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Towards a Model-Based Systems Engineering Approach for Robotic Manufacturing Process Modelling with Automatic FMEA Generation

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Abstract

The process of generating FMEA following document-centric approach is tedious and susceptible to human error. This paper presents preliminary methodology for robotic manufacturing process modelling in MBSE environment with a scope of automating multiple steps of the modelling process using ontology. This is followed by the reasoning towards automatic generation of process FMEA from the MBSE model. The proposed methodology allows to establish robust and self-synchronising links between process-relevant information, reduce the likelihood of human error, and scale down time expenses.

Keywords: *model-based systems engineering (MBSE), process modelling, process analysis, failure mode and effects analysis (FMEA), reliability*

1. Introduction

1.1. Background

Proliferation of new technologies adopted across industries to deliver better systems often results in growing system complexity, raises challenges for their robustness both from a manufacturing viewpoint and in operation. Addressing the growing system complexity requires increased focus on robust design at the system development stage. Failure Modes and Effects Analysis (FMEA) is a well-known method to support systematic analysis of a product or process to identify potential failure modes and plan for robustness measures, including robust control plans for a manufacturing process, at the design stage.

While the FMEA has been extensively used over the past decades in a wide range of industries, particularly aerospace, nuclear and automotive, following well defined methods and procedures for conducting FMEAs (AIAG, 2019; 2021; Ford Motor Company, 2011), weaknesses in the process for the FMEA deployment have been often discussed. FMEA is regarded as a labour intensive, often unstructured and time-consuming process, which is ultimately reflected in the integrity of the analysis. The failure modes and their causes are typically identified via unstructured brainstorming, therefore the quality of the analysis is subject to the experience and engagements of the analysts (Bell et al, 1992; Kmeta & Ishii, 1998). Furthermore, FMEAs tend to evolve into very large and cumbersome documents due to the level of detail required to identify every possible failure mode. Such documents can be difficult to keep up to date and to interpret, and ultimately the effort to complete the FMEA can sometimes exceed the product or process development timing (Hawkins & Woolons, 1998). As a result, FMEAs are often regarded as a deliverable to the customer, rather than a tool used by engineers to influence design decisions (Johnson & Khan, 2003).

Based on these observations, efforts to improve the FMEA process should concentrate on three aspects: (i) time and effort required to complete the analysis; (ii) integrity of the FMEA reasoning and analysis; and (iii) traceability of the FMEA documents across multiple levels of analysis within a complex system. While efforts to address items (i) and (ii) have been reported in the literature as early as 1990s (e.g., Bell et al, (1992) discussed the use of causal reasoning to automate the FMEA), progress has been somewhat limited, with the exception of electronics and systems where failure behaviour can be modelled with Boolean logic (e.g., Hip-Hops (Papadopoulos (2013)).

Driven by the need to demonstrate effective risk management for the complex safety and autonomous features, there has been renewed interest over the last decade for enhancing the FMEA process in conjunction with Model-Based Systems Engineering (MBSE) systems modelling methods and tools (Huang et al., 2018). Approaches of integrating FMEA with MBSE attempt to address the issues identified above, including traceability of the risk management based on FMEA across the systems levels. For example, Huang & Hansen (2017) and Huang et al (2017) have presented work towards the integration of SysML MBSE modelling with FMEA, identifying the relevance and use of different diagrams for the FMEA as well as the integration with the requirements management system, and highlighted challenges and opportunities for further development. Qamar et al (2017) have presented a comprehensive MBSE approach to support an FMEA centred Failure Mode Avoidance framework for driver assistance systems, illustrating the integration across multiple systems levels of analysis (feature, system, subsystem). Several authors have reported work towards the automation of the generation of FMEA and other reliability risk assessment methods (e.g., Fault Trees) from UML state machines associated with functional flows; as relevant industry-based examples, we refer to the work of Kaukewitsch et al (2020) and Nordman & Munk (2018).

1.2. Research motivation and aims

The industrial context for this research is provided by a disruptive approach to the electric propulsion systems manufacturing based on the vertical integration in fully automated robotic micro-factories. Within an Industry 4.0 environment, vertical integration refers to the setting up an internal chain of manufacturing process values, including devices, robots, manufacturing execution system software and human operators (Marques et al, 2017). The robotic micro factory vision implies easy re-configurable architectures of the vertically integrated manufacturing processes to deliver complex products in small to medium sized volumes at competitive compared to large scale manufacturing. From an OEM point of view, this offers the opportunity for volume customisation of vehicles, with potential significant competitive advantage.

From a process modelling point of view, the challenge is to develop an integrated modelling blueprint for the robotic manufacturing system with full traceability of robustness assurance, from critical characteristics in the system requirements specification to the lean I4.0 digitalisation that implements optimal control plans to assure these are robustly achieved. The model should also be easily reconfigurable for the manufacturing of new variants or products, with traceable inheritance of the process assurance assets to enable the rapid transition to the new configuration.

