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TOWARDS THE DEVELOPMENT OF A MANUFACTURING FAILURE MODE AVOIDANCE FRAMEWORK FOR AEROSPACE MANUFACTURING

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ABSTRACT

A process based management strategy is crucial to enable productivity and cost effectiveness enhancement in high value manufacturing. This paper introduces a Manufacturing Failure Mode Avoidance (MFMA) framework based on four high level steps, underpinned by a series of structured tools to support a structured function-based decomposition of complex manufacturing processes and a continuous flow of information towards the development of robust control plans. The approach draws from experience from the automotive industry where Failure Mode Avoidance (FMA) has been adopted as a strategy to achieve a step change in the effectiveness of business and engineering processes associated with the product creation process. The paper illustrates a pilot implementation of the MFMA framework on a case study for the manufacturing of an aerospace component, followed by a discussion of the broader applicability of the framework and directions for further work.

Keywords: Failure Mode Avoidance, Process FMEA, Robust Process Control Planning

1 INTRODUCTION

Increasing volume and production efficiency of high value / high complexity aerospace parts, components and assemblies requires a robust strategy for the design, development and control of manufacturing processes. This is a significant shift from the traditional emphasis placed upon part control and heavy reliance on complex and accurate machining centres and highly skilled and experienced operators. However, modern aircraft products have increasingly complex parts with tighter tolerances and greater requirements for the interchangability of components and assemblies. A change to process based management, focussed on the identification and control of critical process parameters, ensuring consistent delivery of parts first time through, is required to meet these demands whilst capably managing pressures to increase production rates in a cost conscious environment.

In order to achieve the transition to a process driven manufacturing strategy, robustness and reliability need to be designed into processes through a deepened understanding of the relationships between desired process outputs and the characteristics which are used to create them (Glodek et al., 2006). As robustness, defined by Clausing and Frey (2005), is “the ability of a system to function (i.e. to avoid failure) under the full range of conditions that may be experienced in the field”, reliable manufacturing processes can be achieved through identification and prevention of potential process failures. For the greatest impact, countermeasures to prevent failure need to be designed and deployed early in the design of manufacturing process when the freedom for change is highest. However, as it is difficult to avoid a potential failure that has not been identified (Kmenta, Finch and Ishii, 1999), a systematic method for the early identification of potential process failures and the deployment of robust countermeasures for their prevention is required.

Failure Modes and Effects Analysis (FMEA) has been extensively applied across industries (Liu et al., 2011) as a proactive failure avoidance tool. FMEA aims to assess and improve the reliability of products and processes by discovering and correcting design or process deficiencies through the analysis of potential failure modes, effects, and mechanisms, followed by a recommendation of corrective action (Yang, 2007). While Kmenta et al (1999) have recognized differences between many definitions of the term 'failure mode', for the purposes of this paper the functional basis suggested by AIAG (2008) has been adopted, i.e. a failure mode is defined as 'any way or manner in which a product or process could fail to perform its desired function'. Applying FMEA encourages engineers to identify potential failure modes and understand their causes, which enables effective countermeasures to be deployed to prevent their occurrence, thereby avoiding the failure and its associated costs. Despite its widespread application, particularly in the aerospace, nuclear and automotive industries, there are many reported shortcomings with FMEA, such as:

- FMEAs are highly labour intensive and there is a tendency to produce large, cumbersome documents (Bell et al., 1992); FMEAs are often seen to be 'just more paperwork' and as a result little benefit is expected (Johnson & Khan, 2003);
- FMEAs often require an extensive time scale to complete the analysis, often incompatible with the set timing and resource allocated (Hawkins & Woollons, 1995);
- FMEAs are not used effectively to support design decisions as failure causes are often not identified (McKinney, 1991), and the deployment of the tool is too late (Webb, 2002);
- Without an organized approach to identifying failure modes, the analysis can become subjective limited by the level of experience and engagement of the engineering team conducting the analysis (Kmenta & Ishii, 1998).

To address these issues, a systematic method is required to facilitate the effective and efficient identification of failure modes early in the design process, allowing preventative countermeasures to be implemented based on their causes.

