Risk-Driven Derivation of Operation Checklists from Multi-Disciplinary Engineering Knowledge

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***Abstract*—During the ramp-up of a production system, complex and difficult to resolve product quality issues often result in tedious experimentation and costly delays. A particular challenge in this context is insufficient guidance for operators on how to resolve issues and adapt their actions to a new production context. Failure Mode and Effects Analysis (FMEA) can help to identify and address likely causes of production quality issues. However, FMEA models are typically (i) isolated from engineering domain models on product, process and resource (PPR) concerns, and (ii) not actionable for operators. This paper introduces the FMEA-to-Operation (F2O) approach to reduce the risk of ramp-up delays and recurring quality issues by integrating the required domain knowledge for model-driven, machine skill-centric, and actionable process FMEA. The F2O approach (i) validates likely root causes of a production quality issue by linking these causes to engineering reality in a graph database, and (ii) derives operation checklists with prioritized countermeasures. In a feasibility study on a real-world welding cell for car parts, we evaluated the effectiveness and efficiency of the F2O approach. Results indicate that the F2O approach is feasible and effective, and provides operators with actionable, context-specific guidelines that are well grounded in engineering models.**

***Index Terms*—Production Systems Engineering, Industry 4.0, Process FMEA, PPR, Skills, Digitalization.**

I. Introduction

Ramping up a production system, i.e., rapidly assembling a manufacturing system and bringing it to full production capacity [1], is a risky life cycle phase that involves frequent adaptations [2], [3] and requires careful management [4]. Particular challenges in ramp-up management [4] include reducing the need for human intervention through digitalization and automation, better transparency with stronger interconnectedness and information sharing, and improving decision-making competencies of self-learning digital systems.

Successful production system ramp-up requires engineering information provided by planners from several engineering disciplines [5] that plant operators use to plan the sequence of ramp-up activities. This is difficult because production systems are highly volatile during ramp-up [6]. In particular, late changes to product, production process, or production systems due to new design or operation knowledge may cost significant time and resources [7], [8].

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To address such risks and ensure fulfillment of certification requirements, FMEAs are typically conducted during product, production process, and production system engineering to cover knowledge on potential errors and system failures [9], [10]. The resulting FMEA models aim to provide plant operators with additional knowledge for ramp-up management. Furthermore, FMEA experts shall iteratively update the FMEA model with new knowledge from operation and production changes. Independent of the FMEA variants, model structures, and integration [11] in ramp-up processes, FMEAs [12] generally describe failure modes, their likely causes, and countermeasures to analyze and mitigate risks [10].

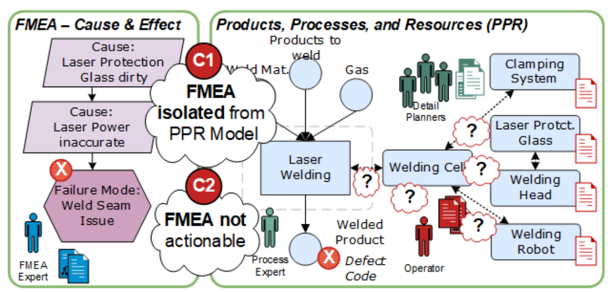

Fig. 1. Research challenges, based on DIN EN 60812 [13] and VDI 3682 [14].

Fig. 1 shows FMEA experts, detail engineers (incl. the process expert), and plant operators, who provide and require different information, e.g., knowledge on the production system, to efficiently identify and address likely causes of high-risk effects that may impact production quality during ramp-up [4]. Fig. 1 illustrates two major challenges in a ramp-up project. *C1. FMEA models are isolated from engineering models*, e.g., Product-Process-Resource (PPR) models that integrate data from several detail engineering models [15]. Further, FMEA models refer to production assets only implicitly [16], which may lead to insufficient representation of engineering changes to the production system, hindering the effectiveness of FMEA implementation [17]. *C2. FMEA models are, in general, not directly actionable* to inform the operator on how to address production issues on the shop floor [10].

To tackle these challenges, this paper aims to integrate FMEA knowledge into and update it during production ramp-up processes with an approach (i) for validating an FMEA model with a multi-disciplinary engineering model [15] that integrates the required views of domain experts; and (ii) for efficiently deriving prioritized operation checklists from a detailed FMEA that is grounded in and has been validated with technical resources.

The remainder of this paper is structured as follows. Section II summarizes related work on knowledge management in production systems engineering, on using engineering data in production ramp-up processes, and on FMEA. Section III motivates the research question and approach. Section IV proposes the *FMEA-to-Operation (F2O)* approach for validating FMEA with engineering knowledge and for deriving operation checklists for failure modes. Section V introduces the case study *operation checklists for laser welding issues*. Section VI reports and discusses results from a feasibility study that applies the F2O approach with real-world industry data. Section VII concludes and delineates future work.

II. Related Work

This section summarizes related work on knowledge management in production systems engineering, use of engineering data in production ramp-up processes, and FMEA.

