallel to the physical structure, Maintenance_Resource categorizes the necessary execution conditions, with subclasses for Tooling_Resource and Human_Resource enabling the validation of resource availability. To address the limitations of geometric models, Constraint_Requirement explicitly models non-geometric process mandates, such as Sequence_Constraint and Torque_Constraint. Finally, Risk_Type defines the taxonomy of potential failure modes, including Risk_Deformation and Safety_Hazard, serving as the output targets for inference.

These isolated concepts are interconnected into a logical network through object properties. requires_resource links interface features to necessary tools, while must_satisfy binds features to mandatory constraints. Crucially, has_potential_risk is reserved for the reasoning engine to dynamically associate detected defects with specific risk types, completing the semantic description of the maintenance context.

2.4.Ontology-MBD Semantic Integration and Hybrid Semantic Reasoning

This section details the computational core of the framework, delineating the transformation of static geometric models into intelligent semantic instances and the automated inference of design risks.

2.4.1.MBD Semantic Enrichment and Integration Strategy

Traditional Model-Based Definition (MBD) models are geometry-centric and often lack the process semantics required for automated logic checking. To bridge this gap, a Semantic Enrichment Strategy is employed directly within the CAD environment. Design engineers utilize User Parameters and Annotation Sets to inject logic-based attributes into geometric features without altering the topology. This includes assigning functional tags to define engineering contexts and embedding non-geometric requirements as structured attributes or PMI text parameters.

To enable interoperability, a structural mapping mechanism transforms this enriched MBD data into ontology instances. User-defined parameters are mapped to corresponding ontology Data Properties, while unstructured annotation texts are parsed into text properties. This process reconstructs the static CAD tree as a Semantic Instance Graph, where design features become individuals populated with rich semantic data, ready for logical evaluation.

2.4.2.Hybrid Knowledge-Based Reasoning Mechanism

The framework utilizes a hybrid reasoning engine combining DL and SWRL to execute a two-level verification process.

The first level performs Implicit Semantic Classification via DL Subsumption. The ontology formally defines semantic equivalent classes for high-risk design features based on their quantitative and structural attributes. Driven by the Open World Assumption (OWA), the reasoner autonomously evaluates the mapped MBD instances and implicitly classifies them into specific risk-prone categories, realizing structural semantic inference.

The second level conducts Constraint Validation via SWRL. Building upon the DL classification, SWRL rules are designated to handle unstructured text pattern matching and multivariable arithmetic comparisons. By coupling these two logical layers, the reasoning engine dynamically deduces complex consequences, materializing them as new risk assertions linked to specific design features, thereby providing designers with immediate, actionable feedback

3. Case Study

3.1.*Case Description and Risk Scenario*

To validate the proposed semantic reasoning framework, the disassembly process of a flywheel housing was selected as the verification object.

The disassembly of the flywheel housing involves multiple M10 bolt connections. According to reliability engineering principles, the disassembly sequence is a critical process parameter. Improper disassembly sequences lead to stress concentration, which significantly increases the probability of component deformation and subsequent sealing failure.

However, during the Model-Based Definition (MBD) design phase, critical non-geometric process constraints are often omitted or lack systematic validation. To comprehensively evaluate the reasoning capability of the proposed ontology, this study constructs a verification scenario encompassing dual latent hazards during the disassembly process of a high-bolt-count flange interface. First, the interface lacks a specified disassembly sequence annotation; this design omission is prone to inducing stress concentration and subsequent deformation risks (Risk_Deformation). Second, the disassembly operation requires specific tooling (Res_Wrench_13), which strictly demands a minimum operational clearance. Nevertheless, the actual available clearance extracted from the MBD model annotations measures only 7 mm, constituting a severe spatial interference and accessibility conflict (Risk_Clearance_Conflict). This case study aims to verify whether the proposed hybrid reasoning engine can leverage deep semantic classification and rule constraints to achieve autonomous inference and precise identification of these complex, interconnected quality and maintainability risks.

3.2.*Semantic Enrichment and Data Mapping*

The raw CAD model lacks the semantic interoperability required for automated reasoning. As shown in Fig.2, we utilized CATIA User Parameters and Annotation Sets to inject semantic constraints into the geometric model.

