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Efficient FMEA Re-Validation: Multi-view Model Integration in Agile Production Systems Engineering

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Felix Rinker [1,2]
Sebastian Kropatschek [3]
Thorsten Steuer [3]
Elmar Kiesling [4]
Kristof Meixner [1,2]
Patrik Sommer [5]
Arndt Lüder [6]
Dietmar Winkler [1,2]
Stefan Biffl [2,3]

[1] *CDL for Security & Quality Improvement in the Production System Lifecycle*
[2] *Institute of Information Systems Engineering, Technische Universität Wien, Austria*
[3] *Center for Digital Production, Vienna, Austria*
[4] *Institute of Data, Process, and Knowledge Engineering, WU Wien, Austria*
[5] *Neuman Aluminium, CAG Holding GmbH, Austria*
[6] *IAF at FMB, Otto-v.Gueriche University, Magdeburg, Germany*

QSE - Quality Software Engineering
Quality Software Engineering | Faculty of Informatics | TU Wien

Abstract

In agile Production Systems Engineering (PSE), multi/disciplinary teams work concurrently on a variety of PSE artifacts in an iterative process, which can be supported by common concept and Product-Process-Resource (PPR) modeling. However, keeping track of the interactions and effects of changes across engineering disciplines on the one hand, and their implications for risk assessment on the other hand, is exceedingly difficult in such settings. To tackle this challenge and systematically co-evolve Failure Mode and Effects Analysis (FMEA) and PPR models during PSE, it is necessary to propagate and validate changes across engineering artifacts. To this end, we design and evaluate a *FMEA-linked-to-PPR assets (FMEA+PPR) meta model* to represent relationships between FMEA elements and PSE assets and trace their change states and dependencies in the design and validation lifecycle. Furthermore, we design and evaluate the FMEA+PPR method to efficiently re-validate FMEA models upon changes in multi-view PSE models. We evaluate the model and method in a feasibility study on the quality of a joining process, automated by a robot cell in automotive PSE. The study results indicate that the FMEA+PPR method is feasible and addresses requirements for FMEA re-validation better than alternative traditional approaches. Thereby, the FMEA+PPR approach facilitates a paradigm shift from traditional, isolated PSE and FMEA activities towards an integrated agile PSE method.

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Intro 1

1.1 Introduction

In recent years, a technological revolution in industrial systems has been discussed under various labels – in Europe, most notably under the term Industry 4.0 (I4.0) [14]. Key goals of I4.0 include, among others, IT-enabled mass customization of manufactured products and automatic and flexible adaptation of the production chain [34, 33]. These goals require a flexible approach towards the engineering of industrial systems and a shortening of development cycles. Consequently, Production Systems Engineering (PSE) has become agile as engineers from several disciplines work iteratively and in parallel to develop Product-Process-Resource (PPR) assets, such as product designs, production process models, and production resource plans, using PPR modeling approaches [30, 1].

In such agile engineering processes, engineers are likely to update their PPR design assumptions multiple times throughout an engineering project [5]. Reasons for such revised assumptions include changed requirements derived from product design updates, changes in process design, or a better understanding of system characteristics resulting from collaborative design, simulation, and testing. Design changes are made frequently and routinely by stakeholders across engineering disciplines. Consequently, these changes make it exceedingly difficult to assess potential quality implications and risk factors as PSE artifacts evolve. Therefore, managing risks efficiently and effectively has become a significant challenge in multi-disciplinary, agile PSE [13].

In this context, the Failure Mode and Effects Analysis (FMEA) is an established method in early project phases for evaluating the effects of potential failures of system components, assessing risk factors, and detecting and isolating faults [45]. FMEA reports are typically required to demonstrate compliance with safety and quality requirements, such as ISO 9001, QS 9000 and ISO/TS 16949 [21]. However, document-driven or paper-based FMEA impedes one of its key purposes, i.e., to reduce design effort by identifying potential design flaws and to mitigate risks in the early stages of system design. Furthermore, in late project phases, i.e., after requirements analysis, design, and development, the re-validation of FMEA results is often limited; late changes in the design documentation are often not considered. Therefore, error-prone and laborious reconstruction of knowledge from design documentation is often necessary [32] to maintain the FMEA.

This paper aims to facilitate FMEA re-validation as an integral part of the PSE process. To this end, it is necessary to implement FMEA re-validation into engineering workflows to maintain the FMEA, track the validity of its elements, and foster the continuous reflection of changes to engineering assets. In the following, we present challenges that hinder the efficient re-validation of FMEA in multi-disciplinary PSE settings [5].

Challenge 1. *Scattered and implicit domain expert knowledge.* Typically, there are semantic gaps between concepts used by stakeholders who conduct FMEA analyses and other domain experts in PSE projects. Bridging that gap requires domain knowledge, which is often not explicitly documented or scattered across heterogeneous artifacts. This makes the process of comparing and aligning FMEA models and PSE artifacts inefficient and error-prone.

Challenge 2. *Inefficient analysis of changes.* FMEA analyses shall reuse concepts from PPR models to use shared knowledge. However, it remains unclear how to efficiently re-validate FMEA elements after PSE artifact changes. To this end, it is necessary to automate capabilities such as configuring (i) a multi-view PPR model that integrates and preserves the PSE stakeholder perspectives; (ii) change dependencies in and between PPR assets and FMEA model elements; (iii) a data integration process that can propagate updates from local stakeholder views in artifacts to PPR asset property values; and (iv) analyzing which FMEA model elements require re-validation due to PPR asset changes.

In this paper, we tackle these challenges by exploring how PPR Asset Network (PAN)-based coordination [8] can facilitate the efficient integration of multi-view PPR and FMEA models. As an illustrative use case, we showcase the change of a *torque value* in particular engineering views (quality, mechanics, engineering, automation) and its effect for the FMEA re-validation w.r.t. *joining quality* (cf. Section 1.4).

We build on and, following a Design Science approach, extend our previous work [6, 28] to (i) conduct a domain analysis to identify requirements, (ii) design and evaluate the *FMEA-linked-to-PPR assets (FMEA+PPR) meta model* to represent relationships between FMEA elements and PPR assets and trace their change states and dependencies in the design and validation lifecycle; (iii) design and evaluate the *FMEA+PPR method* to provide capabilities for change analysis with FMEA concepts and constraints in agile PSE. We evaluate the FMEA+PPR model and method in a feasibility study on the quality of a joining process automated by a robot cell in an automotive PSE context.

The main contributions of this paper are: (i) The provision of *insights* to Model-based Systems Engineering (MBSE) researchers on PSE domain concepts and issues. (ii) The *FMEA+PPR meta model* to represent the concepts required for FMEA re-validation after updates to PSE artifacts. (iii) The *FMEA+PPR process* to define multi-view model integration as a foundation for efficient FMEA re-validation after updates to PSE artifacts. (iv) Results of a *feasibility study* on the FMEA+PPR approach by providing a FMEA+PPR model instance for a use case derived from real-world data in comparison to two traditional approaches.

The remainder of this paper is structured as follows. Section 1.2 summarizes related work on Knowledge Management in PSE and FMEA. Section 1.3 motivates the research question and describes the research method. Section 1.4 introduces an illustrative use case for evaluation and requirements for efficient FMEA re-validation in PSE. Section 1.5 outlines the FMEA+PPR meta model and process for the representation of knowledge and the steps for efficient FMEA re-validation after changes to PSE artifacts. Section 1.6 reports on a feasibility study with a FMEA+PPR model instance based on real-world industry data to validate the research results. Section 1.7 discusses the research results and limitations. Section 1.8 concludes and delineates future work.

1.2 Related Work

This section summarizes related work on Knowledge Management in PSE and the FMEA method.

1.2.1 Knowledge Management in PSE

In PSE, engineers collaborate in a Multi-Disciplinary Engineering Environment (MDEE) to design a production system [2]. This requires an iterative, consistent, and highly qualitative design, construction, and validation process [5]. The challenge is to integrate the discipline-specific engineering views, concepts and artifacts into a holistic data view. This requires effective and efficient collection, selection, and transformation of scattered and heterogeneous information.

