Manufacturing Systems Design Decomposition and Process Failure Mode Effect Analysis

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Abstract

Since its development for the Apollo project in 1963, Design Failure Mode Effects Analysis (FMEA) has been increasingly employed, especially in the automotive industry, as a means for understanding and managing risk. When this analysis is applied to an existing process or manufacturing line, the manufacturing processes are established and existing process data can be employed in the determination of severity, occurrence and detection of process failures. When a new manufacturing line is being developed or scaled up from a pilot process, there is less certainty and limited analogous process data. This paper describes the use of Manufacturing System Design Decomposition (MSDD) in the design of manufacturing processes in conjunction with definition of the Process FMEA model.

***Keywords**: PFMEA, MSDD, Severity, Occurrence, Detection*

1 Introduction

A new dual-stage overmolding process for the packaging of automotive electronic crash sensors is being developed in a pilot process at TRW Automotive LLC. This activity has coincided with an initial investigation into the application of Axiomatic Design in the definition of manufacturing Functional Requirements for the development of manufacturing processes and simulation models as a part of the DEMS program at Lawrence Technological University.

As with any new endeavor, or change in product or practice, risks of failure represent a potential outcome of unforeseen events. That is, one or more of the functional requirements of the product or process that is required in order to satisfy customer wants is not adequately sustained by the product or process design parameters. In 1963, NASA developed Design Failure Mode Effect Analysis (DFMEA) for the Apollo space program in order to reduce the inherent risks in a new space exploration system. By 1977, Ford Motor Company had began applying FMEA to automotive systems.

Verband der Automobilindustrie (VDA) in Germany published their first FMEA method specification in 1986 [1]. With the most recent Volume 4 revision of the VDA guideline, there is a shift from a component by component failure mode analysis to a model based on the failure to satisfy system functions. This could be the function of an automotive system or as demonstrated in the case illustrated here, it could be the function of a manufacturing system.

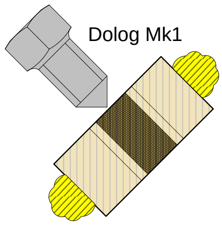

Figure 1: Prototypical Part

For this discussion, a simple three-step manufacturing process for the manufacture of the Dolog Mk1 in Figure 1 is used as the example. In this hypothetical process, the Dolog's plastic body is molded, followed by assembly of a threaded fastener and finally a functional test is performed on the device. One of the process functional requirements might be to inject plastic into a mold cavity in order to form the body of the Dolog. Since a certain volume of plastic is required in order to form that shape in the mold, it is possible to envision that too little plastic might be injected due to variability in the process, or the intrusion of unwanted conditions. This failure mode of plastic injection which is shown in Figure 2, insufficient plastic, has some impact on Dolog performance and might occur with some frequency through-out the course of a production run. This is defined as the occurrence of the actual or probable failure and a score ranging from one to ten is assigned based upon predetermined industrial criteria standards.

Function	Potential Failure Mode	Potential Effects of Failure	Sev	Potential Causes of Failure	Occur	Current Design Controls	Detect	RPN	Recommended Actions	Responsibility and Target Completion Date	Action Taken
FR 1.2.1.5 Inject plastic into cavity	Insufficient volume injected	Insufficient part strength	8	Screw position sense variation	3	Fill volume based on time	7	168	Add mold cavity pressure sensor	Miklos Molnar 10 July 2012	
								0			
								0			

Figure 2: Example FMEA Form

If insufficient plastic represents a failure mode of the process, then excess plastic might also be included as a failure mode. With too little plastic, this process failure might affect the safety of the customer while too much plastic might only represent an inconvenience and loss of profit to the producer. Accordingly, different types of process failures might be judged to have different levels of "Severity", that is potential effect on the customer. As with Occurrence, Severity is assigned a score of ranging from one to ten from the industrial standards published by one of the associations such as the Automotive Industry Action Group (AIAG) or VDA [1,2] A series of tables have been defined and published as a reference and benchmark for Occurrence, Severity and Detection by the Automotive Industry Action Group. The combination of Severity and Occurrence can be countered by Detection. The overall risk score is calculated by multiplying the Severity, Occurrence and Detection scores and this product is known as the Risk Priority Number (RPN). From our example, if pressure transducers are fitted to each cavity in the mold, the failure mode of insufficient plastic can be detected from the reduced cavity pressure. So, while Severity and Occurrence might have high scores, it would be countered by a low number for Detection resulting in a reduced RPN score.