Multi-disciplinary engineering. Production system engineering is a multi-disciplinary and multi-model process, where different engineering disciplines develop the necessary documents to physically set and ramp up a production system [5]. Increasing digitalization of all production system life cycle phases has resulted in engineering domain models that aid shop-floor operators in managing the ramp-up progress [4].

Results of the production system engineering phase cover the production resources and their relations to the production processes to automate as well as the involved materials and products. This Product-Process-Resource-Skill (PPRS) orientation is traditionally covered by separate models. Recent research has shown that an integrated model of all assets within a production system, such as a PPR Asset Network (PAN) [15], can be beneficial. It provides a foundation for capability-based engineering [18], which has recently gained momentum as a method to plan reusable production systems by abstracting the interface between production processes and resources.

Production ramp-up. For successful ramp-up management, operators require an integrated view on the production process and system [4], bringing together their own knowledge with knowledge in engineering models and artifacts from several disciplines [2], [3].

Surbier *et al.* [3] and Colledani *et al.* [2] report on approaches and challenges of production system ramp-up, highlighting (among others) the critical importance of learning curves and the need for operator support with IT systems and appropriate methodologies. In their survey on future challenges on ramp-up management, Schmitt *et al.* [4] find that in the face of increasing dititalization and self-learning capabilities, the role of humans within ramp-up management will be reduced. For ramp-up process effectiveness and efficiency, Scrimieri *et al.* [8] and Zimmer *et al.* [1] identify explicit learning and knowledge integration capabilities as essential success factors. Dombrowski *et al.* [7] indicate how concepts of Industry 4.0 – in particular a network of Industry 4.0 asset administration shells – can help to manage the complexity of ramp-up processes. In this paper, we build on PANs [15] to represent the information on assets and properties in these networks as first-class citizens for knowledge integration.

FMEA models for production ramp-up. FMEA models typically play a key role in production system ramp-up management [4]. Their cause-and-effect semantics (often represented in a graph-based notation) can support the work of engineers and operators by highlighting pain points.

FMEA is a mature methodology applied in various fields – Sharma *et al.* [12] provide an overview on the development of FMEA methods in general, whereas Wu *et al.* [9] focus on the use of FMEA models in manufacturing. Ouyang *et al.* [11] cover performance in technical systems, which is critical for the ramp-up of production systems.

To integrate engineering knowledge in the creation and use of FMEA models, Huang *et al.* [16] proposes to combine FMEAs with model-based engineering. Although such integration or combined use of FMEA and engineering models can be challenging [17], the benefits are significant – making it possible to derive rule-based information sets to guide ramp-up processes [10]. Recently, Kropatschek *et al.* [19] introduced a method to explore causes in an FMEA model with engineering assets in a PPR model, building on the PAN coordination artifact [15]. To this end, the method links FMEA and PPR assets as a foundation to express dependencies between domain concepts in a combined model covering FMEA and PPR.

In this paper, we build on this knowledge integration process [19] and extend the FMEA+PPR meta model with links between FMEA characteristics and PPR properties in order to achieve a sufficiently detailed description of causes. This results in a knowledge-based F2O approach that (i) leverages resource skills to dynamically link FMEA knowledge to knowledge in engineering models in order to validate an FMEA model in a concrete production environment; and (ii) transforms FMEA knowledge into actionable guidelines for the machine operator.

III. Research Question and Approach

To address the research goal – i.e., validating an FMEA model with a multi-disciplinary engineering model and deriving operation checklists – we followed the *Design Science* approach [20]. First, the authors reviewed literature on FMEA in production quality applications [9]. Next, four authors conducted stakeholder focus workshops with seven FMEA and engineering experts at three large European system integration companies in automotive manufacturing. The workshops focused on product quality issues with robot cells for joining car parts. In particular, the workshops focused on (i) required multi-disciplinary knowledge for risk analysis, (ii) their approaches to risk analysis and FMEA modeling, (iii) gaps in the integration of multi-disciplinary knowledge, and (iv) requirements for knowledge representation, validation, and analysis to identify and rank root causes of production issues. From the domain analysis, we abstracted the use case *operation checklists for laser welding issues* (cf. Section V) and derived the following research question (RQ).

RQ. *What model-based approach can effectively and efficiently integrate and validate FMEA and multi-disciplinary engineering knowledge to provide operator guidance during ramp-up?*

The F2O approach that resulted from the investigation of this RQ consists of (i) the *F2O meta-model* and (ii) the *F2O method*.

The F2O meta-model provides the concepts necessary to validate a process FMEA with a Product-Process-Resource-Skill (PPRS) model of a production environment. In particular, the model makes it possible to link an FMEA model to a PPRS model for coordinated validation in an expert team [15], [19]. These links help to inform the ratings of FMEA causes with knowledge on system components and their relation to production processes.