An MBSE approach for modelling the robotic micro-factory as a system of systems is not only a natural choice to ensure traceability and inter-operability, but also enables the coupling with the MBSE model for the drive unit system design, thus providing an integrated MBSE modelling continuum across the system development. This does not only facilitate re-configurability, but also enables the concurrent design of the system and its manufacturing process, which is essential to achieving the desired cost-competitiveness. From a modelling point of view this is a significant challenge, as current MBSE modelling approaches for processes commonly follow a process mapping approach (i.e., the MBSE model captures the way in which the process works), with process models resulting from the composition of operation models. However, the design of the manufacturing process requires a top-down approach to modelling, with strong co-ordination of process assurance for complex quality features, including documentation of the Process FMEAs and the robust control plans.

A first aim for this work was to develop a top-down systems engineering approach to robotic manufacturing process design, modelling and analysis, underpinned by an MBSE framework. A second research aim was to automate the generation of the PFMEA and related process risk modelling methods

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(in particular, Fault Tree Analysis, FTA) based on the MBSE model. This approach will underpin the robust process assurance framework, focussed on the traceability of the key characteristics from design through to manufacturing process operation. This paper presents preliminary work on the development of the MBSE process model and the automatic generation of PFMEA from the MBSE model.

The organisation of the paper is as follows: section 2 provides a review of related research, section 3 presents the proposed modelling methodology, followed by the MBSE framework description in section 4 and implementation of the PFMEA reasoning based on the MBSE process model in section 5. Finally, section 6 summarises the research outcomes, conclusions and directions for further work.

2. Review of related research

2.1. Overview of MBSE within Industry 4.0

The current vision for robotic manufacturing process is often described within an Industry 4.0 context. Marques et al. (2017) have defined four key characteristics underpinning Industry 4.0 in manufacturing:

- Vertical integration: refers to setting up an internal chain of manufacturing process values (including devices, robots, manufacturing execution system software and human operators).
- Horizontal integration: expands globally to set up logistics chain, product maintenance and delivery arrangements for final consumers.
- Consistent engineering: integration of digitalization in systems engineering to capture product lifecycle from design and development to disposal and aftersales services.
- Human-technology synergy: development of new skills and qualifications for the workforce to increase productivity and level of attraction.

In practical terms, model-based systems engineering (MBSE) is commonly applied to capture engineering knowledge to support process modelling. The term MBSE was first formulated by Wymore (1993), who looked system structure and relationships in mathematical terms. Nowadays, MBSE is deployed more to support modelling of complex engineering systems. Its concepts are often associated with engineering architecture development, which is a coherent representation of system structure and corresponding behaviour (Promyoo et al., 2019). The applications are found in wide range of field, including unmanned systems (Giles et al., 2019), electric vehicles (Draxler et al., 2019), military technologies (Sarathi et al., 2021) and others. The primary MBSE aim is to define functional and non-functional requirements in a way that linkages between functional, logical and physical architecture were traceably across all levels of abstraction (Promyoo et al., 2019).

2.2. Overview of FMEA / PFMEA

Historically, the FMEA was governed by two approaches:

- The BE EN 60812:2018 (and previous versions, originating in military standards) bottom-up approach to FMEA – which is completed from components up, with failure modes causes identified as failure mechanisms, and effects propagated up the system, with risks identified and mitigated with corrective actions. From a product development point of view this approach is mainly reactive as it requires the design to be complete before the FMEA analysis can be carried out. The implication is that any design changes required following the FMEA risk analysis, will have a significant knock-on impact on the design, leading to spiralling development costs.
- The AIAG (2019) approach to FMEA is focussed on a product development paradigm and adopts a top-down development of the FMEA, deployed within a system engineering V context. Potential failure modes are defined using a function failure taxonomy (no function, partial function, intermittent function and command failure), with causes sought as function failures of subsystems, down to component level where the causes are identified as failure mechanisms. The effects are identified at the highest level of the system (considering the user, environment and legal considerations) and are cascaded down through the levels of analysis associated with the system level of decomposition. Function failure modes identified by the system level analysis as potentially leading to a severe effect (either hazardous or loss of primary function)

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are identified as potential *key characteristics* (either critical or special) that must be traced through the design process to ensure effective countermeasures are adopted to mitigate the risks.

While the AIAG FMEA approach is clearly set up in a systems engineering context, the deployment of the FMEA in industry - in particular, from the perspective of automotive OEMs as systems integrators, is often not following the systems structure, and mainly concentrates on the subsystem level (Henshall et al, 2014). The fact that companies across the supply chain have been following different FMEA procedures has also contributed to this state. Examples of hierarchical deployment of the FMEA alongside the systems levels of decomposition have been provided by Henshall et al (2014) for an automotive aftertreatment system, and Goodland et al (2013) for an aerospace manufacturing process system.

The AIAG-VDA (2019) FMEA handbook has provided a much welcome unification of the two approaches, by providing comprehensive updated guidance to the FMEA methodology and the context for the analysis in relation to the system level. From a process FMEA point of view, the AIAG-VDA approach prescribes a two-phase approach, each including three steps:

- System Analysis - including scope, structure analysis and function analysis;
- Failure Analysis and Risk Mitigation - including failure analysis, risk analysis and optimisation.

The theoretical failure chain model (Figure 1) lies at the core of the FMEA reasoning. For a process step, failure modes (FM) are defined in relation to the product and process characteristics (e.g., non-conformities; partially executed tasks; unintentional activities; unnecessary activity). The failure causes (FC) are sought in relation to the subsystems and actors (generally man / machine / material / environment factors) that contribute to the realisation of the process step function. The failure mode effects (FME) are defined in terms of the experience of the customer of the process step, which could be internal (next / subsequent operation), external (next tier up level), legislative bodies (including health and safety and the environment), or product end user / operator.