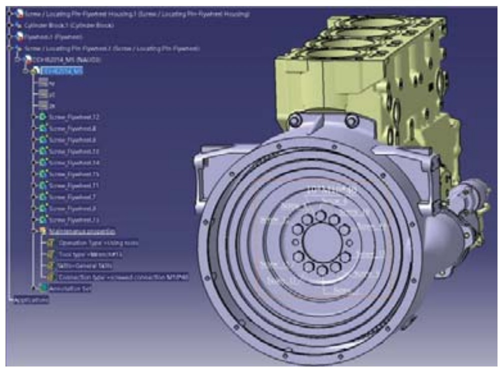

Fig. 2.Flywheel housing information marking

To bridge the gap between the geometric domain and the knowledge domain , a semantic mapping mechanism was established. As listed in Table 1, geometric features and PMI (Product Manufacturing Information) are extracted and instantiated into ontology individuals.

Table 1.Mapping relationships between MBD design parameters and ontology properties

Parameter Name	Mapped Ontology Property
Operation Type	Maintenance_Resource
Tool type	Tooling_Resource
Skills	Human_Resource
Connection type	Interface_Feature
Annotation set	Mechanical_Component、Interface_Feature

3.3. *Ontology Construction and Hybrid Reasoning Rule Definition*

To formalize domain maintenance knowledge, a specific maintenance error prevention ontology was constructed. Fig. 3 illustrates the class hierarchy and core semantic relationships of the ontology, explicitly introducing advanced conceptual nodes such as High_Stress_Interface and Accessibility_Risk to support deep logical inference. To address the complexity of design semantics, this framework employs a Hybrid Reasoning Mechanism, which integrates structured semantic classification with unstructured constraint validation to achieve genuine semantic reasoning.

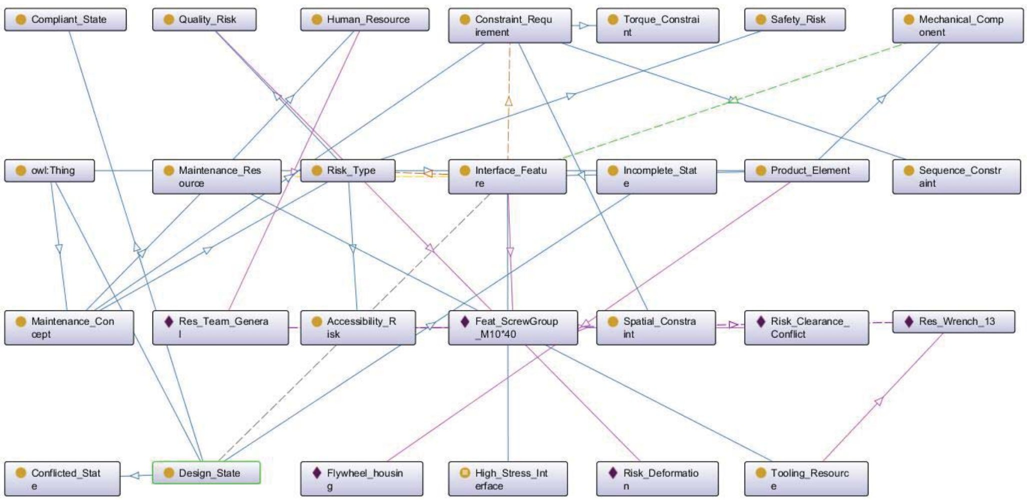

Fig.3.Class hierarchy and core relationships of the Maintenance Error Prevention Ontology

1) DL-Based Subsumption Reasoning and Implicit Classification

The framework utilizes Description Logic (DL) to handle structured classification based on quantitative attributes. In the ontology, the semantic equivalent class High_Stress_Interface is formally defined using the Manchester syntax:

Interface_Feature and (item_quantity some xsd:integer[> 4])

Based on the Open World Assumption (OWA) and the DL subsumption mechanism, the reasoner can autonomously and implicitly classify geometric instances into this high-risk category according to their inherent properties (e.g., the number of fasteners), without relying on explicit external trigger rules.

2) SWRL-Based Constraint Validation

Building upon the foundational structural classification accomplished by DL, the framework introduces SWRL rules specifically designed to process unstructured text pattern parsing and multivariable numerical comparisons.

Rule 1 (Sequence Integrity Check):

Used to identify missing assembly process constraints on high-stress features.

High_Stress_Interface(?f)^pmi_text_content (?f,?text)^swrlb:matches(?text,"^((?!Sequence).)*$") -> has_potential_risk(?f, Risk_Deformation)

Rule 2 (Spatial Clearance Conflict Check):

Evaluates physical maintenance accessibility risks by comparing the available spatial clearance extracted from the design model against the standard operational specifications of the required tools.