The Failure Mode Avoidance (FMA) framework discussed by Campean & Henshall (2012) offers a pragmatic approach to robust automotive system engineering design, facilitating early discovery of failure modes through the use of a structured sequence of proven engineering tools that are built around a central FMEA. The strength of the approach is underpinned by the introduction of a structured and systemic approach to function analysis which is focused on capturing interface functions which support the integration of the system. Failure modes analysis is strongly facilitated by the comprehensive function analysis, and it is focused on identification and prioritisation of function failure modes and their causes. This is followed by robust countermeasure development and design verification and validation. By developing a functional understanding of the system, FMA ensures that all potential mechanisms of failure are identified systematically through the design process, thereby facilitating actions for their avoidance. A clear flow of information between the integrated tools maintains scope throughout the analysis, which results in contained, concise and manageable documentation. This process has been proven through industry implementation (Campean et al 2013), and has a strong take up within the automotive industry.

This paper presents the development of a Manufacturing Failure Mode Avoidance (MFMA) framework which adopts the principles and practices of FMA and applies them towards the design of robust and reliable manufacturing processes. After an overview of the proposed MFMA process, a case study of an aerospace manufacturing process is used to illustrate its deployment, followed by a discussion of the effectiveness of the approach and reflection on opportunities for future work.

2 MANUFACTURING FAILURE MODE AVOIDANCE PROCESS

Similar to the FMA framework (Campean and Henshall, 2012, Campean et al, 2013), the proposed MFMA process is structured on four high level process steps and based on the ideology that in order to identify the manner in which a process can potentially fail, it is first necessary to understand how it is intended to "function" in order to deliver the critical part or assembly characteristics. Accordingly, the first step, Process Function Analysis (Figure 1), aims to map the process in a structured top-down approach, systematically identifying the manner in which critical characteristics of the part are achieved and the process factors that can affect each part characteristic as "noise" factors. On this basis, the following step, Process Failure Mode Identification, aims to identify and prioritise potential failure modes of the process as ways in which the process does not deliver the required functions, and to systematically identify causes for potential failure modes in relation to the "noise" factors identified in the previous MFMA process step. The next process step revolves around the development and implementation of effective process improvements and control methods required to avoid the critical failure modes. Finally, step four – Process Control and Validation, focuses on the deployment of dynamic process control plans (Ford Motor Company, 2004) to validate and monitor on going production, underpinned by the process function and function failure mode analysis, and incorporating any process improvement actions.

Figure 1 summarises the MFMA process and the key tools utilised to support each process step. In order to illustrate the deployment of the proposed MFMA framework a case study has been considered and will be presented and discussed in the following section.

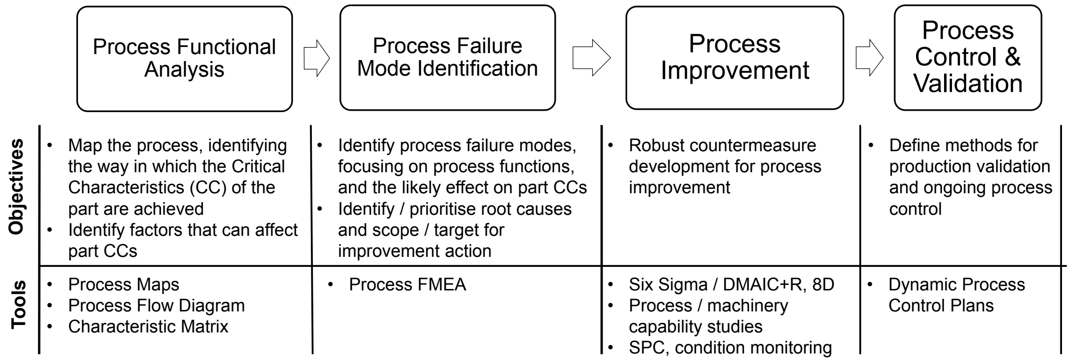

Figure 1: MFMA process framework: steps, objectives and supporting tools

3 CASE STUDY

This case study was based upon a machining process for the manufacture of a stainless steel aircraft bracket using a 5-axis CNC machining centre. This is an existing process that has been used to assess the feasibility of the MFMA framework. The deployment of the process was carried out with support from the engineering team responsible for the operation of the process.