System Modeling in PSE. Typically, the engineering information in PSE projects is encapsulated in discipline- and tool-specific artifacts [39]. Discipline-specific artifacts and processes hinder a seamless and traceable information exchange across disciplines and stakeholders [42], which is needed to support the Industry 4.0 transformation in PSE. Wortmann*et al.* [44] identify domain-specific modeling languages and model-driven engineering as essential to facilitate complex data-driven use cases in the Industry 4.0 context. The Reference Architecture Model for Industry 4.0 (RAMI40) it a main building block of the Industry 4.0 initiative and is supported by established standards and technologies, like AutomationML (AML), Systems Modeling Language (SysML), Data Exchange in the Process Industry (DEXPI) and OPC Unified Architecture (OPCUA), which aim at alleviating these limitations [15].

Multi-view Modeling and Common Concepts in PSE. Multi-view modeling [4] aims at preserving description-specific concepts and views to support collaboration and knowledge integration in MDEE. Achieving multi-view models in PSE projects, requires to identify relevant information across domain-specific concepts and models that are defined as boundary objects [38]. We use Common Concepts (CCs) as boundary objects to define assets that unify all properties that stakeholders share on a particular concept [27]. Such common views on assets [27] seem promising to describe Industry 4.0 components [20, 25]. Schleipen*et al.* [31] introduced PPR modeling, representing requirements and an integrated model in PSE. PPR modeling is based on the three main aspects of a production system: (1) *products* with their properties, (2) *processes* that produce products, and (3) *resources* that execute production processes. Meixner*et al.* [23] introduced the PPR Domain Specific Language (DSL), a machine-readable and technology-agnostic DSL for PSE modeling. A PPR Asset Network (PAN) [8] is an integrated multi-view engineering model that consists of these common concepts, their properties, and multi-disciplinary interfaces [22].

Multi-view Model Integration in PSE Adequate multi-view process and framework support is a major concern to support interdisciplinary PSE [42, 4]. Tunjic*et al.* [40] introduce a Single Underlying Model (SUM), a common unified model, to enable multi-view modeling environments. To populate a SUM, previously defined mappings between the common and the single views, are used. Biffl*et al.* [7] define *Engineering Data Logistics* as a socio-technical system ensuring that engineers receive the required data at the right amount, quality, and point in time using an integrated model. Several framework architectures [16, 19] propose AML for modeling such a integrated model in the PSE context. Rinker*et al.* [28] propose a Multi-view Model Transformation (MvMT) architecture, which uses AML to enable and automate an multi-disciplinary and view-specific data integration pipeline.

1.2.2 Failure Mode and Effects Analysis (FMEA)

Quality assurance is crucial in the engineering of technical systems [17]. It involves many disciplines and related engineering roles, but is mainly centered around quality engineering that uses appropriate quality models [13]. The FMEA is an engineering and quality assurance method to identify and mitigate risks and potential production failures before a customer can be effected by poor product performance [37, 45]. A typical FMEA identifies known and potential failure modes along with their corresponding causes and effects, prioritizes them, and defines corrective actions. Several FMEA types have been reported [37]. The *process FMEA* focuses on failure modes occurring during the manufacturing and/or the assembly process. The *design* and *concepts FMEA* addresses product-level or concept-level failure modes [35]. Other approaches aim at enhancing the FMEA method to identify waste modes or to monitor service quality [10, 41].

In multi-disciplinary engineering processes, the FMEA typically starts with assembling a FMEA team of experts with relevant domain knowledge [45]. This team analyses the system's architecture, functions, and characteristics. Utilizing expert meetings, (a) potential failure modes of the analyzed objects, (b) the respective impact and consequences, and (c) potential mitigation actions are identified and assessed. The evaluation is based on the criteria severity, occurrence, and detection [45], represented by the Risk Priority Number (RPN). All steps of the analysis are documented in a comprehensive FMEA report, including a priority list of failure modes and corrective actions.

Although there exists a number of tools to support the FMEA, the monitoring of artifact updates remains challenging [36]. Therefore, we explore the feasibility of representing FMEA model elements alongside with PSE model elements in a PPR Asset Network for facilitating efficient analysis and updates.

Traditional FMEA Applications. We observed the following FMEA application areas, relevant for automation system integrators:

FMEA model representation. FMEA knowledge can be represented in plain text, spreadsheet tables, graph modeling tools and dedicated FMEA tools. However, few FMEA representations consider the knowledge of PSE tools or databases. Established FMEA tools, such as APIS[1], focus on the textual description (in natural language) of FMEA concepts. Therefore, it is difficult to provide tool support for the efficient identification of FMEA elements that require re-validation.

Early FMEA as living documentation. Early FMEA can start after the initial definition of the production system, as soon as the main resources are specified. In this case, findings from FMEA can inform detail engineering to mitigate important risks early and efficient.

FMEA as documentation for regulators. To fulfill regulatory requirements for risk management, the FMEA is created/updated before delivering the production system to the customer. If the FMEA approach is applied in this context, often no frequent updates are required/executed. Consequently, findings in late project phases can lead to expensive late design changes.

Knowledge Management for FMEA re-validation. Two main approaches have emerged to manage knowledge in PSE for FMEA re-validation. They can be categorized based on their capabilities for knowledge representation and access as well as capabilities for data collection and process coordination.

FMEA re-validation based on Engineering Artifacts is common for FMEA models and engineering artifacts that have been developed and maintained independently [13]. Quality engineers re-validate the correctness of FMEA models based on their knowledge of the engineering project. Therefore, they manually review PSE artifacts and the semantics of the engineering objects, which typically requires support by domain experts. The re-validation results in new or revised versions of FMEA models. Feedback to the engineering team is given manually based on document exchange. Hence, the quality of the FMEA re-validation outcome hinges on the experts' knowledge and their coordination capabilities.

FMEA re-validation in Tool Suites aims at improving FMEA re-validation by exploiting tool suites that can integrate engineering artifacts into engineering objects. These engineering objects represent the data required by a selected subset of the engineering disciplines in an engineering organization [16]. Tool suites simplify the re-validation process by supporting (i) the review of engineering artifact changes to engineering objects and (ii) the interaction and coordination with domain experts. In addition, tool suites can enable the integration of FMEA models into the tool suite to provide automatic feedback to experts. However, typical PSE tool suites do not provide the required re-validation support.

In this paper, we explore the *FMEA re-validation with dependencies to a PPR Asset Network* by representing dependency links between FMEA models and PPR asset concepts [8]. This facilitates the concurrent engineering of the FMEA model and PPR assets. To provide sufficient access to integrated PPR knowledge, this approach is based on engineering data logistics [9], which provides integrated information management on engineering artifacts coming from the disciplines required in an engineering project. This approach builds on handling engineering objects similar to the asset administration shell in Industry 4.0 [25]. To this end, we integrate all engineering information on these objects as stakeholder views, including FMEA-based information that forms a PPR Asset Network. This is similar to the coordination artifact described in [8], but in addition integrates additional cause and effect assets. This integrated information can strongly support the quality engineer in the re-validation process by efficiently providing the relevant system knowledge required for FMEA re-validation and for efficient coordination with domain engineers [8]. However, this approach requires efficient management of dependencies between engineering objects of the different disciplines involved and tools of the engineering organization.

[1] APIS: www.apis-iq.com/

1.3 Research Questions and Approach

To tackle the identified challenges and to improve the coordination of FMEA re-validation after changes in PSE, we followed a *Design Science* approach [43].

First, we reviewed literature on PSE and multi-view model integration related to FMEA. Next, we conducted workshops with stakeholders at four engineering organizations with 9 domain experts coming from 3 domains and 6 researchers with focus on exploring PSE risks, engineering artifact exchange between work groups, required knowledge, and gaps in artifact exchange. Building on the domain analysis at large PSE companies in automotive manufacturing [22], the guidelines for coordinating agent systems [24], and on the Industry 4.0 initiative [25], we derived the following research questions (RQs).

RQ1. Knowledge representation for FMEA integration into agile production systems engineering. *What model in agile PSE can represent FMEA concepts linked to PSE assets and their change/validation states to manage the efficient re-validation of FMEA model elements after updates to PPR asset property values?* To address RQ1, we built on and extend the *PAN* [8] meta model to design the FMEA+PPR meta model, including FMEA and PPR concepts, FMEA links and change/validation states. These foundations allow designing the FMEA+PPR with coordination states and multi-aspect change dependencies as a basis to design business processes in engineering projects. We illustrate the design with examples from the use case *FMEA Re-Validation after Changes to Engineering Artifacts* (cf. Section 1.4).