Interface_Feature(?f)^requires_resource(?f, ?t)^has_available_clearance(?f,?avail)^requires_minimum_clearance(?t,?req)^swrlb:lessThan(?avail,?req)>has_potential_risk(?f,Risk_Clearance_Conflict)

3.4. *Reasoning Results and Analysis*

The ontology and instances were processed using the Pellet reasoner. The reasoning results confirmed the effectiveness of the proposed framework in executing genuine semantic reasoning and multidimensional risk identification.

1) Automated Semantic Classification (DL Subsumption)

The reasoner leveraged the hierarchical logic of the ontology to automatically classify instances. As shown in Fig. 4, Res_Wrench_13 was inferred to be a type of Maintenance_Resource, validating the inheritance mechanism of the knowledge model. Furthermore, Fig. 5 demonstrates the application of Description Logic (DL) subsumption. The system successfully parsed the geometric quantification (item_quantity = 10) of the instance Feat_ScrewGroup_M10*40. Driven by the predefined equivalent class axioms, the reasoner implicitly classified this instance as a High_Stress_Interface without any external rule intervention. This highlights the framework's capacity to deduce implicit structural knowledge.

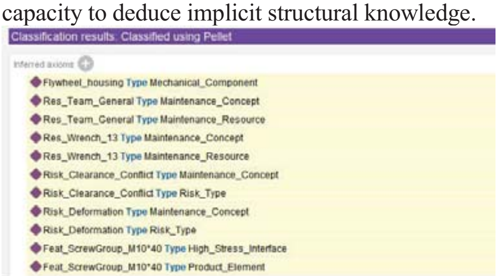

Fig.4.Semantic classification results of instances

Fig.5.Inference result of the high-stress interface

2) Hybrid Risk Inference

Building upon the structural classification, the hybrid reasoning engine executed the SWRL constraints to identify specific maintenance vulnerabilities. Fig. 6 presents the inferred object property assertions, where the system concurrently detected two distinct risks for the target instance:

Quality Risk: The reasoner successfully inferred the object property has_potential_risk Risk_Deformation. The system analyzed the PMI text content, detected the absence of "Sequence" constraints, and triggered Rule 1 to assert the latent risk. This assertion was inferred because the autonomously classified High_Stress_Interface lacked the mandatory specifications.

Accessibility Risk: The system additionally inferred has_potential_risk Risk_Clearance_Conflict. This operational risk was identified by dynamically comparing the available spatial clearance extracted from the MBD model against the minimum clearance requirement of the assigned tooling resource (Res_Wrench_13).

By propagating these localized risks through transitive topological relations, the framework provides comprehensive feedback regarding the overall maintainability state of the assembly. This semantic bridge enables designers to proactively identify and rectify complex, interconnected design defects prior to physical prototyping.

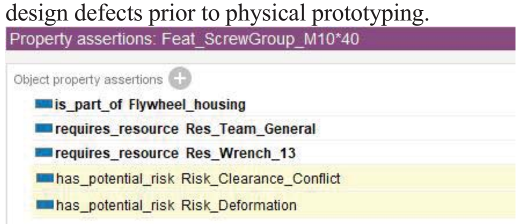

Fig.6.Inferred potential maintenance risks

4. Conclusions and Future Remarks

This study proposes a knowledge-driven framework for proactive maintenance error prevention in early design. We established a foundation for the system by acquiring reusable maintenance knowledge from sources like technical manuals and FMEA records through domain analysis. This knowledge was formalized into a Maintenance Error Prevention Ontology, which defines the logical relationships between product elements, resources, and process constraints. To integrate this with design environments, we developed a semantic mapping mechanism. This approach links MBD data, particularly user parameters and annotation sets, directly to ontology instances. To perform semantic inference and constraint validation, a hybrid reasoning engine integrating DL subsumption and SWRL was implemented. Its effectiveness was demonstrated through a dual-defect case study on a flywheel housing. The framework successfully achieved the autonomous classification of high-stress interfaces and concurrently identified interconnected multidimensional risks, specifically quality risks arising from omitted assembly sequence constraints, and maintainability risks induced by spatial clearance conflicts.

Future work will focus on enhancing the framework's scalability. Currently, knowledge extraction relies on manual analysis; therefore, we plan to use Large Language Models (LLMs) to automate the extraction of rules from unstructured text. Additionally, we aim to improve interoperability by mapping the custom semantic parameters to neutral standards like STEP AP242, facilitating data consistency across different software platforms.

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