Failure Mode Effect Analysis (FMEA) and Axiomatic Design (AD) have a common basis in that they both focus upon Functions and Functional Requirements. AD decomposes Functional Requirements into Design Parameters and thence into process variables. In comparison, the FMEA defines the system element and then the function. These functions are correspondingly associated with failure modes and a quantified RPN risk assessment for each failure mode. The following example shown in Figure 2 provides the basic structure of the FMEA. In this example, a function, identified as "Functional Requirement FR 1.2.1.5 Inject plastic into mold cavity" is identified with a potential failure mode of "Insufficient volume injected". In order to counter this failure mode, a Recommended Action - Design Parameter is specified to incorporate mold cavity pressure sensing to ensure that the mold cavity is properly filled. This design criteria is then fed back into the Axiomatic Design model. Essentially, the design can be optimized and risk managed by employing Axiomatic Design to define the Functional Requirements and Design Parameters, and then employing Failure Mode Effects Analysis on that product or process design.

Pappalarado and Naddeo [4] extensively describe this relationship in failure mode analysis. They restrict their discussion to the non-probabilistic information models. Their basic model in axiomatic terms is that Potential Cause of Failure (DP) relates to the Functional Requirement through the relationship matrix. The general practice in the development of a FMEA is to identify a selection of potential failure modes, from experience, historical data, intuition, etc. and then map these to the physical design domain. Alternatively, they describe the identification of functional domain as a failure mechanism domain and the physical domain as the source of stress in relation to that domain.

2 The Model

As previously stated, the example consists of three process steps to manufacture the module: mold the body, assemble the screw, and perform a functional test. The following flowchart Figure 3 provides a simple conventional sequential process view.

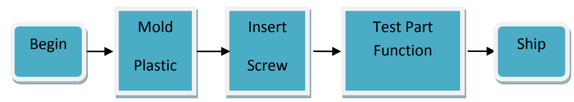

Figure 3: Process Flow Chart

Alternatively, this same three-process manufacturing system could be considered from the perspective of Manufacturing Systems Design Decomposition as shown in Figure 4 [3].

0	FR	Manufacture molded module	DP	Lean molding cell that includes molding,	PV	Manufacturing cell with takt time of 4.75 seconds
1	FR	Mold sub assembly	DP	85 Ton Arburg Injection molding station	PV	Molding process takt time of 4.5 seconds
2	FR	Assemble threaded fastener	DP	Screw assembly feeder and station	PV	Assembly takt time of 3.5 seconds
3	FR	Test part function	DP	Functional tester	PV	Testing takt time of 3.1 seconds

Figure 4: Decomposition and FMEA

David Cochran and others proposed specific application of functional decomposition and related design parameters from Axiomatic Design theory to manufacturing system design which they called "Manufacturing System Design Decomposition", (MSDD). Within the MSDD methodology, the main focus is on the decomposition of functional requirements and the association of design parameters. Other aspects of Axiomatic Design such as the Information Axiom are not explicitly employed. [3].

The top level Functional Requirement (FR0) is to "Manufacture molded module". For the first level of decomposition, this can be decomposed as shown in Figure 5 into FR1: Mold-sub-assembly, FR2: Assemble threaded fastener, and FR3: Test part function.

The Axiomatic Design Parameters (DP) correlates to system architecture FMEA elements as shown in Figure 5. FR2: Assemble threaded fastener is expanded through decomposition. As shown, the manufacturing system can be broken down into finite entities (e.g. Design Parameters) associated with the FR's, such that the entities work together to deliver the function of the system. In FMEA terminology, a system element is a component, part, process or entity of the FMEA that is being created. It is shown on the structure editor as a box. All of the system elements together show the physical component, part, or entity logical breakdown of the FMEA. Creating the interrelationships between the system elements is the first step in creating a FMEA and this is enabled using the Axiomatic Design model. This supports the system architecture model from the VDA.