RQ2. Process for FMEA integration into agile production systems engineering. *What process can integrate multi-view FMEA and PSE asset models as a foundation for analyzing the required re-validation scope of FMEA model elements after updates to PPR asset property values?* To address RQ2, we built on the FMEA+PPR meta model coming from RQ1 and (a) designed the FMEA+PPR process to define a FMEA+PPR model for an application scope and (b) to configure and run a multi-view data logistics for identifying FMEA elements to re-validate after changes to PSE assets.

For evaluation we conducted a feasibility study on instantiating a FMEA+PPR model from typical PSE artifacts to answer key stakeholder questions regarding the re-validation of FMEA elements. We investigated the number of the FMEA+PPR model elements and the dependencies that drive the effort for modeling, data provision/maintenance, and the analysis for FMEA re-validation. Therefore, we considered work cells of different sizes in a typical automotive production plant with up to 300 work cells. Further, we used the FMEA+PPR model instance to evaluate the FMEA+PPR model concept regarding the identified requirements in comparison to traditional best-practice approaches in PSE.

1.4 Illustrative Use Case

This section introduces the use case *FMEA Re-Validation after Changes to Engineering Artifacts* to elicit requirements for improving the efficiency of FMEA re-validation in PSE with PPR asset-based coordination [8]. We report on PSE and FMEA re-validation processes abstracted from real-world use cases from system integrators of high-performance automation for car part manufacturing in Germany and Austria. The goal of this illustrative use case is to automate discrete assembly processes, such as positioning and joining of car parts, with robot work cells. A typical car production plant consists of 200 to 300 robot work cells that use 20 to 30 robot types [22]. This large number of components makes frequent and manual re-validation complex and expensive.

Engineering process. In traditional PSE projects, engineers follow a sequential engineering process in several engineering phases, including among others quality engineering for system design validation and risk management with FMEA. However, engineers typically work in parallel and iteratively within a phase. Due to change requests, engineers often need to work on PSE artifacts that belong to several phases (e.g., artifacts that evolve over different phases). These parallel engineering activities of several engineers require flexible and agile solutions. An early-stage FMEA can be conducted based on an initial PPR model that results from basic planning. However, the FMEA model has to be refined and updated as new FMEA-relevant knowledge emerges in engineering activities along the PSE project course. These activities are driven by change requests, which may be triggered by engineering needs or FMEA results and consequently require (a) changes to (validated) engineering results and (b) the re-validation of FMEA elements that depend on changes. Such changes become significantly more expensive within late phases [7].

Design and validation lifecycle. In the PSE process, assets and their properties have to be designed and validated. For the coordination of design and validation activities, these elements are usually assigned to *design* and *validation states* [8], e.g., "to design", "in design", "designed"; "to validate", "in validation", "validated ok", "validated with issue". Based on these states, related stakeholders can describe processes/rules for the re-validation (and rework) of assets after changes. Traditional approaches often lack in explicitly defining and using design and validation states [8]. To address these shortcomings, we explore the FMEA+PPR approach to efficiently link FMEA concepts to PSE artifacts via a PAN. Note that the PAN holds FMEA concepts and can be efficiently derived from PSE artifacts [6].

Stakeholder views on FMEA and PPR assets and artifacts. PSE stakeholders usually come from several disciplines, including mechanical, electrical, software/automation, and simulation engineering [8, 22].

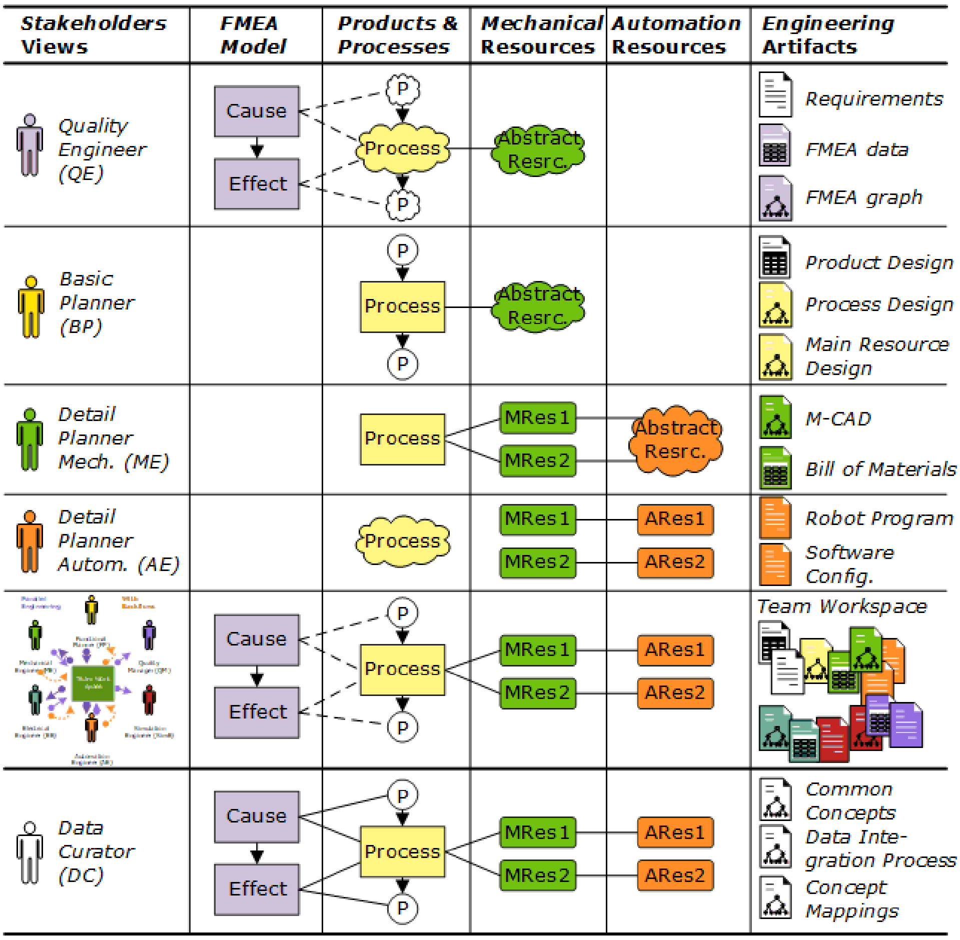

Figure 1.1: Stakeholder concepts and artifacts for the use case *FMEA Re-Validation after Changes to Engineering Artifacts*, based on [8, 22].

Fig. 1.1 illustrates selected stakeholder views on FMEA and PSE assets – in particular, products and processes, resources (e.g., mechanical and automation resources), and shared engineering artifacts along the progress of a typical PSE project. Each row shows a stakeholder view of assets and associated engineering artifacts that they design in *private work spaces* and share in a *team work space* (cf. Fig 1.4 in Section 1.5.3). A major challenge for quality engineers is to keep the FMEA model synchronized with design changes and shared engineering assets.

The *Quality Engineer* (QE) designs an FMEA model by collecting and analyzing FMEA data to identify, prioritize, and mitigate risks related to the production system that have an impact on business performance, such as product quality, production throughput, and cost. The QE typically refers to PSE/PPR concepts but does not maintain links between FMEA and PSE models explicitly. *Basic planners* design high-level solutions for PSE assets, e.g., resources such as high-level library elements and parameters. *Detail planners* design plans for technological aspects of production system parts to automate the production processes. PSE artifact changes, such as the design of the product, can have a critical impact on dependent resource assets and on the key parameters of the production system (e.g., product quality or production cycle time and throughput). Therefore, the QE interacts with related engineers to identify and describe candidate failure modes, e.g., breaking of a screw, and possible relationships to causes, e.g., insufficient torque regulation and a robot's position accuracy.

In Fig. 1.1, the fifth row shows the team work space where engineering teams share their results as human- and machine-readable artifacts. Example artifacts are spreadsheets or engineering tool data, e.g., in (AML) [3]. Depending on engineering knowledge management capabilities, the PSE assets are mostly represented as engineering data with implicit domain knowledge. Thus, the PSE asset representations may be incomplete and inconsistent and often require the interpretation of domain experts. However, the engineering artifacts should provide a consistent shared view on engineering requirements and designs.