3.1 Process Functional Analysis

Firstly, the inputs and the outputs of the process must be defined in terms of their specific characteristics and the metrics used measure to them. Once this is known, Process Mapping was iteratively applied to decompose the process at successive levels of abstraction into finite operations which provide a succinct description of how and when each of the part characteristic is created, as shown in the Process Map in Figure 2. Through this segregation of activities, the process is deconstructed into manageable components that facilitate the rest of the analysis by specifying each of the individual requirements of the process operations.

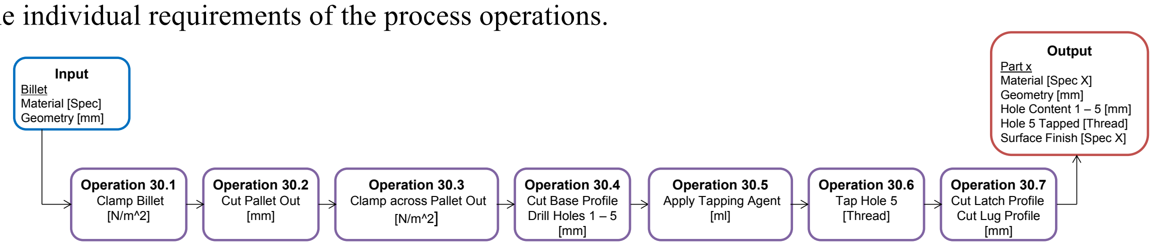

Figure 2: Process Map for the Case Study part

A Process Flow Diagram (PFD) was constructed next, illustrated in Figure 3, adding technical detail which allows the part characteristics to be defined in greater depth. For this case critical coordinates of the components profile are detailed along with hole positions, diameters and tolerances. Furthermore, the process characteristics that create or affect the part characteristics are documented. These are defined as inputs to the process that can be actively controlled and monitored. "Noise" factors or sources of variation are also listed, which are, contrastingly, process inputs that cannot easily be controlled, i.e. they vary but are difficult to monitor or change at will. The format of this document, as the extract shown in Figure 3 depicts, means that these additions are documented against each process operation, which is beneficial as it forms the basis of establishing the relationships between part and process characteristics. This document also provides the scope and level of resolution for the Process FMEA.

Sources of Variation	Process Function	Graphical Flow	Part Characteristics	Process Characteristics
Tool sharpness Tool length Material hardness Age of coolant Pull back pressure Contamination Ambient temperature	Cut Base Profile, Drill Holes 1 - 5	Operation 30.4	**Cut Base Profile** (x,y)mm from Datum AB; 1. (XX,XX) 2. (XX,XX) 3. (XX,XX) 4. (XX,XX) 5. (XX,XX) 6. (XX,XX) **Drill Holes 1 - 5** (x,y)mm from Datum AB; Positional tolerance ± X.Xmm 1. (XX,XX) φ X.Xmm 2. (XX,XX) φ X.Xmm 3. (XX,XX) φ X.Xmm 4. (XX,XX) φ X.Xmm 5. (X,X) φ Xmm	Machining program [XXXX] Tool type [XXXX] Tool feed rate [m/s] Spindle speed [RPM]

Figure 3: An extract from a Process Flow Diagram

The Characteristic Matrix takes the part and process characteristic information stored by the PFD, identifies the specific causal relationships between them and characterises their nature. By classifying the causal relationship between the part and the process sequence at specific operations, and the effects that they have at subsequent operations, this document provides an important record of the part-process linkages, facilitating total process understanding and supporting the development of the Process FMEA. For instance, as the extract in Figure 4 shows, the part characteristics created in operation 30.4 are used for clamping and location in operation 40.2. As a result, it is identified that the process characteristics used during operation 30.4 have a significant effect on the ability of operation 40.2 to achieve its function.