DP2 describes the assembly workstation for assembling screws into the molded part. The MSDD model demonstrates decomposition to the second level. Further decomposition is possible.

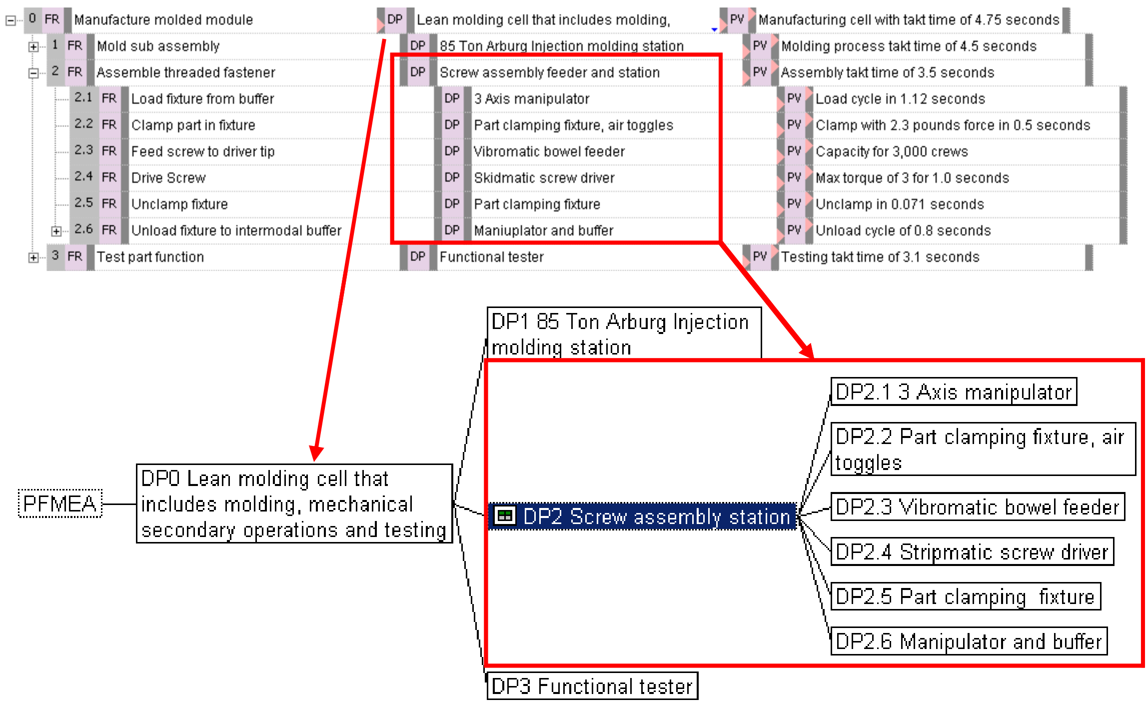

Figure 5: Decomposition and FMEA

For example the function FR2.3 Feed screw to driver tip could be decomposed further into FR2.3.1 Maintain quantity of screws, FR2.3.2 Orient screws, FR2.3.3 Transport screw and FR2.3.4 Gate screw to driver tip. This decomposition is shown in Figure 6 to illustrate the point that decomposition can continue to increasingly fine levels of resolution. How far should this decomposition proceed? Failure modes are derived from lessons learned, engineering experience, manufacturing experience, analogous designs or processes, logic, fault analysis, failure data, etc. If the stated objective of the FMEA process is to analyze and manage risk, then the decomposition and identification of failure modes should proceed to a level where prior or analogous process failure mode knowledge exists.

Axiomatic Functional Requirements (FR) correlate to FMEA Functions as shown in Figure 7 (functions shown in green, failures shown in red). A function is the action and / or an activity assigned to or required of the system element. These functions are attached or anchored to the system element. Each function has one or more failure modes attached or anchored to the function. A failure mode describes how the function operates improperly. Figure 7 illustrates the failure modes for each function.