The FMEA model for a typical work cell in automotive production (cf. Fig. 1.5) contains dozens to hundreds failure modes and causes that refer to several hundreds PSE assets and properties defined in many engineering artifacts, such as CAD drawings and data sheets. The heterogeneity of engineering artifacts and data often results in a semantic gap between the FMEA model and local stakeholder views. Therefore, the comparison of the FMEA model and PSE concepts and the FMEA re-validation becomes inefficient and error-prone. To overcome this gap, multi-view model integration [28] can provide a PSE asset model [8] as a foundation to explicitly model dependencies between FMEA and PSE asset concepts. In this paper, we assume the role of a *data curator* (cf. Fig. 1.1, bottom row), who focuses on (a) eliciting PSE concepts that are common to several stakeholders and (b) configuring data logistics for multi-view model integration to extract the common concepts from engineering artifacts.

FMEA concerns for efficient re-validation. The aim of a screwing process is joining two or more components or materials with a screw, e.g., two or more objects (cf. Fig. 1.5). Therefore, a key characteristic focuses on the quality of the joining process and the joint itself. An important fault in this context is an incorrect or insufficient screwing process, potentially caused by an incorrect torque caused by abrasion and friction. Friction, in turn, depends on the position of the blind rivet nuts, which need to be inserted with the required precision (cf. Fig. 1.5, property *M.Pos.accuarcy* of the resource *Robot*). However, if the setting process does not join the rivet element properly, the friction may be insufficient to install the screw, and the desired breakaway torque might not be achieved. A setting process is only reliable if the force *M.Torque* and the position are controlled and monitored. Furthermore, the setting speed should also be adapted to the rivet element and material. A setting process that slows down towards its end ensures more precise process control and outcome but will increase the process property *Q.cycle time*. Insufficient friction may result in the failure mode *screw breakaway out of tolerance* (cf. Fig. 1.5) and incur high costs or result in liability claims by end customers. Hence, a change of the torque or calibration of the robot may have immediate effects on the corresponding failure mode in the FMEA. A divergence between FMEA and PSE concepts can result in too many or too few quality checks during the production process. Therefore, updates of values of related concepts in engineering views require the re-validation of FMEA model elements by involved domain experts. There may be hundreds of FMEA conditions for a machine concerning hundreds of engineering concepts in a variety of stakeholder views. Therefore, the efficient re-validation of the FMEA model requires capabilities for the prioritization of FMEA model elements related to changes in stakeholder views and the grouping of FMEA concerns to involved stakeholders to conduct focused workshops for re-validation.

Requirements. Based on the use case, we identified the following requirements (Rx) for an efficient FMEA+PPR re-validation approach.

R1. FMEA concept representation. The model shall represent FMEA concepts – in particular failure modes, causes, their relationships and characteristics, such as severity and probability.

R2. PAN concept representation. The model shall represent PAN concepts [8] – in particular products, production processes, production resources, and their relationships and properties.

R3. FMEA-to-PPR dependency representation. The model shall represent links between FMEA concepts and PAN concepts, e.g., PPR concepts, that are semantically similar to concepts used in the FMEA.

R4. FMEA/PPR change coordination representation. The approach shall represent design and validation states for change coordination, such as model elements that changed or have to be re-validated after changes.

R5. Efficient FMEA re-validation after PPR changes. The process shall provide capabilities (a) for defining and instantiating an FMEA+PPR model and (b) for the efficient identification of FMEA model elements that require re-validation after changes.

1.5 Linking FMEA Models to Engineering Assets

This section introduces (a) the FMEA+PPR Meta Model, (b) the FMEA+PPR Process, and (c) the FMEA+PPR System Architecture that link FMEA models to engineering assets. We explore the *FMEA+PPR approach* to efficiently link FMEA concepts to PPR assets in a PAN [8].

1.5.1 FMEA+PPR Meta Model

To address RQ1 (cf. Section 1.3) and the requirements (cf. Section 1.4), we introduce the FMEA+PPR meta model that is based on (a) the insights and knowledge we acquired in the domain analysis [22], (b) the CPPS-RA approach [6], and (c) the coordination artifact PAN [8]. We extend the PAN meta model with FMEA concepts and elements that link them to the PAN, depicted in Fig. 1.2.

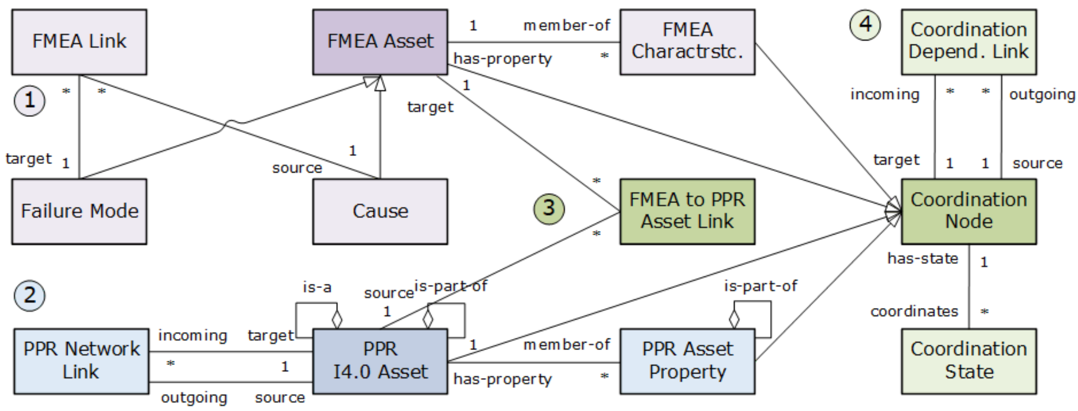

Figure 1.2: FMEA+PPR Meta Model using UML notation, based on [8, 22].

FMEA concepts. To address the requirement R1 (cf. Section 1.4), the FMEA+PPR meta-model represents *FMEA Assets* (cf. Fig. 1.2, tag 1) with their *Characteristics* and *Links*. An *FMEA Asset* can be a *Failure Mode* (effect) or a Cause.

PAN concepts. To address requirement R2 (cf. Section 1.4), the meta-model represents *PPR I4.0 Assets* (cf. Fig. 1.2, tag 2) with their *Asset Properties* and *Links*, similar to the coordination artifact PAN in [8].

Links between FMEA and PAN concepts. To address requirement R3 (cf. Section 1.4), the meta-model includes *links between FMEA and PAN concepts* (cf. Fig. 1.2, tag 3), i.e., mappings between PPR concepts that are semantically similar to FMEA concepts.

Change coordination states of and dependencies between PPR and FMEA assets/concepts. To address requirement R4 and R5 (cf. Section 1.4), the meta-model represents (a) change coordination states of PPR and FMEA assets and concepts and (b) coordination dependencies between PPR and FMEA assets and concepts. (cf. Fig. 1.2, tag 4). These coordination states can represent states in the design and validation life cycles of a model element (cf. Section 1.4), e.g., whether a model element has changed and need to be re-validated (cf. Fig. 1.5, state markers in diamond shape). The coordination dependencies facilitate the representation of domain-specific dependencies, e.g. mechanical, topological, or logical links between PPR and/or FMEA elements, indicating model elements to evaluate for re-validation in case of a changes in a PPR or FMEA asset.

1.5.2 FMEA+PPR Process

To address RQ2 (cf. Section 1.3), we propose the FMEA+PPR process (cf. Fig. 1.3) including the following steps:

Step 1. Specify scope for FMEA and PPR models. In this step, FMEA and domain experts determine the scope of the FMEA and identify relevant PSE artifact models from use case data. Furthermore, in cooperation with domain experts, FMEA experts design an FMEA model (cf. Section 1.5.1) according to FMEA guidelines. The data curator designs an integrated multi-view model, i.e., the PAN (cf. Section 1.5.1), using the SUM approach [4] in the context of a multi-view model integration pipeline [28].