The F2O method is a knowledge validation and discovery tool to describe and rate the causes of product quality issues in an industrial process. It shall guide FMEA and domain experts in the validation of a process FMEAs. This can be accomplished by combining FMEA tools (such as APIS[1]), which represent a cause-effect tree, with a model of PPRS elements in a graph database. The validated model in the graph database enables computational analysis through graph queries both on FMEA cause-effect hypotheses and on domain-specific engineering dependencies. Based on that, automated checklist generation can efficiently transform FMEA knowledge into actionable knowledge applicable in a given production system context.

IV. Solution Approach

This section introduces the F2O meta-model and the method. Fig. 2 provides an overview of the solution approach.

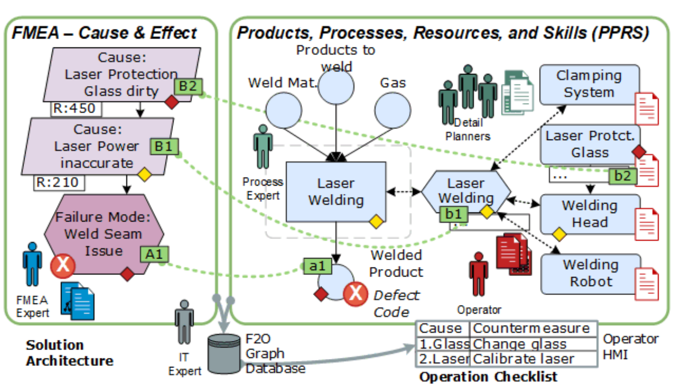

Fig. 2. FMEA-to-Operation (F2O) Solution Overview.

The F2O meta-model provides a foundation to link previously isolated FMEA and PPRS models. Using elements from this meta-model, the FMEA expert can link FMEA causes to PPRS assets and properties. By integrating these disparate models, the FMEA expert (i) first validates FMEA completeness and correctness against engineering models, and (ii) then rates FMEA causes in the specific context provided by the PPRS engineering model, using the linked knowledge on resource risks in the process. Based on these ratings, the approach can then automatically generate ranked operation checklists for given failure modes.

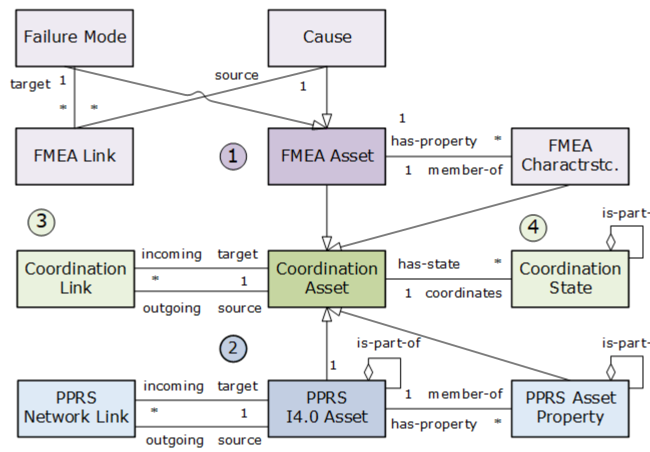

Fig. 3. F2O Meta-model (in UML notation) based on [21].

F2O meta-model. To represent the required FMEA and PPRS assets and knowledge, we introduce the F2O meta-model (cf. Fig. 3), extending the *FMEA-linked-to-PPR assets* meta-model [21] with skills [22]. It provides and links:

1. FMEA concepts. Key concepts are *Failure Modes* and *Causes*, which are modeled as subclasses of *FMEA Assets* (cf. Fig. 3, tag 1) and related through *Links*. Assets hence represent a key connection point for the alignment of the FMEA and PPRS models. Finally, *Characteristics* – such as e.g., cause ratings – can be assigned to FMEA assets. Linked FMEA Assets can form a cause-effect tree (cf. Fig. 2, left-hand side).

2. PPRS concepts. The meta-model represents *PPRS Assets* (cf. Fig. 3, tag 2) with their *Links* and *Asset Properties*. Linked PPRS Assets can represent dependencies between product quality and production processes and resources via machine skills (cf. Fig. 2, right-hand side).

Skills in the PPR model [22] can reduce the complexity of FMEA analyses and validations. Specifically, the transfer of FMEA knowledge to the shop floor benefits from a model-based approach that structures FMEA knowledge around *machine skills*. This skill-centric organization of FMEA models provides an interface between reusable, abstract descriptions of product and processes that require resource capabilities [14] and detailed resource models.

3. Coordination links between FMEA and PPRS elements. To link the FMEA and PPRS models, the meta-model provides coordination links that connect FMEA and PPRS elements (cf. Fig. 3, tag 3). These links represent mappings between PPRS concepts that are semantically similar to domain concepts used in FMEA assets (cf. Fig. 2, green rectangles, e.g., A1).

