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Expert-in-the-Loop Framework for MBSE-assisted Automatic Process FMEA Generation

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This paper introduces an expert-in-the-loop framework for MBSE-assisted automatic FMEA generation to enhance the productivity and integrity of the manufacturing process design assurance. The MBSE-assisted FMEA tool is implemented in the Matlab System Composer environment, and supports the implementation of the framework as an iterative process including three activities: MBSE process model development; detailed process dependencies analysis to enhance the detail of the MBSE model; and MBSE-assisted FMEA generation based on a failure mode taxonomy and ontology with continual learning. The principle guiding the framework and the design of the user interaction with the tool is that the expert should evaluate the validity of the MBSE model and the FMEA generated based on the engineering inputs provided, with corrections applied to the inputs rather than the outcomes. This ensures both traceability of the analysis, and also that all the system design and development documents are updated. The industrial validation of the framework with a complex robotic manufacturing process showed good results in terms of robustness, integrity and productivity.

Keywords: model-based systems engineering (MBSE), process modelling, process analysis, failure mode and effects analysis (FMEA), robustness, design and process assurance..

1. Background

While significant progress has been made with the development and adoption of computer modelling and simulation tools to assist with the systems design, many of the engineering analysis methods, in particular those focussed on robustness and reliability for the design and process assurance, such as Failure Modes and Effects Analysis (FMEA), still remain expert-centred, thus time and resource intensive. While standards like the AIAG (2019) provide up-to-date guidance for the FMEA, many of the widely discussed weaknesses of the FMEA process, including (i) human factors effectiveness (labour intensive, time consuming and error prone process, with outcomes often difficult to update and interpret); (ii) uncertainty of the integrity of the FMEA (completeness and integrity across multiple and often iterative levels of analysis within a complex system); and (iii) lack of traceability and integration across the whole product lifecycle, remain unaddressed. Recent effort to comprehensively address these issues, largely driven by the development of intelligent robotic and autonomous systems, have centred on the integration of FMEA with Model-Based Systems Engineering (MBSE), to ensure traceability within a Product Lifecycle Management (PLM) digital environment. E.g. Huang et al (2018) have presented MBSE approaches to support FMEA development. In addition, recent efforts to address the resource effectiveness of the methodology have focussed on the automation of the FMEA generation, e.g. Korsunovs et al (2022), Girard et al (2020). This paper builds on this state of the art with the introduction of a comprehensive expert-in-the-loop framework for MBSE-assisted automatic process FMEA generation.

2. Expert-in-the-Loop MBSE-assisted Process FMEA Generation Framework

The proposed framework integrates within a comprehensive modelling implementation three hitherto separate activities: (i) development of an MBSE process model; (ii) analysis and capture of process dependencies within the MBSE model); and (iii) generation of the FMEA analysis. The workflow is implemented within the Matlab System Composer environment, as an MBSE-assisted PFMEA Toolbox. The role of the expert is to provide the engineering inputs required for model generation at and evaluate and validate the outcomes at each step of the activity. Figure 1 illustrates the proposed approach.

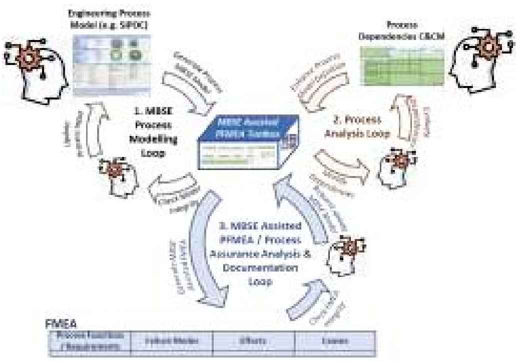

Fig. 1. Framework for Expert-in-the-Loop MBSE-assisted Process FMEA Generation

In the first loop, an MBSE process model is automatically generated (Matlab coding) from an engineering process model (e.g. a detailed process SIPOC analysis) supplied by the process analysts. The generated MBSE model, visualised in System Composer, is evaluated by the process expert; if any changes are required, this will require corrections to the SIPOC input, and the MBSE model will be regenerated. This is an iterative process until the model integrity is accepted. In the next loop an enhanced process MBSE model is developed with information about process dependencies. This is necessary in order to support causal and propagation analysis for product and process failure modes, centred on the critical characteristics. Information about process dependencies is collected from the process experts using a tabular format based on the robust process dynamic control planning methodology described by Ford Motor Company (2011). This is again an iterative process where the expert visualises the revised MBSE model, with additions or corrections to the inputs applied as necessary. In the third loop, the process FMEA (P-FMEA) is generated based on the enhanced MBSE model, using an intelligent failure modes dictionary (ontology) developed based on the function failure taxonomy (AIAG, 2019), with continual learning from expert-generated input, both on-line and offline (from previous FMEAs). The generated FMEA is evaluated by the experts; any changes should address the modelling inputs (either the MBSE model or the failure modes ontology), rather than edits to the FMEA document. This ensures traceability of the analysis, such that the MBSE process model, process documentation and process FMEA are all aligned.

3. Discussion and Conclusions

The proposed framework has been validated through implementation on real world industrial case study of robotic manufacturing process design for an electric drive unit. The interaction with process experts has provided validation for the proposed framework, highlighting the practical benefits in terms of productivity, robustness and integrity of the outcomes, and traceability and governance of the documents.

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