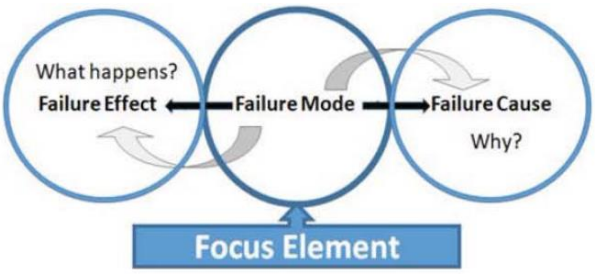

Figure 1. Theoretical failure chain model (AIAG-VDA, 2019)

The management of the deployment of the FMEA within a systems engineering context for a process revolves around the traceability of the risks associated with the key characteristics across process chain. This starts with the necessary linkage between the FMEA analysis of the system being designed (e.g., the Design FMEA, DFMEA, for an electric drive unit), identifying key characteristics traceably linked from the user to the designed components, which need to be communicated as end effects to the PFMEA process (AIAG-VDA, 2019). Ultimately, the process FMEA analysis has to systematically identify process risks associated to the key characteristics through the causal dependencies, and implement appropriate mitigations, including a robust process control plan.

Complex manufacturing operations often bring complexities that manifest in non-hierarchical and/or non-deterministic linkages within the failure chain. This requires a deeper consideration of the robustness factors impacting on the process realisation. A structured approach to this challenge was introduced in the FMEA with Robustness Linkages handbook (Ford Motor Company, 2011). There are two main issues that are addressed by this approach:

1. The process flow analysis considers key sources of variation for each process step, alongside part and process characteristic;
2. The correlation and characteristics matrix (CCM) which maps the linkages (or dependencies) between the part output characteristics at the process step and the key process characteristics across the whole process flow.

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The identification of dependencies in the CCM is important because it facilitates the understanding of the failure propagation modes within the process. This further enables key characteristics to be mapped to process characteristics earlier in the process, which would not have been otherwise identified as critical. The consideration of robustness through systematic identification of sources of process variation and across process dependencies through the CCM, underpins the development of a dynamic control planning for the process (Ford Motor Company, 1997; 2011).
Figure 2 illustrates an approach to integrated Process FMEA with robustness and dynamic control planning, synthesised from the aerospace manufacturing case study presented by Goodland et al. (2013).

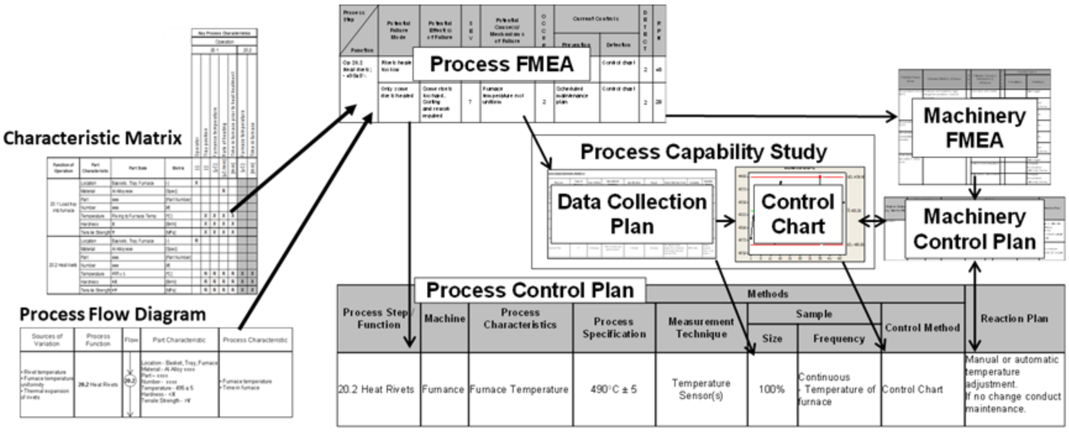

Figure 2. Integrated process FMEA with dynamic control planning

2.3. State of the art on MBSE assisted FMEA

There have been several attempts to facilitate FMEA generation using MBSE approach. Huang et al. (2017) proposed 5 steps towards MBSE-assisted generation of FMEA and, as evolution of this methodology, later proposed to completely move away from document-based reliability tools and incorporate FMEA as a part of MBSE, aiming at higher efficiency of the entire analysis process (Huang et al., 2018). However, the authors did not concentrate on the automation aspect and their work is focused around representation of the relevant information within MBSE.
Another approach of MBSE model building for automatic generation of FMEA has been presented by Hecht et al. (2014). Although the authors provide information on the model structure, the process of FMEA generation is not detailed, and the resulted FMEA presented differs from the standard FMEA document and thus the information it carries is not sufficient for comprehensive failure analysis. Similarly, Girard et al. (2020) described their vision of MBSE system model structure and automatic generation of fault trees and FMEA. The authors illustrated the generation of a simple fault tree and basic FMEA, however, still being far from comprehensive failure analysis.
An interesting and inspiring work has been published by NASA researchers (Day et al., 2012; Donahue et al., 2015), where authors introduced ontology to define relationships between components, their activities, goals and state variables. This approach allowed them to establish robust MBSE model capable to capture every aspect of a space mission and provide highly detailed FMEA.