Key
X - Characteristic created on changed by process parameter
C - Characteristic used for clamping
L - Characteristic used for location
R - Process parameter at one operation has a strong effect on product characteristic generated at another

				Process Characteristics – Operation 30.1	30.2				30.3	30.4				30.5		30.6				30.7			40.1	40.2
				Clamp Pressue	Machining Program	Tool Type(s)	Tool feedrate	Spindle Speed	Clamp Pressue	Machining Program	Tool Type(s)	Tool feedrate	Spindle Speed	Type of tapping gel	Quantity of tapping gel	Tap (Tool) Type	Tapping Depth	Tool feedrate	Spindle Speed	Tool Type(s)	Tool feedrate	Spindle Speed	Deburring tool	Clamping Pressure
Operation	**Function of Operation**	**Part Characteristic**	**Metric**	n/m^2	XXXXXXX	XXXXXXXX	m/s	RPM	n/m^2	XXXXXXX	XXXXXXXX	m/s	RPM	XXXXXXXX	ml	XXXXXXXX	mm	m/s	RPM	XXXXXXXX	m/s	RPM	XXXXXXX	n/m^2
30.4	Cut Base Profile, Drill Holes 1 - 5	**Cut Base Profile, (x,y)mm from Datum AB;** 1. (XX,XX) 2. (XX,XX) 3. (XX,XX) 4. (XX,XX) 5. (XX,XX) 6. (XX,XX)	[mm] (x,y)		R	R	R	R	R	X	X	X	X											CL
		Drill Holes 1 - 5, (x,y)mm from Datum AB; 1. (XX,XX) φ X.Xmm 2. (XX,XX) φ X.Xmm 3. (XX,XX) φ X.Xmm 4. (XX,XX) φ X.Xmm 5. (XX,XX) φ Xmm	Position - [mm (x,y)] Diameter - [mm]		R	R	R	R	R	X	X	X	X											

Figure 4: An extract from the Characteristics Matrix

3.2 Process Failure Mode Identification

Supported by the inward flow of information generated by the previous documents, the Process FMEA is effectively segmented into process steps and the part characteristics they create, which aids in the identification of failure modes based on any deviation from these requirements. Figure 5 shows how the knowledge generated in the Characteristic Matrix effectively populates the Process FMEA. Effects and causes of failure modes are derived from examining the process characteristics that are related to the creation of the part characteristics. Identifying causes is further supplemented by the sources of variation recorded in the PFD (Figure 5). Once specific causes of failure are understood, then robust countermeasures can be effectively deployed to avoid failure. This occurs in the subsequent MFMA steps not included in this paper. Failure modes are ranked according to their severity and the likelihood of their occurrence by using a consistent scale, which allows process improvement actions to be prioritised.