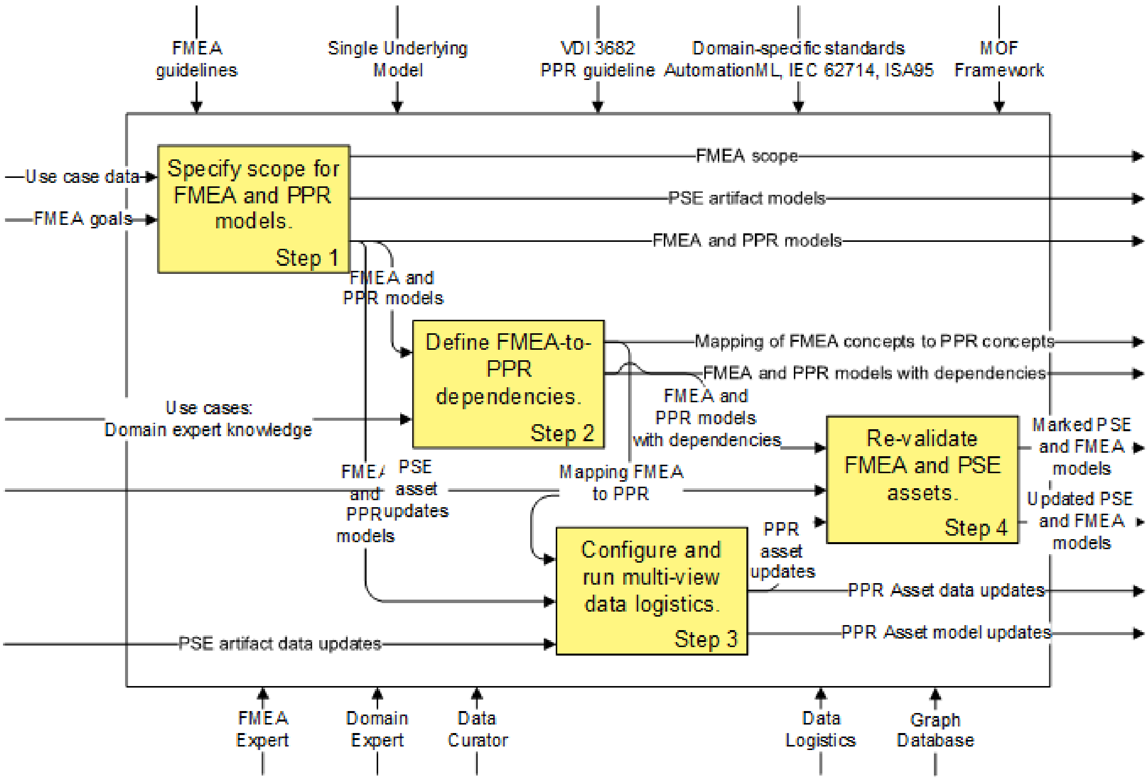

Figure 1.3: FMEA+PPR process steps (in IDEF0 notation [11]).

Step 2. Define FMEA-to-PPR dependencies. In Step 2, the FMEA expert builds on the FMEA and PPR models mapping both model's concepts (cf. Section 1.5.1, links between FMEA and PAN concepts). Furthermore, this expert cooperates with domain experts to collect and explicitly model re-validation dependencies (cf. Section 1.5.1, change coordination states and dependencies).

Step 3. Configure and run multi-view data logistics. In this step, the data curator configures a multi-view data logistics with links between PSE artifacts and PPR assets [8] to extract the asset information from the artifacts. The data curator operates the data logistics to instantiate the FMEA+PPR network – e.g., in a graph database – which provides a foundation for reading or setting change and validation states and coordination dependencies. Furthermore, the data logistics propagates changes in PSE artifacts to PSE/FMEA assets. This propagation results in PPR asset model updates that facilitate their efficient analysis, e.g., by querying a graph database holding a PAN instance.

To define the FMEA+PPR network, the PPR DSL [23] is utilized to specify the Common Concepts (CCs) and links between discipline-specific concepts and views. The resulting FMEA+PPR model represents the basis for deriving a SUM to setup the multi-view model integration, using the *model generator* [28].

Step 4. Re-validate FMEA and PSE assets. In this step, the FMEA expert or the data curator analyze and mark the scope of assets in the FMEA and PPR models for re-validating, e.g., update of PPR asset property values. The FMEA expert and domain experts re-validate and improve FMEA and PPR models to reduce the risk of invalid assets in the FMEA model.

1.5.3 FMEA+PPR System Architecture

To automate the FMEA+PPR process, a *Engineering Data Logistics System Architecture* is designed, based on [7, 28, 26]. Fig. 1.4 illustrates the system architecture consisting of three parts: (1) The **Data Integration** handles the import of engineering artifacts coming from the data providers *private work* spaces to the *team work space*. Discipline-specific *transformers* [28] are used to transform discipline-specific artifacts such as Extensible Markup Language (XML) or Comma Separated Value (CSV) files into view models. These view models are integrated using the *model integration services* [28] consisting of four operation services, such as the *converter*, *comparator*, *merger*, and the *rule engine* which handles the integration of different views and calculate changes to the SUM. (2) The **Engineering Data Logistics System** manages the *common unified model* and all semantic links between engineering views. Here, the data curator supervise multi-view model integration to import and integrate updates from several stakeholders into the common view. For instance, a specific view within a Common Concept (CC) is linked to another view in the same CC (e.g. black link between green and orange or red and orange view). Also views across CCs can be linked (e.g. yellow views in drive and motor). (3) The **Data Delivery** handles specific data consumer requests such as the FMEA model. Data consumers can request data deliveries (a) in their domain-specific hierarchy (e.g., a simulation view for the simulation expert) or (b) as domain-agnostic networks (e.g., for analysis tasks across several engineering views for the FMEA expert) [6]. The domain experts can specify their request themselves or the data curator must address requests by selecting and delivering required views on parts of the common unified model. The requested data are converted to the discipline-specific hierarchy using related *transformers*.

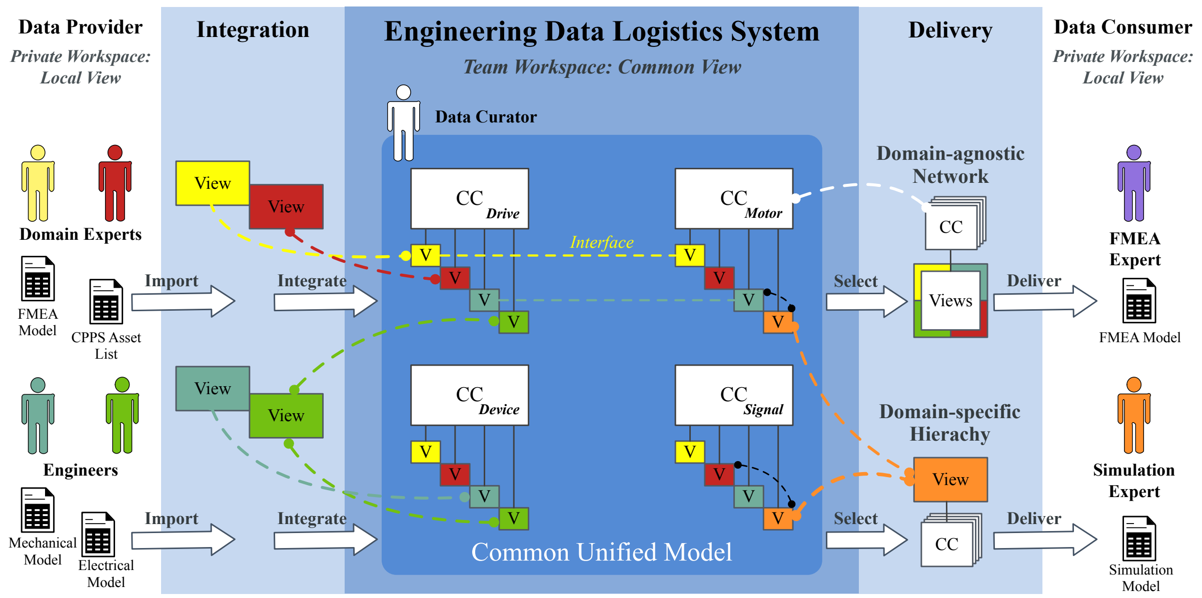

Figure 1.4: Traceable *Engineering Data Logistics System* with private and team workspaces, based on [26].

A described, the data logistics enables the transformation of engineering data from stakeholder specific formats and to a FMEA+PPR model instance e.g. implemented in a *Neo4J*[2] database. Alternatives could be a XML database with AML [3] or *Semantic Web*[3] technologies. The *Neo4J* graph database, used for the evaluation in the next section, provided sufficient capabilities for browsing and querying the FMEA+PPR model instance.