3. Proposed methodology for MBSE assisted FMEA

The challenge for this work was to develop a methodology for an MBSE-assisted automatic generation of PFMEA to support the design of a fully robotic manufacturing process. A distinguishing feature of the proposed methodology is the consistent process systems engineering top-down approach to represent generic solutions suitable for a wide range of assembly process modelling within manufacturing. From an industrial viewpoint, this provides a significant advantage when the robotic manufacturing process can be modelled and simulated, to support optimal decisions for the process, equipment and controls.
Figure 3 illustrates the proposed methodology at a conceptual level. Domain expert knowledge, typically available in the form of SIPOC (Suppliers, Inputs, Process, Outputs, Customer) documents, which contains the core information needed to set up the process flow model with the corresponding information flow logic. The

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process flow model describes the operations by defining process characteristics, inputs and outputs. In other words, it forms basis for system architecture model, which is the skeleton for further MBSE modelling. The relationships between process characteristics are established in the Correlation and Characteristics Matrix tool, capturing the logical and behavioural linkages between operations, detailed at the level of part and process characteristics. This enables to attach significance to characteristics associated with a particular operation given their effect on downstream operations. The CCM is a crucial tool for identifying *failure mode effects* (FME). The methodology illustrated in Figure 3 also shows that higher-level models can be decomposed further into sub-operations and activities, to analyse detailed operational and machinery aspects, which may also require SIPOC analysis from different domain expert teams.

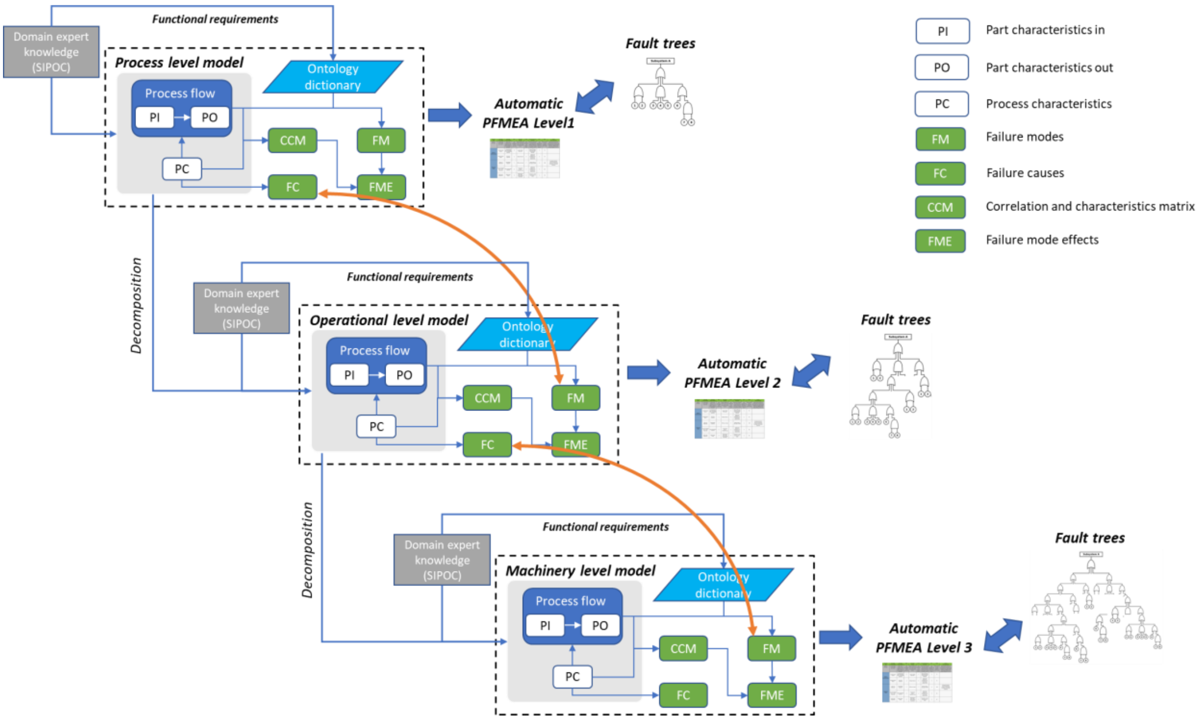

Figure 3. Generic methodology towards automatic PFMEA

The key information that is required for PFMEA generation is Failure Modes data (FM), Failure Causes data (FC) and Failure Modes Effects data (FME). These three elements are interlinked through the "Failure Chain" (AIAG-VDA, 2019). By representing the "Failure Chain" relationship on multiple levels, for a focus element on a particular level with defined FM, the FC are defined by the lower-level FM, and the FME are defined by the higher-level FM. In simple terms, failure chain is established via operational decomposition and this relationship is shown with orange double-headed arrow in Figure 3. However, defining the potential FM automatically is challenging. Normally, this requires modelling and representing system behaviour, e.g., using state effect diagrams. Capturing all relationships is very difficult, and the engineer / analyst is expected to evaluate the output of automatic FMEA and augment with any missing details (Hecht et al., 2014). On the other hand, a robotic assembly process often involves elemental operation steps or sequences that appear repeatedly in the overall topology of the process model. Consequently, this underpins the compositionality the MBSE process model, and in turn, using a model-based basis for failure modes and effects analysis enables the use of *stereotypes* to enable the reuse of elemental analysis, facilitated by a pre-defined ontology dictionary of failure modes.