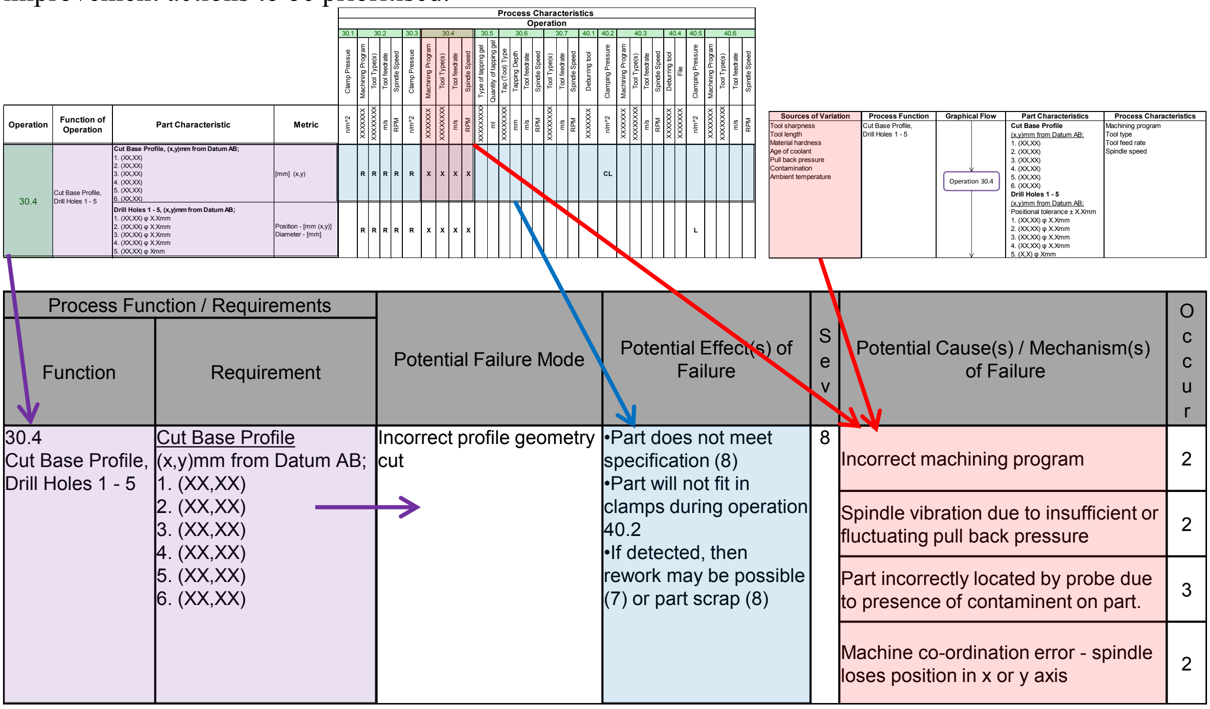

Figure 5: An extract from the Process FMEA, demonstrating the cascade of information from the Characteristics Matrix

4 DISCUSSION AND CONCLUSIONS

The case study provided a good validation of the MFMA framework, showing that it is effective at identifying and mapping the critical part against process characteristics, as the basis for process failure modes analysis, which in turn identifies the scope for improvement action and control plans.

The case study confirmed that the sequence of the tools is appropriate, beginning with a Process Map that deconstructs the process and its requirements into finite operations, which then provide the scope and structure for the following documents, allowing them to be contained and consistent. Furthermore, a strong flow of information demonstrates the integration between the tools, which facilitates effective and efficient completion. This is particularly true of the Process FMEA, as the information used for its population is collected in a logical and structured way, rather than through boundless and disordered brainstorming activities which can prove subjective.

The case study also provided opportunities for potential improvements to be made to the MFMA framework. The causes of failure that are documented in the extract of the Process FMEA (Figure 5) demonstrate a mixed level of detail. For example, spindle vibration is identified as a potential cause of failure, but the pull back pressure on the machine tool is just one of the factors that could contribute to this. As a result, it is acknowledged that the spindle vibration is not only a cause of the failure, but a failure mode in itself at a machinery level, which will have its own variety of causes. Therefore, a machinery FMEA should be conducted in order to identify and prevent all the potential causes of spindle vibration, which will consequently allow the part's geometry to be cut correctly. Without doing so, only the pull back pressure will be controlled, and the failure mode may still occur through an alternative cause. This identifies that there is a requirement for different levels of FMEAs with increasing resolution so that all potential failure causes can be identified at an appropriate level to facilitate the development of countermeasures for their prevention.

Given that the case study was based on an existing process with no specific requirements for improvement, the opportunity to engage process improvement actions was limited. Instead, an audit has been carried out on the current control plan for the part / processes against the Process FMEA. This validated the MFMA information flow, as any output from process improvement actions will be documented in the FMEA with a revised criticality analysis.

In conclusion, this study has demonstrated that the FMA framework and its principles can be effectively applied in a manufacturing process design context, in order to provide robustness and reliability of processes on the basis of avoiding potential failure modes through the implementation of preventative controls. The main innovations in the approach consists of (i) introduction of a structured top down approach for process decomposition based on functional mapping; (ii) the use of an enhanced Process Flow Diagram and Characteristics Matrix, which identify process "noise" factors and map relationships within the process which include the effect of noise factors; (iii) a strong and coherent information flow between tools, facilitating the development of the Process FMEA, and effectively addressing the pitfalls of conventional Process FMEA deployment. The latter point has been confirmed through feedback from the engineering team that supported the case study. Future work is focused on deployment of the MFMA framework to more comprehensive case studies involving larger teams to fully validate the effectiveness of the approach.

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