1.6 Evaluation

This section demonstrates the FMEA+PPR approach's feasibility employing the illustrative use case, introduced in Section 1.4. We build on a data sample, coming from automotive manufacturing, for the FMEA of 100 production process steps with their associated production resources. In the feasibility study, we (a) instantiated the *FMEA+PPR model*, (b) analyzed and estimated the number of FMEA elements, PSE assets, and coordination dependencies in FMEA+PPR models for typical robot work cells as part of a manufacturing plant, and (c) assessed the fulfillment of FMEA+PPR requirements and the FMEA+PPR model in comparison to the traditional FMEA approach and engineering artifacts.

Model instantiation. To explore the feasibility and to estimate the effort required for creating a FMEA+PPR model instance, we selected a sample of robot cells. Next, we collected typical PSE artifacts described in the FMEA, such as bills of materials, processes, resources, and their links, for several instances of the use case *FMEA Re-Validation after Changes to Engineering Artifacts* in a manufacturing work line [22].

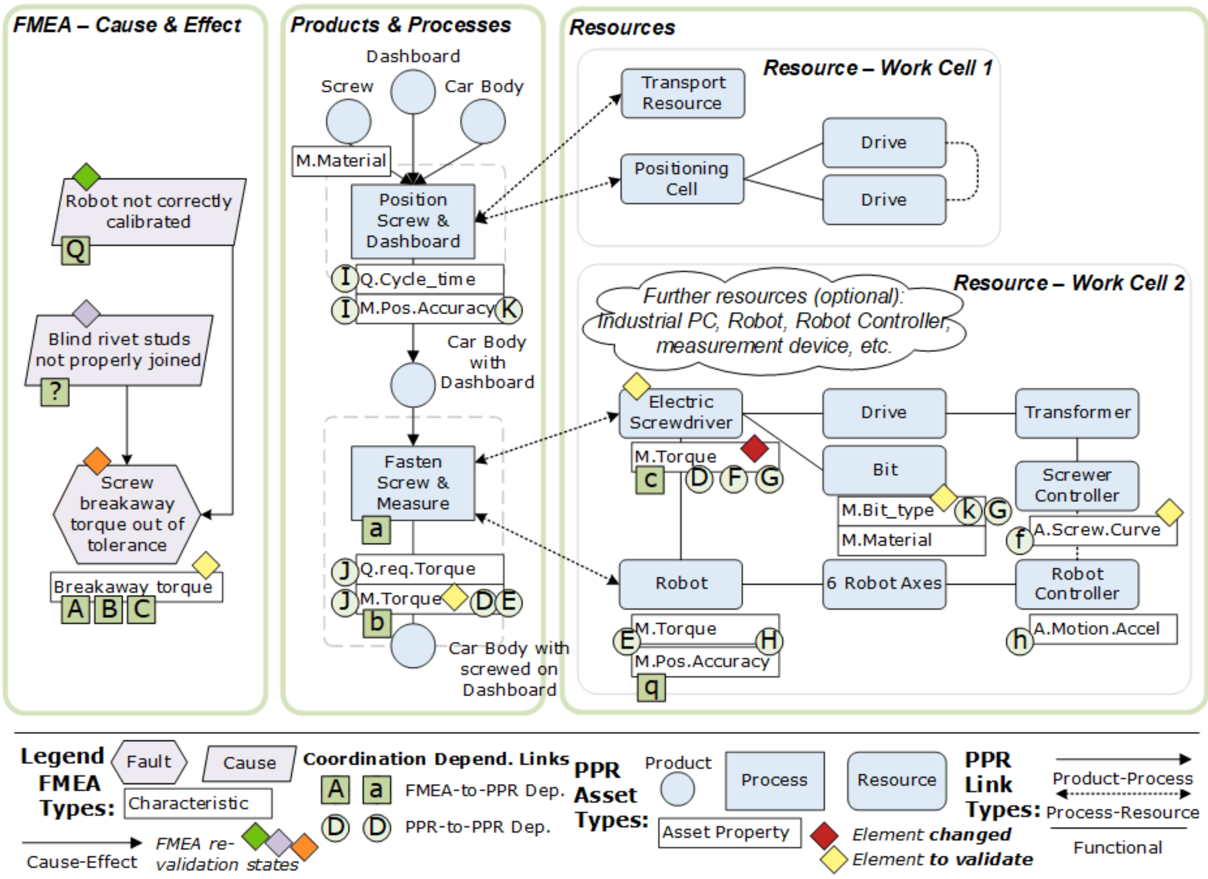

Figure 1.5: FMEA model elements with coordination links to a PPR Asset Network for the use case *FMEA Re-Validation after Changes to Engineering Artifacts*, based on [8].

[2]Neo4J: neo4j.com/
[3]SemanticWeb: www.w3.org/standards/semanticweb/

```
MATCH (startnode)-[edge]-(endnode)
  WHERE startnode.ChangeState = "Changed"
  SET endnode.ValidationLifeCycleState="To Validate"

MATCH (startnode:FMEAAttribute)-[edge]-(endnode:FMEAAsset)
  WHERE startnode.ValidationLifeCycleState="To Validate"
  SET endnode.ValidationLifeCycleState="To Re-Validate"
```

Listing 1: Selected Cypher queries for FMEA element re-validation.

Fig. 1.5 illustrates the derived instance of the FMEA cause-effect diagram linked to a PAN. Column *FMEA - Cause & Effect* in this figure shows an example failure mode *Screw breakaway torque out of tolerance* linked to two potential causes, (a) *i.e., Robot not correctly calibrated* and (b) *Blind rivet studs not properly joined.* The column *Products & Processes* contains two processes, including *Fasten Screw & Measure* with the property *M.Torque*, automated by resources, including an *Electric Screwdriver* with the property *M.Torque.* The failure mode has a characteristic *Breakaway torque* that is linked to PPR assets and properties. Specifically, the property *M.Torque* of the process *Fasten Screw* and the resource *Electric Screwdriver* (FMEA+PPR links *B* and *C*).

In our example, a change to an engineering artifact related to the *Electric Screwdriver* is – via a data logistics process described in [8, 28] – reflected in an update of the respective property *M.Torque*. Consequently, the coordination state of this property is set to *changed* (red diamond marker). Following a PPR re-validation policy, the affected PAN assets and properties are marked as *to validate* (yellow diamond markers). Next, based on the FMEA re-validation policy (cf. Section 1.4), (i) the property failure mode characteristic *Breakaway torque* gets marked as *to validate*; and (ii) failure mode *Screw breakaway torque out of tolerance* gets marked as *to re-validate* (orange diamond markers). FMEA cause *Robot not correctly calibrated* carries a marker *validated* (green diamond) from a recent validation task. FMEA cause *Blind rivet studs not properly joined*, by contrast, carries a marker *unclear* (grey diamond) because there is no valid FMEA+PPR link (cf. Fig. 1.5, FMEA+PPR link with label *?*)

The FMEA/PPR assets, properties, and links provide a foundation for graph database queries in *Neo4J* that answer the questions coming from the FMEA re-validation policy, e.g., *which FMEA assets are linked to a changed PAN node?* An instantiation of such a graph in *Neo4J* notation is accessible in the following repository[4]. The following *Cypher*[5] query sets coordination markers to PAN and FMEA elements.

FMEA+PPR model size. To investigate the viability of collecting and maintaining a FMEA+PPR model for typical production processes automated by robot cells in automotive manufacturing, we built on an FMEA data sample. The analysis was conducted for 100 production steps automated by robot cells varying in size from a small cell that automates one production step to a large cell that automates 19 production steps. Fig. 1.5 shows a typical robot work cell with a single robot with an electric screwdriver. Larger robot cells contain further resources, such as an industrial PC, robots, and measurement devices, leading to a similar structure of the PAN containing more assets and links.

FMEA Graph	#min/avg/max	FMEA+PPR & Coordinatn.	#min/avg/max	PPR Asset Network	#min/avg/max
FMEA Asset	5/70/280	FMEA+PPR Links	8/115/394	PPR Asset	12/124/198
FMEA Characteristic	3/52/134	FMEA/PPR Coord. States	40/192/518	PPR Asset Property	12/248/990
FMEA C-E Link	5/85/320	FMEA/PPR Coord. Links	6/50/220	PPR Asset Link	19/186/396
Sum	**13/207/734**	**Sum**	**54/357/1132**	**Sum**	**43/568/1584**

Table 1.1: Number of FMEA/PAN graph elements and FMEA+PPR & coordination links for a typical range of robot work cells in automotive manufacturing.