[1]APIS FMEA Tool: https://www.apis-iq.com/software/

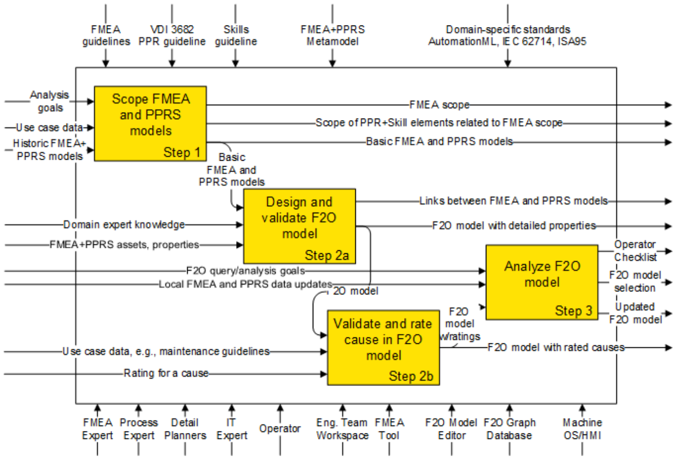

Fig. 4. F2O Method (in IDEF0 notation [23]).

4. Coordination states of FMEA and PPRS elements. The meta-model represents *Coordination States* of PPRS and FMEA elements (cf. Fig. 3, tag 4), e.g., markers for the FMEA validation state or markers for inputs to and results of a graph database query (cf. Fig. 2, colored diamond markers on FMEA and PPRS model elements).

F2O method. To integrate and validate the FMEA and PPRS knowledge required to provide operator guidance during ramp-up, we propose the F2O method (cf. Fig. 4) that results in prioritized operation checklists over a set of failure modes. The method is conducted in the FMEA/engineering environment, supported with an FMEA tool, a F2O model editor, and a graph database, and consists of three steps. These steps can be performed iteratively to consider new knowledge in the goals or use case environment.

Step 1. Scope FMEA and PPRS models. In this step, the FMEA and (e.g., laser welding) process expert determine the FMEA's scope, i.e., the locality of a specific product quality issue. They select product quality issues with high business value (such as, e.g., weld seam issues on expensive car parts) and identify relevant FMEA and PPRS assets in the data.

Inputs to this step are (i) the analysis goals for a product quality issue, e.g., rework risk reduction for weld seam issues in a robot welding cell for car parts; (ii) the use case data, typically PPRS models [15] provided by detail planners, e.g., for a robot cell instance with its engineering artifacts; and (iii) the initial FMEA and PPRS models, as available.

Results of this step are (i) the selected FMEA assets, in particular, failure modes; (ii) the PPRS assets related to the FMEA assets, in particular, domain concepts used in FMEA elements; and (iii) the initial FMEA and PPRS models, which may be (partially) linked, with their properties.

Step 2. Design/validate a F2O model and rate causes. *Step 2a. Design and validate a F2O model.* In this step, the FMEA expert details the FMEA for a given product quality issue. To this end, they (i) identify causes in input products, production steps, and skills of machines that automate the production process (cf. Fig. 2, tags *B1* and *b1*) and (ii) identify causes in resource assets that may impede machine skills (cf. Fig. 2, tags *B2* and *b2*).

Inputs to this step are (i) the domain expert knowledge, (ii) the use case data, and (iii) the initial or updated FMEA and PPRS models. This step results in a validated F2O model with detailed properties and links (cf. Fig. 2, green tags).

For PPRS domain concepts used to describe FMEA elements, the FMEA expert and domain expert annotate PPRS assets with properties that refer to stakeholder views (cf. Fig. 5). The property *(PE,O).Laser Power Setting*, for instance, refers to the views of the process expert (PE) and the operator (O). Furthermore, they add skills as required to represent machine capabilities, e.g., *Laser Welding.Accurate Positioning*.

Specifically, the FMEA expert links the FMEA and PPRS model elements by placing marker pairs, e.g., *A1-a1* and *B2-b2*, on the corresponding model elements (cf. Figs. 2 and 5, green rectangle tags). The FMEA expert validates the F2O model by checking (i) the complete and correct assignment of FMEA and PPRS assets according to the F2O meta-model, (ii) the completeness of mapping FMEA elements to PPRS elements, and (iii) the completeness of paths in the PPRS model regarding the technical impact from a root cause to a skill to a product quality issue. The F2O graph database facilitates these validation analyses by providing selected sub-graphs of the F2O model.

Step 2b. Validate and rate a cause in the F2O model. In this step, the FMEA and domain experts explore FMEA and PPRS paths in the F2O model from the issue under investigation to a selected root cause, considering assets along the technical paths in the PPRS model (cf. Figs. 2 and 5, model elements marked with colored diamonds). Inputs to this step are the use case data, e.g., maintenance guidelines on resource assets linked to a cause, and rating information. Result of this step is a F2O model with validated and rated FMEA causes.