The failure modes ontology dictionary is underpinned by a teleological link to the functional requirements, facilitated by the standard function failure modes taxonomy, i.e., No Function, Partial Function, Intermittent Function, and Unintended Function (AIAG, 2019). Thus, it is feasible to establish rules to extract key information and words from functional requirements, failure mode taxonomy and operations themselves, and to elicit the potential failure modes for each case, as shown in Section 4.

Once all the information is available, the PFMEA can be automatically generated using through scripted data processing. This development and validation of the above methodology was carried out with a case

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study of a differential gear system robotic assembly process. The process includes assembly-involved parts identification and delivery, as well as assembly manipulations, such as pressing and securing (threaded joint), overall totalling to 31 process steps (not counting machinery level), out of which only 8 operations were unique. Detailed process description, captured in process flows and detailed SIPOC analysis, was available as input. The MBSE implementation framework was implemented in the Matlab System Composer environment, through a comprehensive set of Matlab scripts.

4. Framework for MBSE for Process Modelling

Robotic manufacturing process decomposition is performed via top-down approach. The visualisation of the decomposition is illustrated in Figure 4. The decomposition process starts with the top level, represented by the robotic manufacturing process itself. The robotic manufacturing process is further decomposed into the operations and sub-operations that it consists of, and this is represented by the operational level. Each of the sub-operations on operational level is further decomposed into constituent basic machinery operations, which form the machinery level. Each of the operations on every level is supported by a set of relevant critical characteristics, which form the cascade of critical characteristics through the process decomposition. The key part of decomposition of robotic manufacturing process is that each process step, at any level, must be named in the form of: "verb" (representing the action that needs to be performed, essentially denoting the function) + "noun" (representing the item of interest that the action is performed on) + any other relevant information. By ensuring the correct naming of the robotic manufacturing process steps, it is possible to handle this information afterwards with the application of ontology dictionary, which is discussed further in this section.

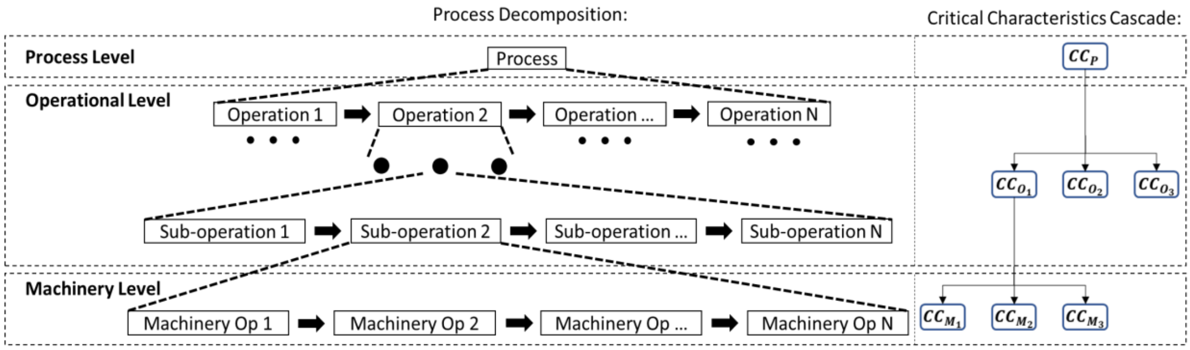

Figure 4. Top-down robotic manufacturing process decomposition

Once the process is decomposed, MBSE model is built around all the levels mentioned in Figure 4.
Figure 5 illustrates the database structure of all the elements involved in the robotic manufacturing MBSE robotic model, which is split into four main domains: Engineering Knowledge domain, Process Architecture domain, Characteristics domain and Failure Mode Analysis domain.
Engineering Knowledge domain includes external information input that is used to define fields within the rest of MBSE model that are important for further processing. Primarily, the key input to the MBSE model is SIPOC, which defines part of the information stored within Matlab System Composer environment and covers the manufacturing process steps architecture (here 'process step' block represents process architecture element within Matlab System Composer, at any level of process hierarchy), part in/out and process characteristics.
The Ontology Dictionary is based on a pre-defined set of common faults and their causes related to a particular robotic operation, which also is a part of robotic manufacturing process decomposition element. In essence, the Ontology Dictionary was implemented through an ensemble of Matlab functions that are triggered at the processing stage if the decomposition element name is recognised as part of pre-defined database. For the recognised element, the Ontology Dictionary updates the Faults Structure cell array within Matlab workspace, as well as Failure mode information within the Matlab System Composer environment. Both, the Failure mode information, and Faults structure are in synchronisation and information in these blocks can be manually amended if required. The architecture model is built using the information

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stored in the Faults structure cell array using a processing script. The architecture model component view within the Matlab System Composer environment enables visualisation as a Fault tree with OR gates only.