The next step is to create Function Nets and Failure Nets. Function nets form trees of higher level functions on the left and the lower level functions on the right that are required to perform the higher level functions. The function nets are built one function at a time. Failure nets are mapped according to the function net mapping. What this means is that function net relationships dictate failure net relationships. Failures can only be populated that are part of the function net tree.

The next step is to populate preventative actions, occurrence ratings, detection actions, and detection ratings which are anchored to the failures. Severity ratings are also created and anchored to the top level failure modes in Figure 8. As the failure rate drops (in PPM), so does the severity of the rating. For higher product knowledge and greater maturity of development, a lower severity rating is acceptable. The scale is from ‘low-1’ to ‘high-10’. Detection ratings are identified by the letter “D”. As the diagnostic capability increases, the severity of the rating goes down. Scale is from ‘low-1’ to ‘high-10’.

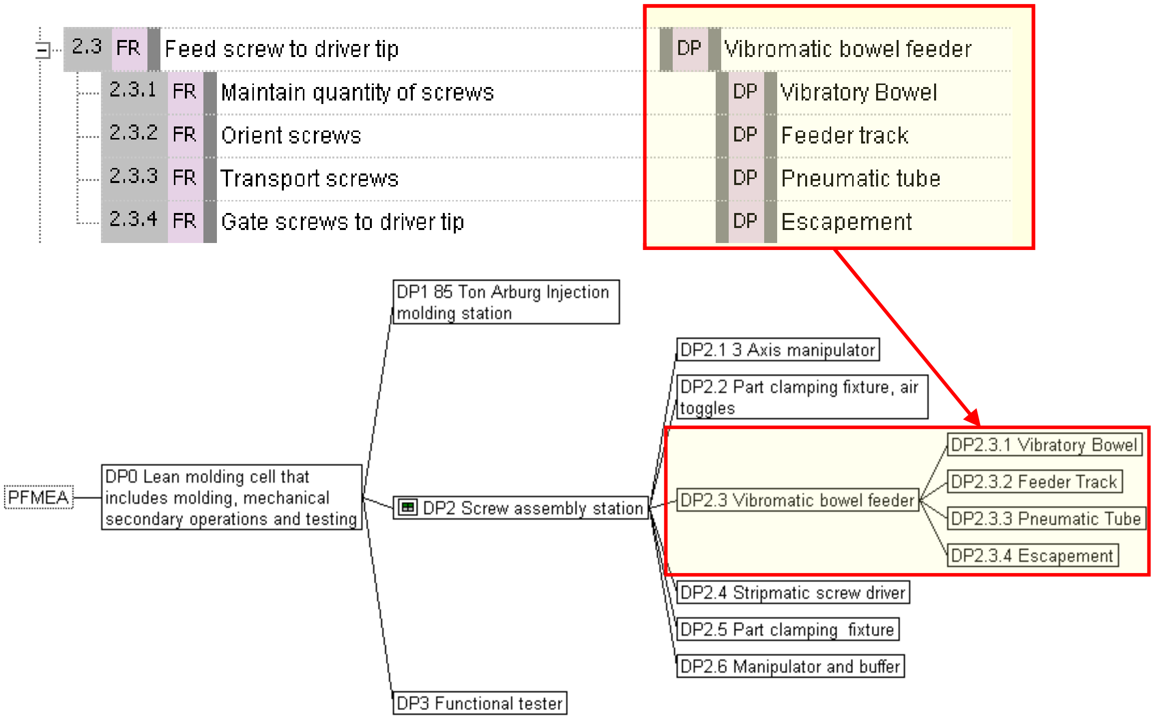

Figure 6: Decomposition and FMEA for FR2.3

With table 1, the RPN numbers are apparent as a means to assess risk for the molding process along with preventative actions.