To this end, the FMEA expert validates in detail the completeness and correctness of F2O elements and links along the FMEA and PPRS paths from the issue to a root cause. The FMEA expert rates a cause on the FMEA path considering the Risk Priority Number (RPN) and factors for (i) the technical impact of PPRS assets linked to the cause along the PPRS path, and (ii) the ratings and technical impact of related causes, or combinations of causes.

Step 3. Analyze F2O model to derive operation checklist. In this step, the FMEA and IT expert design and run queries on the F2O model in the graph database to answer stakeholder questions, possibly updating data in the F2O model.

Inputs to this step are F2O analysis goals, e.g., a product quality issue, and local F2O data updates from the use case, e.g., a changed value of an asset property.

Results of this step are an updated F2O model to reflect new knowledge and an operation checklist (cf. Tab. I) regarding likely causes and promising countermeasures for a product quality issue as a foundation for configuring the operator user interface on a machine.

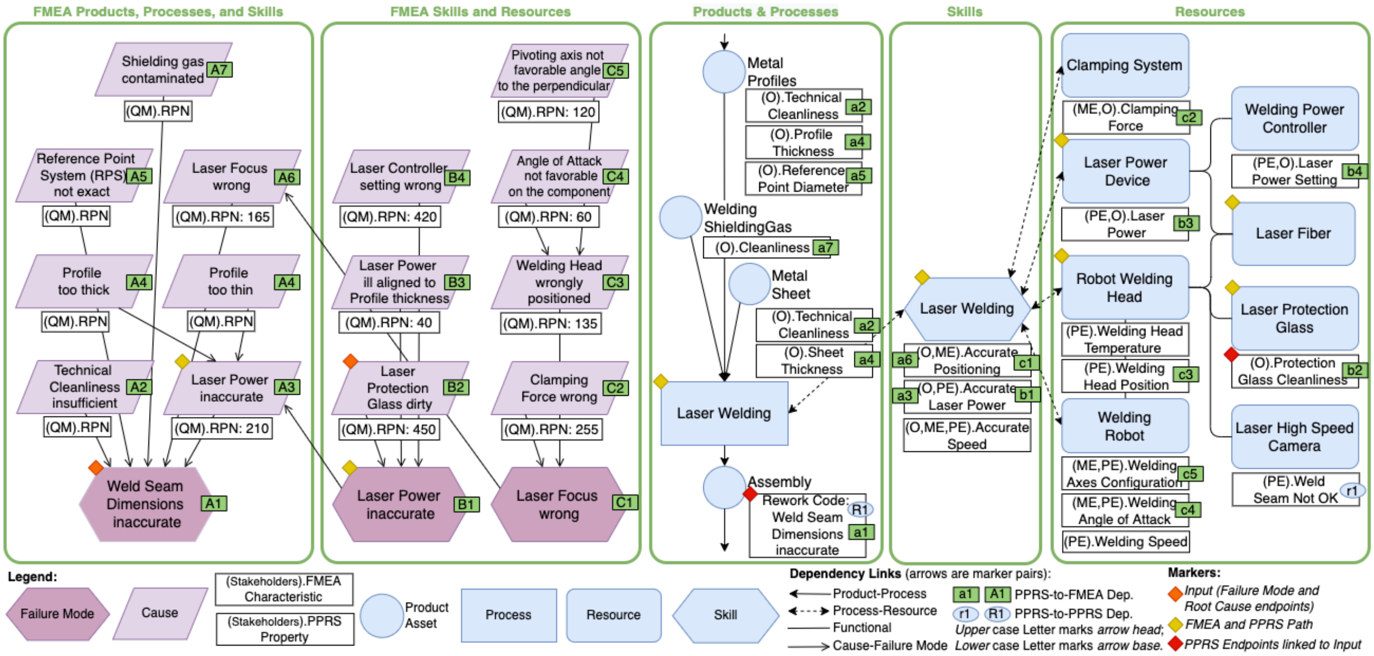

Fig. 5. F2O model for issue *Weld Seam inaccurate*: FMEA failure modes and causes linked with Product, Process, Resource, and Skill assets and properties.

V. Case Study Laser Welding

This section introduces the use case *operation checklists for laser welding issues*. We abstracted the use case from a domain analysis focused on product quality issues during ramp-up with robot cells for joining car parts in automotive production at three large European system integration companies [19], [24]. This domain analysis provides a setting for evaluating the derivation of operation checklists from multi-disciplinary engineering knowledge to facilitate the identification of production issue causes in the automotive industry.

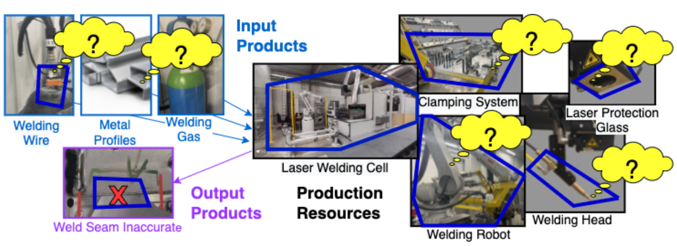

Fig. 6. Failure mode in Laser Welding with selected cause candidates.