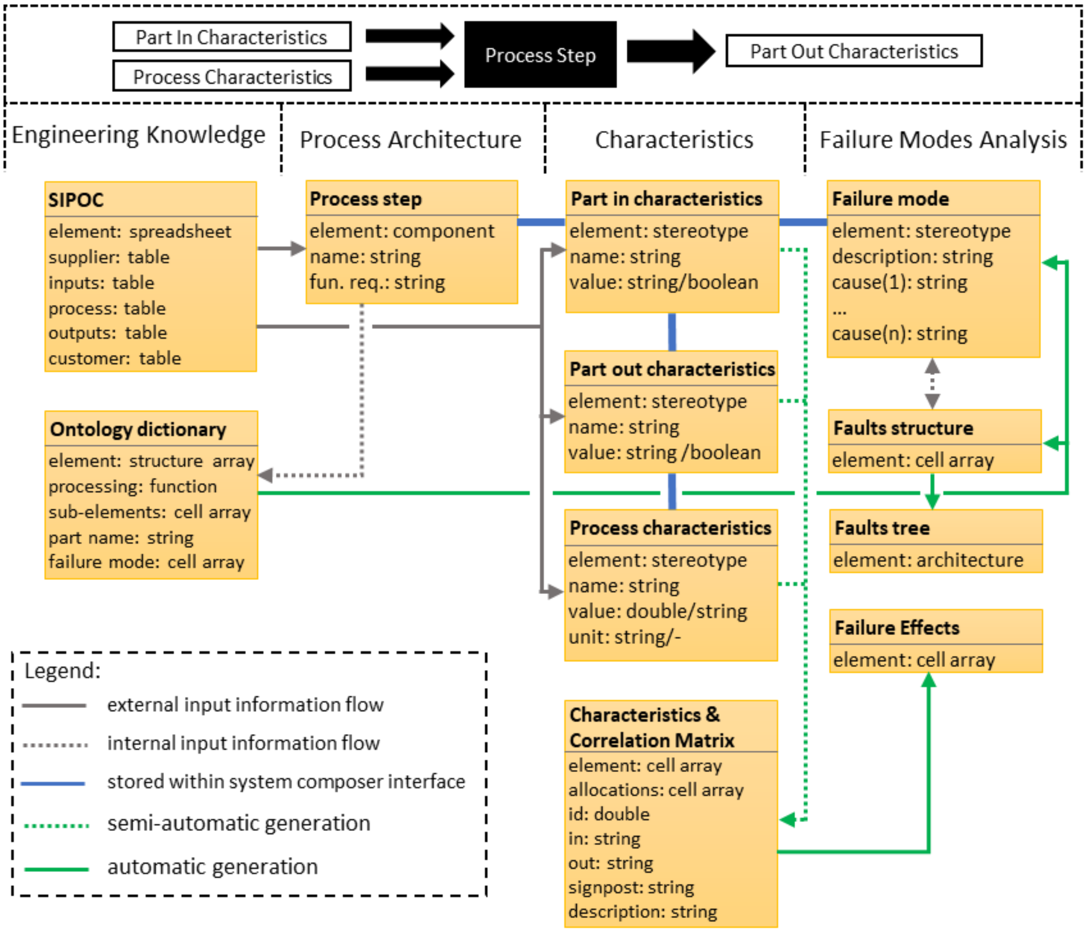

Figure 5. MBSE robotic manufacturing process model database structure

The Characteristics field includes, in addition to the part and process characteristics information, the Characteristics & Correlation Matrix, represented as cell array in Matlab workspace. The generation of Characteristics & Correlation Matrix is semi-automatic, because it requires assignment by the analyst of allocations between the characteristics through the allocation manager within Matlab System Composer. Based on these allocations, Failure effects is automatically enabled / supported.

5. Automatic PFMEA reasoning from MBSE

The MBSE process model described in Figure 5 holds sufficient information that can be automatically propagated in into the PFMEA. As discussed in Section 3, the "*Failure Chain*" information is key to the PFMEA generation. This way, the FM and FC information, following processing through the Ontology Dictionary, is stored within the Failure Modes & Causes information block, and exported to the "Potential Failure Mode" and "Potential Cause/Mechanism of Failure" columns of PFMEA. The FME information is stored within the Failure Effects block after the relevant effects are defined through the Correlation and Characteristics Matrix, and exported to the "Potential Effect(s)" column. The process step operation and requirements associated with it are stored within the *Process Architecture* block and generate the "Process Functions / Requirements" columns of the PFMEA. Figure 6 shows this information processing flow, along with the model information output into PFMEA, illustrating the views of the relevant blocks within the MBSE model and the generated PFMEA for a case study of a differential assembly - as a subsystem of the drive unit robotic manufacturing.