Table 1.1 summarizes a sample of FMEA/PAN graph elements and FMEA+PPR and coordination

[4]FMEA-PAN.NEO4J: `github.com/tuw-qse/fmea-revalidation-resources`
[5]Cypher: `www.opencypher.org/`

Req. Rx/FMEA + coordination artifacts	FMEA+EA	FMEA+TS/EO	FMEA+PPR
R1. FMEA concept representation	o	+	++
R2. PPR Asset Network concept representation	−	o	++
R3. FMEA-to-PPR dependency representation	−	+	++
R4. FMEA/PPR change coordination representation	−	+	++
R5. Efficient FMEA re-validation after PPR changes	–	–	+

Table 1.2: FMEA re-validation capabilities of FMEA+EA, FMEA+TS/EO, and FMEA+PPR coordination approaches, based on the PAN coordination artifact [8].

links showing the minimal, average, and maximal number of (a) FMEA graph elements, (b) FMEA+PPR and coordination elements, and (c) PAN elements. According to the FMEA+PPR model topology, the number of FMEA+PPR links was comparable to the *sum* of FMEA asset and characteristics. In the study, the number of FMEA/PPR coordination states was driven by the *sum* of FMEA/PPR assets and their characteristics/properties. The number of FMEA/PPR coordination links is the number of dependencies that domain experts make explicit, e.g., to define change dependencies in the PAN.

The FMEA+PPR model for a process automated by a small robot cell, consisting of 12 PPR assets, was defined by 13 FMEA assets, characteristics, and cause-effect links, and by up to 8 FMEA+PPR link candidates, 40 FMEA/PPR coordination states, and 6 FMEA/PPR coordination link candidates.

The FMEA+PPR model for 19 processes automated by a large robot cell, consisting of 198 PPR assets, was defined by 734 FMEA assets, characteristics, and cause-effect links, and by up to 394 FMEA+PPR link candidates, 518 FMEA/PPR coordination states, and 220 FMEA/PPR coordination links.

We assume the FMEA graph to be available and the PAN to be efficiently derived from engineering artifacts in a team work space (cf. Section 1.5). FMEA/PPR coordination can be determined efficiently with graph queries (cf. Listing 1), given a sufficiently complete linking of the FMEA graph and the PAN. However, the considerable number of FMEA+PPR links and FMEA/PPR coordination links will require an approach for the prioritization and/or automation. Similar structures of robot cells can typically be generalized, i.e., FMEA+PPR links and FMEA/PPR coordination links can be defined on robot cell and FMEA/PPR asset types, which allows for an efficient definition of graph queries that will be applicable to a range of similar robot cell types [29]. Furthermore, domain experts can start by modeling an initial small set of high-priority FMEA characteristics, FMEA+PPR links and FMEA/PPR coordination links.

Evaluation of requirements for FMEA re-validation capabilities. For evaluation purposes, we compare the FMEA+PPR to the traditional approaches (a) FMEA+EA: *FMEA re-validation based on Engineering Artifacts* in a team work space, requiring manual mapping and co-evolution of FMEA models and PSE artifacts, and (b) FMEA+TS/EO: *FMEA re-validation in Tool Suites* that manage engineering objects in a data base as a basis for co-evolution with FMEA model versions. We used a 5-point *Likert* scale (++, +, o, –, −), where ++/− indicate very high/low capabilities, to evaluate the fulfillment of the requirements in comparison with alternative approaches. Table 1.2 summarizes the results.

R1. FMEA concept representation. For all approaches, we assume the use of a best-practice FMEA tool, such as APIS, with FMEA concepts and conditions represented in natural language, possibly with references to PSE concepts. FMEA+EA is rated average as the FMEA concepts can refer to stakeholder views in heterogeneous engineering artifacts (EAs), requiring for one FMEA concept the management of references to several stakeholder views, e.g., mechanical/electrical identifiers in M-CAD/E-CAD, software identifiers in programs and configurations, which concern an Electric Screwdriver. FMEA+TS/EO is rated high as one FMEA concept can refer to one engineering object, e.g., the Electric Screwdriver, which represents several stakeholder views in the tool suite data model. However, the tool suite data model covers only a limited set of stakeholder views and falls back to engineering artifacts for stakeholder views not covered by the tool suite. FMEA+PPR is rated very high as one FMEA concept can refer to PPR concepts and, if required, stakeholder views attached to a PPR asset. By design, the FMEA+PPR model represents the required FMEA graph concepts (cf. Fig. 1.2, tag 1, model elements in violet color).

R2. PPR Asset Network concept representation. FMEA+EA is rated very low as the approach concerns engineering artifacts that, in general, do not consider PPR assets. FMEA+TS/EO is rated average as the engineering objects may represent PPR assets and their properties, but do not consider dependencies between PPR assets. Furthermore, the tool suite covers only a limited set of PPR assets. FMEA+PPR is rated very high as it represents all relevant stakeholder views as PPR assets and their properties. Moreover, explicit dependencies between PPR concepts represent domain expert knowledge, e.g., on change dependencies (cf. Fig. 1.2, tag 2, model elements in blue color).

R3. FMEA-to-PPR dependency representation. FMEA+EA is rated very low as the approach considers dependencies to engineering artefacts, not PPR assets or properties. FMEA+TS/EO is rated high as the approach considers dependencies to engineering objects, but with limited stakeholder views. FMEA+PPR is rated very high as the FMEA+PPR model explicitly represents FMEA+PPR links between FMEA and PPR Asset Network concepts (cf. Fig. 1.2, tag 3, *FMEA to PPR Asset Link*).

R4. FMEA/PPR change coordination representation. FMEA+EA is rated very low as change coordination is limited to engineering artifacts in the team work space and neither covers FMEA nor PPR concepts. FMEA+TS/EO is rated high as change coordination concerns individual engineering objects. However, there is no consideration of a network of change dependencies and the scope of stakeholder views is limited. FMEA+PPR is rated very high as the model represents the required change coordination states, e.g., markers for representing the state of change and re-validation, missing links (cf. Fig. 1.5, diamonds), and dependencies of PPR and FMEA assets/concepts (cf. Fig. 1.2, tag 4, coordination model elements in green color).

R5. Efficient FMEA re-validation after PPR changes. FMEA+EA is rated low as comparing FMEA concepts to changes in heterogeneous engineering artifacts involves significant manual effort from domain experts to identify FMEA concepts for re-validation after each change to an engineering artifact. FMEA+TS/EO is rated low as the automation of FMEA re-validation in the tool suite would require adding the FMEA view to the tool suite with considerable effort to design. However, once implemented, the FMEA re-validation could become very efficient in the limited scope on engineering disciplines in the tool suite. FMEA+PPR is rated high as the approach considers the relevant scope of engineering disciplines and tools in a PSE project assuming the multi-view data logistics capabilities for efficient update of PPR assets from engineering artifacts.

Overall, the FMEA+PPR approach seems well suited to provide FMEA re-validation capabilities as a foundation for integrating FMEA with agile PSE. This is demonstrated in the *Neo4J* graph instance, enables efficient queries to analyze linked FMEA and PPR knowledge, e.g., for efficient FMEA re-validation based on queries to graph database to select and prioritize relevant FMEA elements for re-validation.

1.7 Discussion

This section discusses this work regarding the research questions and limitations.

RQ1. *What model in agile PSE can represent FMEA concepts linked to PSE assets and their change/-validation states to manage the efficient re-validation of FMEA model elements after updates to PPR asset property values?*

We introduced the FMEA+PPR meta model that simplifies the coordination of FMEA re-validation in agile PSE. Introducing a FMEA+PPR model as advanced coordination artifact for the re-validation of FMEA models appears particularly beneficial in medium-to-large PSE projects. In such projects artifact-mediated coordination can be expected to be considerably less risky and more efficient than point-to-point coordination which requires manual analysis of changes that are relevant to the FMEA.

The FMEA+PPR model is a knowledge graph that explicitly represents dependencies among FMEA and PPR assets and their characteristics to provide context for the re-validation of an FMEA asset. Thus, the FMEA+PPR model is the basis for (i) exploring and analyzing a task-specific FMEA+PPR model instance (cf. Fig. 1.5), (ii) automating queries to FMEA and PSE assets (cf. Section 1.6), and (iii) coordinating processes that require expert knowledge and labor, such as identifying FMEA asset candidates for re-validation, reuse, or refactoring.