Product quality issues in laser welding of car parts. The production process in focus (cf. Fig. 6) welds car profiles and is automated with a robot welding cell. The robot cell consists of two positioning systems, two welding robots, and a quality control system.

If quality control in the production process detects a product defect that prevents further production, the faulty product arrives at a rework station. There, the operator receives via an HMI (PC or tablet) a product defect code, which is related to a FMEA failure mode. For a laser welding machine, there are typically approximately 50 failure modes and up to 20 causes for a failure mode, leading to several hundreds of cause-effect relationships that require validation and maintenance. This is particularly challenging in the face of dynamically changing processes and system configurations during ramp-up.

Operators and maintainers have only limited engineering knowledge on a specific production system part for a production step (cf. Fig. 6). They do not know detailed process and technology dependencies, but typically follow procedures and electronic maintenance guidelines for machine components. However, these guidelines are usually not linked to defect codes or to FMEA results. In particular, novice operators are likely to oversee issues (e.g., holes in the weld seam due to inaccurate laser power) and are prone to produce parts with lower quality or to delay production and escalate issues. Therefore, the operator requires advanced and fast guidance when in-process quality control reports low product quality.

Risk analysis with multi-disciplinary knowledge. A common goal of the stakeholders in the use case is to provide the operator with the current best knowledge on countermeasures to a production issue during ramp-up. In this context, the FMEA model reflects the current working hypotheses of the FMEA and engineering experts on causes of a production issue and the impact of countermeasures on operations.

The FMEA expert wants to update the FMEA model for a production process efficiently to changing product quality and production risks during the ramp-up phase. The process technology expert, e.g., for welding processes, wants to express technology knowledge on FMEA causes and failure modes, collected from engineering models and artifacts coming from detail planners in mechanics, electrics, automation, and other engineering disciplines. However, the modeling means available in modern FMEA tools, such as APIS[1], are limited to modeling FMEA trees rather than graphs that relate to engineering knowledge, making it difficult to connect FMEA concerns with a network of production assets.

Traditional approach to FMEA modeling. According to the domain analysis, traditional approaches to FMEA for product quality consider detailed causes to define countermeasures during engineering, in particular, to inform production improvement during the ramp-up process. However, we found that the resulting FMEA models are complex and only implicitly related to engineering models, similar to findings in [3], [4]. Furthermore, traditional FMEA did not leverage the FMEA knowledge to provide operating guidance to reduce product quality risks. The operator had maintenance guidebooks for a machine type and had to rely on experience to use the guidebooks. Further, the operator had no input based on FMEA for a particular machine, leading to longer delay and to missing defects that the operator could have found [3].

For an advanced method to guide the operator, assuming better integrated access to engineering knowledge on production resources, the FMEA experts proposed operator guidance that considers for FMEA cause prioritization (i) resource knowledge, such as the mean time between failures for the resource linked to a FMEA cause, (ii) the availability of maintenance activity guidelines, and (iii) the expected duration and impact of countermeasures during operation.

VI. Results and Discussion

This section reports on and discusses results from employing the F2O approach in the case study context. In a feasibility study, three authors of this paper guided three FMEA and laser technology experts to conduct the F2O method to evaluate the feasibility, effectiveness, and efficiency of the F2O approach. They (i) designed *F2O models* for failure modes, such as *Weld Seam Dimensions inaccurate* (cf. Fig. 5); (ii) estimated the number of FMEA elements, PPRS assets, and links in F2O models for typical robot work cells in a manufacturing plant as input to effort analysis; (iii) analyzed the effort necessary to apply the F2O method based on a sample of FMEA and PPRS models; and (iv) collected feedback from the domain experts on the F2O approach and compared it to their traditional approach that relies on isolated FMEA without PPRS models.

Conducting the F2O Method. Step 1. Scope FMEA and PPRS models. In this step, domain experts focused on a specific defect – the failure mode *Weld Seam Dimension inaccurate* – of a high-value car body part (cf. Fig. 5). In their traditional approach, experts had collected product data that was sufficient for data analysis in a quality control lab, but not detailed enough to derive guidelines for an operator. Therefore, they collected engineering artifacts on resources and selected a set of PPRS assets (cf. Fig. 5, elements in blue color) related to the weld seam issue. This step took 30 person hours (excluding data collection) for the FMEA expert and a process expert with a process facilitator. It resulted in a list of FMEA and PPRS assets and properties and in an initial graph on a shared whiteboard.

```
MATCH FMEApath=
  (r)-[:has_FMEA2PPRS_Dependency]-
  (a:Cause {Marker:"Diamond.Red"})-
  [:has_FMEA_Dependency *..5]-
  (b:FailureMode {Marker:"Diamond.Red"})-
  [:has_FMEA2PPRS_Dependency]-(p:Product)-
  [:has_PPRSDependency *..10]-r
FOREACH (n IN nodes(FMEAPath) |
    SET n.Marker="Diamond.Yellow")
```

Listing 1: Cypher query to mark FMEA and PPRS paths between a marked failure mode and a marked cause (cf. Fig 5).