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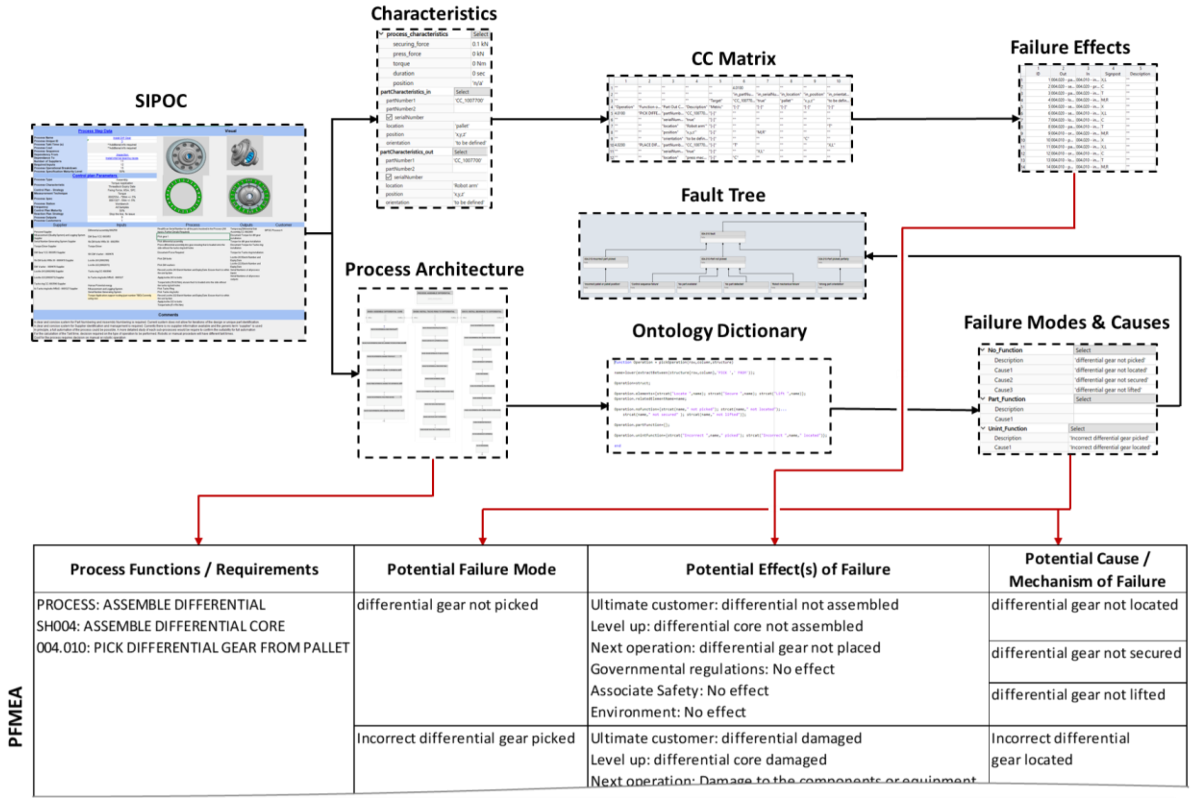

Figure 6. MBSE output information flow into PFMEA

6. Discussion and Conclusions

This paper has introduced a top-down systems engineering approach to manufacturing process design, with integrated co-ordination of process assurance embedded in an automatically generated Process FMEA. The automatic generation of the PFMEA is important both in order to address the known weaknesses of the FMEA process deployed for the analysis of large scale complex systems, and to deliver efficiency gains for the design and development of the manufacturing process.

The main contribution of the paper stems from the integration of the process functional failure analysis toolchain with the MBSE process modelling tools and models architecture, achieved through the augmented object data structures summarised in Figure 5 and software scripts to deliver the required logic and functionality. The MBSE-assisted automatic generation of the PFMEA is critically underpinned by two key elements: (i) the ontology dictionary to generate the potential failure modes based on process function stereotypes; and (ii) the Correlation and Characteristics Matrix (CCM), to capture the dependencies between characteristics across the operations flow, deployed across the levels of process-as-a-system decomposition.

The case study referred in Section 5 has provided preliminary empirical validation for the proposed framework. This is a small part of a much larger analysis carried out within the industry context of the work. The generated PFMEA was validated by the robotic process engineering experts, and found to have a good level of integrity. The intention of the MBSE-assisted PFMEA tool is to act as an *augmented intelligence* assistant (AI-A) for the process assurance engineering experts, therefore validation of the collaboration between the human expert and the software expert system is fundamental.

A limitation of the current level of development of the MBSE-assisted PFMEA tool is that it only covers the failure modes, effects and causes. Our current work focusses on the extension of the tool to support the identification of *detection* options, based on the association with automatically generated fault trees. This will further facilitate the synthesis of an optimal robust process control strategy, underpinning the generation of an architecture for the robotic micro-factory Industry 4.0 system.

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References

AIAG - Automotive Industry Action Group, (2019), AIAG & VDA FMEA Handbook, Detroit, MI

Bell, D., Cox, D., Jackson, S., and Schaefer. P., (1992), "Using Causal Reasoning for Automated Failure Modes and Effects Analysis", Proc 1992 IEEE Annual Reliability and Maintainability Symposium, pp. 343 – 353, https://dx.doi.org/10.1109/ARMS.1992.187847

BS EN 60812:2018 Failure Modes and Effects Analysis (FMEA and FMECA), BSI / European Standard.