In this work, we explored the knowledge representation, represented as a graph, required for FMEA re-validation relevant for FMEA experts. However, for daily work, FMEA experts typically want to work with the coordination information in the PPR elements. This representation in the tool would require the exploration of ways to augment FMEA tool data with coordination information, e.g., by repurposing a comment data field to hold markers similar to the graph database (cf. Section 1.6), and import the coordination information into the FMEA tool for further use in search capabilities.

RQ2. *What process can integrate multi-view FMEA and PSE asset models as a foundation for analyzing the required re-validation scope of FMEA model elements after updates to PPR asset property values?*

To address RQ2, we introduced the FMEA+PPR process (cf. Section 1.5) that (i) defines FMEA+PPR dependencies for a particular scope of FMEA and PPR models; and (ii) configures and runs a multi-view data logistics that iteratively instantiates a PAN to configure the *Engineering Data Logistics System* fostering multi-view model integration [28] (cf. Section 1.5) as a foundation for (iii) identifying FMEA assets for re-validation that depend on changes to PSE assets.

The feasibility study (cf. Section 1.6) illustrated the definition of a FMEA+PPR model in a *Neo4J* database instance, from typical PSE artifacts (cf. Fig. 1.5). We use this model instance to evaluate the scaling characteristics of the approach in terms of the number of elements for work cells of different sizes (cf. Table 1.1). Regarding the FMEA re-validation requirements (cf. Section 1.4), the rating of the FMEA+PPR results showed clear improvements over traditional best-practice approaches (cf. Table 1.2). In particular regarding PAN concept representation, FMEA/PPR change coordination representation, and efficient FMEA re-validation after PPR changes. The study results indicate that the FMEA+PPR approach provides a sound foundation for PSE domain experts to identify FMEA elements for re-validation. This provides a foundation for an evaluation of the usability and scalability of the approach in a broader context, including agile PSE scenarios of different sizes and complexities.

In this work, we focused on efficiency by automating the analysis of change impact in PSE artifact property values on FMEA elements. This consideration provides the foundation for exploring the effort in PSE environments for designing and using the FMEA+PPR approach with typical tools and domain experts in comparison to benefits from improved capabilities for FMEA re-validation.

These research results build on coordination artifact design [8, 24], recent advances in I4.0 asset data integration [25], and our previous work in multi-view model integration methods and techniques [28]. The results go beyond the state of the art in the area of coordinating in multi-disciplinary PSE processes [12, 18, 22], in particular FMEA re-validation (i) by defining a sufficiently fine-grained FMEA+PPR models for coordination based on FMEA and PAN concepts and (ii) by demonstrating the feasibility of instantiating the FMEA+PPR model based on data from FMEA and PSE artifacts.

Limitations. The following limitations require further investigation. The *feasibility study* focused on a use case derived from projects at large PSE companies in the automotive industry. This may introduce bias due to the specific selection of FMEA re-validation challenges and approaches considered, as well as the roles or individual preferences of the domain experts. To overcome these limitations, we plan case studies in a wider variety of application contexts.

The *expressiveness* of the re-validation concepts and dependencies used in the evaluation can be considered a limitation. Industrial scenarios may also require more detailed modeling of FMEA conditions. Furthermore, whereas evaluation results with FMEA+PPR model instances with a limited set of attributes required for selected FMEA re-validation tasks were encouraging, the ability to address FMEA models that require many asset types and are linked to large PANs remains an open issue for further investigation.

Finally, our evaluation environment involved a limited number of stakeholders, and we plan to investigate the effectiveness of the approach in more detail in a setting that involves a larger number of stakeholders and roles.

1.8 Conclusion and Future Work

In agile PSE, multi-disciplinary stakeholders, such as mechanical, electrical, and software engineers, work on their partial PPR views in engineering artifacts, such as plans, configurations, and programs, in an iterative parallel process to address requirements towards a functional production system. In such settings, FMEA is vital to reduce the risk of PSE design errors, such as mismatches between stakeholder designs, that may be costly to resolve in late PSE stages. Therefore, there is a strong need to reuse FMEA knowledge on system components from previous projects and efficiently identify FMEA elements to re-validate after updates to PSE artifacts that come from heterogeneous stakeholder views. Efficiently identifying FMEA elements for re-validation requires capabilities to (i) trace or propagate a change in a PSE artifact (ii) a shared PSE object, such as a PPR asset, which reflects the common knowledge in the project team, and (iii) keep track of the change states of shared PSE objects and of FMEA elements. However, in current best-practice knowledge management in PSE, FMEA elements and PSE artifacts represent the knowledge required for FMEA re-validation incompletely. Furthermore, their meaning is difficult to interpret automatically, which makes FMEA re-validation inefficient and prone to error. Therefore, FMEA re-validation may become ineffective in agile PSE, reducing the actual benefit that would be expected from conducting FMEA early.

This paper reports on the use case *FMEA Re-Validation after Changes to Engineering Artifacts*, derived from car manufacturing with automated robot work cells, and identifies a set of requirements for FMEA re-validation capabilities. To address these requirements, we developed the *FMEA+PPR approach* that consists of (i) a meta model to represent the required knowledge for efficient FMEA re-validation, and (ii) a process to map FMEA elements to PAN concepts. The approach provides a foundation for the efficient analysis of which FMEA elements to re-validate after changes to PPR assets and PSE artifacts.

A feasibility study created a FMEA+PPR model instance that represents the required knowledge for analyzing the impact of changes in multi-view engineering artifacts on FMEA models. For a large robot work cell, the study indicated that the FMEA+PPR model's size is considerable requiring an effective approach to select the most relevant FMEA concepts for modeling with tool support.

In the evaluation, we compared the FMEA+PPR approach to two traditional best-practice approaches in PSE that relate FMEA elements (i) to engineering artifacts in a team work space or (ii) to engineering objects in a tool suite database. The study results indicate that the FMEA+PPR method is feasible and more effective than the alternative approaches. These results encourage evaluating the FMEA+PPR approach in a broader context regarding usability and scalability in agile PSE scenarios of different size and complexity.

Future Work. *FMEA and PSE asset model co-evolution.* Modeling researchers and PSE tool providers can build on the FMEA+PPR approach to (i) design and evaluate advanced methods and tool support for the co-evolution of FMEA and PSE assets, (ii) ensure the consistency of these models, and (iii) facilitate advanced analyses that require consistent FMEA and PSE asset models, such as risk analyses of PSE change scenarios, possibly including knowledge coming from production system operation. *Empirical validation.* We plan to investigate the usability and usefulness of the FMEA+PPR approach in various agile PSE settings, e.g., making implicit domain expert knowledge sufficiently explicit in FMEA with PSE models to automate analyses for the quality assurance and reuse. *Scalability.* Due to the comprehensive scope of FMEA and PSE tasks, a model's complexity may grow considerably with the number of data elements and links. This will require research on the scalability of FMEA+PPR models. *Security.* The linked FMEA and PSE knowledge in a model aggregates knowledge both on how to achieve and attack product and production process quality by manipulating the production system components. Therefore, the FMEA+PPR model requires research on security concerns, e.g., using the knowledge to identify and mitigate risks from security attacks on a production system.

Annex: Acronyms A

AML AutomationML. 3, 7, 11

CC Common Concept. 3, 10

CSV Comma Separated Value. 10

DEXPI Data Exchange in the Process Industry. 3

DSL Domain Specific Language. 3, 10

FMEA Failure Mode and Effects Analysis. ii, 1–16

FMEA+PPR FMEA-linked-to-PPR assets. ii, 2, 5–16

I4.0 Industry 4.0. 1, 15

MBSE Model-based Systems Engineering. 2

MDEE Multi-Disciplinary Engineering Environment. 2, 3

MvMT Multi-view Model Transformation. 3

OPCUA OPC Unified Architecture. 3

PAN PPR Asset Network. 2–6, 8, 9, 11–13, 15, 16

PPR Product-Process-Resource. ii, 1–5, 7–10, 12–16

PSE Production Systems Engineering. ii, 1–7, 9–11, 14–16

RAMI40 Reference Architecture Model for Industry 4.0. 3

SUM Single Underlying Model. 3, 9, 10

SysML Systems Modeling Language. 3

XML Extensible Markup Language. 10

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