Step 2a. Design and validate a F2O model. The FMEA and domain experts selected 15 causes in the FMEA model and identified or added associated PPRS assets and properties, iteratively completing the F2O model (cf. Fig. 5) with selected FMEA and PPRS elements. The model was first sketched on a shared whiteboard. It was then modeled using a custom software tool for linking FMEA and PPRS elements and for storing them into the F2O database that was set up according to the F2O meta-model. This step involved several rounds of discussion among the FMEA and process experts, and working with detail planners to identify the most suitable assets and properties for defining a FMEA cause and operator activities (cf. Tab. I). This step took 42 person hours.

Step 2b. Validate and rate causes in the F2O model. The FMEA expert rated each cause in the F2O model, considering its RPN and the availability of a maintenance guideline for a resource asset linked to the cause, e.g., *Laser Protection Glass dirty* (cf. Fig. 5, elements marked with colored diamonds, and Tab. I, column *rating*). This step required 5 person hours.

Step 3. Analyze the F2O model. One author imported the F2O model into a Neo4J graph database. The author then designed *Cypher* queries to answer questions of the FMEA expert and to derive the operation checklist in Tab. I. This step took six person hours.

The *Cypher* query in Listing 1 retrieves a F2O sub-graph that consists of (i) the FMEA path from the failure mode *Weld Seam Dimensions inaccurate* to the cause *Laser Protection Glass dirty* and (ii) the PPRS paths from the PPRS model element *Assembly.Rework Code*, which has been linked to the failure mode, to the PPRS model element *Laser Protection Glass.(O).Protection Glass Cleanliness*, which has been linked to the root cause *Laser Protection Glass dirty* (cf. Fig. 5, F2O model elements marked with colored diamonds). The query collects resource (*r*), product (*p*), and their intermediate PPRS candidates from the graph and marks them with yellow diamonds. The marked concepts are input to further queries or human expert inspection.

Tab. I shows ranked causes and countermeasures for a selected failure mode, derived from a F2O model (cf. Fig. 5). The ratings are associated with the FMEA causes, countermeasures are linked to the resources associated with a FMEA cause. The table is easy to provide on a machine HMI, with countermeasures pointing to resource maintenance manuals.

Size of and effort to design a F2O model. To investigate the viability of collecting and maintaining a F2O model

Failure Mode: Weld Seam Dimensions inaccurate			
Rank	Rating	Cause in FMEA	Countermeasure (at resource)
1	450	Laser Protection Glass dirty	Check/clean Laser Protection Glass
2	420	Laser Controller setting wrong	Calibrate Laser Controller
3	360	Seam Quality Control False Positiv	Check Welding Head Temperature
4	255	Clamping Force wrong	Calibrate Clamping System
5	210	Laser Power inaccurate	Calibrate Laser Power
6	165	Laser Focus wrong	Calibrate Laser Positioning System
7	135	Welding Head wrongly positioned	Check Welding Head Position
8	120	Pivoting axis not favorable angle to	Calibrate Robot Positioning System
9	60	Angle of Attack not favorable on the	Calibrate Robot Positioning System
10	40	Laser Power ill aligned to profile thi	Check input profile with laser power

TABLE I
OPERATION CHECKLIST EXAMPLE.

for typical production processes automated by robot cells in automotive manufacturing, we built on an FMEA data sample from the domain analysis (cf. Section V) [19]. The analysis was conducted for 10+ joining production steps automated by robot cells varying in size from a small cell that automates a single production step to a large cell that automates 17 kinds of production steps.

Fig. 5 shows the F2O model of a typical robot work cell with a single welding robot. Larger robot cells contain further resources, such as an industrial PC, robots, and measurement devices, leading to a similar structure of the FMEA and PPRS graphs that contain more assets and links. The analysis of FMEA data on three types of welding cells resulted in more than 700 FMEA elements. For a typical welding cell, there were 12 processes that concerned 6 products. The FMEA was organized around 12 main failure modes that were refined with location qualifiers into 48 detailed failure modes. These effects were linked to 270 causes.

In the study, factors that determined the number of F2O model elements for a work cell included (i) the number of FMEA failure modes and causes, (ii) the number of PPRS assets and properties, and (iii) factors for links between FMEA and PPRS assets, e.g., the ratio of FMEA causes to links with PPR properties. For a typical failure mode, there were 10 to 25 FMEA assets with 12 to 30 FMEA characteristics and 10 to 30 FMEA links; linked to 12 to 20 PPRS assets with 35 to 50 PPRS properties and 12 to 50 PPRS links.

In the case study, the design of the F2O model and the derivation of operation checklists took around 80 person hours for two failure modes. For addressing further failure modes of the same work cell and production process, the domain experts expected between 3 and 5 person hours per failure mode.