Day, J., Donahue, K., Ingham, M., Kadesch, A., Kennedy, A. and Post, E., 2012. Modeling off-nominal behavior in sysml. In Infotech@ Aerospace 2012 (p. 2576), https://dx.doi.org/10.2514/6.2012-2576

Draxler, D., Neureiter, C., Lastro, G., Schwartzkopff, T. and Boumans, M., 2019, May. A domain specific systems engineering framework for modelling electric vehicle architectures. In 2019 IEEE Transportation Electrification Conference and Expo, Asia-Pacific (ITEC Asia-Pacific) (pp. 1-6). IEEE, https://dx.doi.org/10.1109/ITEC-AP.2019.8903596

Ford Motor Company, (1997) The Strategy of Dynamic Control Planning, Training and Reference Manual.

Ford Motor Company, (2011), Failure Modes and Effects Analysis, FMEA Handbook (with Robustness Linkages), Version 4.2, Dearborn, MI

Giles, K. and Giammarco, K., 2019. A mission-based architecture for swarm unmanned systems. Systems Engineering, 22(3), pp.271-281, https://dx.doi.org/10.1002/sys.21477

Girard, Gaëlle & Baeriswyl, Ivan & Hendriks, Jonathan & Scherwey, Roland & Müller, Christian & Hönig, Philipp & Lunde, Rüdiger. (2020). Model based Safety Analysis using SysML with Automatic Generation of FTA and FMEA Artifacts. 5051-5058, https://dx.doi.org/10.3850/978-981-14-8593-0_4941-cd

Hawkins, P. G. and Woollons, D. J., (1998), "Failure Modes and Effects Analysis of Complex Engineering Systems using Functional Models, Artificial Intelligence in Engineering, 12, pp. 375 – 397, https://dx.doi.org/10.1016/S0954-1810(97)10011-5

Hecht, M., Dimpfl, E. and Pinchak, J., 2014, November. Automated generation of failure modes and effects analysis from SysML models. In 2014 IEEE International Symposium on Software Reliability Engineering Workshops (pp. 62-65). IEEE, https://dx.doi.org/10.1109/ISSREW.2014.117

Hecht, Myron & Dimpfl, Emily & Pinchak, Julia., 2014. Automated Generation of Failure Modes and Effects Analysis from SysML Models https://dx.doi.org/10.13140/2.1.4578.9446.

Henshall, E., Campean, I., and Rutter, B. (2014) A Systems Approach to the Development and Use of FMEA in Complex Automotive Applications. SAE Int. J. Mater. Manf. 7(2):280-290, https://dx.doi.org/10.4271/2014-01-0740.

Huang, Z., Hansen, R. and Huang, Z., 2018, January. Toward FMEA and MBSE integration. In 2018 Annual Reliability and Maintainability Symposium (RAMS) (pp. 1-7). IEEE, https://dx.doi.org/10.1109/RAM.2018.8463084

Huang, Z., Swalgen, S., Davidz, H. and Murray, J., 2017, January. MBSE-assisted FMEA approach—Challenges and opportunities. In 2017 Annual Reliability and Maintainability Symposium (RAMS) (pp. 1-8). IEEE, https://dx.doi.org/10.1109/RAM.2017.7889722

Johnson, K.G. and Khan, M. K., (2003), "A Study Into the Use of the Process Failure Mode and Effects Analysis in the Automotive Industry in the UK", Journal of Materials Processing Technology, 139, pp. 348 - 356, https://dx.doi.org/10.1016/S0924-0136(03)00542-9

Donahue, K., Kennedy, A & Day, J, (2015) "Automated Generation of Failure Modes and Effects Document from a Simple SysML Model," NASA Tech Brief.

Kmenta, S. and Ishii, K., (1998), "Advanced FMEA Using Meta Behaviour Modeling For Concurrent Design of Products and Controls", Proceedings of 1998 ASME Design Engineering Technical Conferences, https://dx.doi.org/10.1115/DETC98/CIE-5702

Marques, M., Agostinho, C., Zacharewicz, G. and Jardim-Gonçalves, R., 2017. Decentralized decision support for intelligent manufacturing in Industry 4.0. Journal of Ambient Intelligence and Smart Environments, 9(3), pp.299-313, https://dx.doi.org/10.3233/AIS-170436

Papadopoulos, Y., (2013), HiP-HOPS - Automated Fault Tree, FMEA and Optimisation Tool User Manual ver. 2.5, available at: https://hip-hops.co.uk.

Promyoo, R., Alai, S. and El-Mounayri, H., 2019. Innovative digital manufacturing curriculum for industry 4.0. Procedia manufacturing, 34, pp.1043-1050, https://dx.doi.org/10.1016/j.promfg.2019.06.092

Sarathi, T., Cyr, J., DeLaura, R., Balcius, J., Collins, P. and Shatz, M., 2021, July. Developing a Model Based Systems Engineering Architecture for Defense Wearable Technology. In INCOSE International Symposium (Vol. 31, No. 1, pp. 1065-1078), https://dx.doi.org/10.1002/j.2334-5837.2021.00887.x

SAE International (2021) Potential Failure Mode and Effects Analysis (FMEA) Including Design FMEA, Supplemental FMEA-MSR, and Process FMEA, Ground Vehicle Standards J1739_202101, https://dx.doi.org/10.4271/J1739_202101

Wymore AM., 1993, Model-Based Systems Engineering: An Introduction to the Mathematical Theory of Discrete Systems and to the Tricotyledon Theory of System Design. Boca Raton: CRC Press