Domain expert feedback regarding perceived ease of use and usefulness after completing the F2O modeling sessions.

The F2O model enabled the domain experts to iteratively express and discuss the knowledge required to efficiently analyze major root causes of welding failure modes. Therefore, the F2O model was a significant improvement over the previously isolated FMEA model that required interpretation of separate production engineering models by domain experts to inform the FMEA expert.

During validation of the F2O graph, the domain experts identified root causes that occurred infrequently, but would take a very long time for the operator to identify and address. The domain experts found exploring the paths from effects to root causes particularly useful – both in the FMEA and the PPRS models – as it helped them to analyze the paths of technical impact of resource linked to a root cause. They highlighted the following benefits (i) validation and more detailed description of FMEA assumptions by explicitly linking the properties of FMEA and PPRS models, which are currently isolated; and (ii) the structured F2O analysis method kept FMEA complexity manageable and improved FMEA completeness, following a sequential integration of stakeholders and their scopes of knowledge, such as basic planners, who know products, processes, and resource capabilities, and detail planners, who know production resource skills and details in diverse disciplines.

Overall, the F2O model provided (i) FMEA experts with a condensed overview on the causes and root causes of an effect that is well connected to the technical reality of the production processes and resources; (ii) domain experts with PPRS asset properties that represented data sources, such as sensors or variables in databases, for informing FMEA; and (iii) the foundation for providing operators with an overview on resources, their technical relationships and most relevant properties, connected to operation data sources and maintenance guidebooks.

VII. CONCLUSION AND FUTURE WORK

To support FMEA experts and operators during the ramp-up of a production system, this paper introduced the *FMEA-to-Operation (F2O)* meta-model and method, which together provide a (i) model-driven [16], (ii) machine skill-centric [22], and (iii) actionable [4] approach to integrate and validate FMEA models with engineering knowledge and to identify likely causes of product quality issues in manufacturing effectively and efficiently, and generate an operation checklist. The approach provides a solid foundation for effective defect diagnosis and resolution on the shop floor and for improving the understanding of causes and effects in manufacturing processes [7], which is especially useful during ramp-up [4].

The F2O method facilitates structured analysis in order to reduce FMEA complexity and improve FMEA completeness. The skill/capability-centric [18] structuring enables a separation of concerns and improves risk analysis with basic and detail planners. Consequently, the FMEA can be conducted in smaller, more manageable steps that result in graphs that together form a comprehensive network of F2O relationships. This comprehensive network can be stored in a graph database for automated querying and analysis to inform the FMEA expert and export powerful, well-founded, and actionable guidance to the operator.

An IT expert can take up the operating checklists for the failure modes of a machine to configure in the machine runtime environment the operator HMI, for showing the operator, in addition to a product defect code, a list of ranked causes and countermeasures linked to maintenance guidelines that are required to quickly and correctly address the cause.

In an initial feasibility study, domain experts conducted the F2O method, guided by authors of this paper, on a real-world robot cell for welding car parts. In this context, the study showed that the F2O approach was (i) feasible in that the F2O knowledge graph provides the FMEA knowledge necessary to guide the operator (cf. Tab. I); (ii) effective in that the F2O method resulted in valid tables for operator guidance (cf. Tab. I), which experts on FMEA, laser technology, and operation found useful and usable; and (iii) efficient as the domain experts found the F2O method to focus on the most relevant production assets and properties by using machine skills to abstract from concrete production resources. While the F2O method requires advanced digitalization maturity, these promising results warrant further empirical studies in a variety of application contexts.

Future Work. *Reusability of F2O models.* We plan to investigate the efficient reuse of FMEA knowledge in a F2O model for similar but different work cells and processes that require similar skills, e.g, accurate welding. The structuring of FMEA patterns based on machine capabilities enables FMEA modularization into skill-centric patterns to increase reusability and ease the application and adaptation of FMEA knowledge to particular production environments, such as similar work cells. We plan to conduct case studies on the applicability and scalability of the F2O approach on manufacturing work lines to reduce the risk of recurring issues.

Towards a digital twin for FMEA of a robot cell. A F2O model can inform the design of a digital twin regarding resource properties, e.g., for configuring an OPC UA system to collect data for monitoring the fulfillment of FMEA causes as a foundation (i) for preventive maintenance planning and (ii) for adjusting FMEA risk probability with operation knowledge. Similar to providing operator guidance, FMEA causes could inform condition monitoring to collect more detailed data from selected data sources, if certain conditions occur, e.g., check the laser control setting, if weld seam quality deteriorates.

Information security. While the F2O method focuses on unintentional causes of product quality issues, it provides a good foundation for information security analysis, which assumes intentional wrongdoing, to provide a bridge between security analysts and the knowledge on product quality relationships to resources with high impact on production quality. Therefore, we plan to apply F2O models with information security experts to explore risk profiles for security monitoring.

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