The next step is to create a FMEA Form. A form is the output that will be reviewed internally at TRW and externally with the customer. A form is created automatically by the IQFMEA software in the industry standard VDA 96 format. The form is created from the failure net trees. The failure modes on the form are the focal point failure elements from the failure net. The effects on the form are the top level vehicle level failure effects. The severity on the form is the severity from the top level vehicle level failure effect. The causes are the direct causes connected in the failure net. The preventative action, detection actions, occurrence ratings, and detection ratings are linked to the direct failure net causes. The RPN is calculated from Severity x Occurrence x Detection.

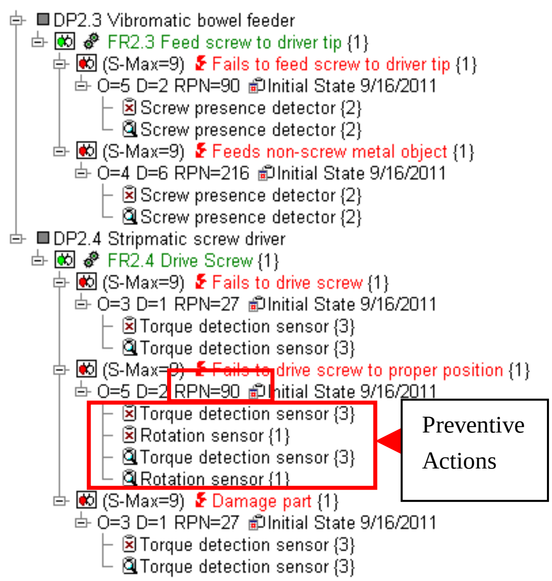

Figure 7: Failure Modes and Countermeasures

The PFMEA provides a static picture of risk, fixed at the point of its completion. Beyond this static analysis, process failure modes can be modeled through the "Breakdowns" tab, in process simulation models so that the Process Failure Mode Effect Analysis (PFMEA) can be simulated with probabilistic Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) affecting cell functionality and capacity. Each cycle in the Multicycle machine is defined as a Functional Requirement and the PFMEA identifies failure modes for each function, establishing a clear linkage. The convention developed is to employ the FR number, i.e. "FR1.2.1.1" and a small letter suffix plus text in the description so that the breakdown is linked to a specific Functional Requirement. The letter suffix is necessary since each function may have more than one failure mode. Unfortunately, Witness does not support the linkage of specific failure modes to specific cycles in the Multicycle Machine object. Note that in this example, not all failure modes are modeled since the objective is to demonstrate methodology which links the Axiomatic model, the simulation model and the Process Failure Mode Effect Analysis (PFMEA).

3 Dynamic Modeling of Risk

The PFMEA and its Risk Priority Number scoring system provides a static picture of risk, fixed at the point of its completion. The AIAG and VDA guidelines for preparing a PFMEA provide a scoring table for characterizing Occurrence with a ranking score. With the addition of a Frequency column to this table, as shown in Table 1, information developed in preparation of the PFMEA based on the Occurrence ranking can also be employed in process simulation modeling. In this way, the process simulation model will more accurately reflect the modeled manufacturing process as well as relating directly to the PFMEA by employing Occurrence in defining process breakdowns. In this proposal, the rate is defined through a probability density function such as the uniform distribution. This would have the form f(x) = Uniform(2000,10000) for the example where the lower bound is set at 1 in 2,000 units and the upper bound set at 1 in 10,000 with a uniform probability of selection. This would be the distribution for a "Moderate" level of risk and a ranking of "5".

Table 1: Occurrence and Frequency Ranking

Likelihood of Failure	Criteria: Occurrence of Cause - PFMEA (Incidents per items/vehicles)	Rank	Frequency
Very High	>_100 per thousand >_1 in 10	10	10 to 20
High	50 per thousand 1 in 20	9	20 to 50
	20 per thousand 1 in 50	8	50 to 100
	10 per thousand 1 in 100	7	100 to 500
Moderate	2 per thousand 1 in 500	6	500 to 2,000
	0.5 per thousand 1 in 2,000	5	2,000 to 10,000
	0.1 per thousand 1 in 10,000	4	10,000 to 100,000
Low	0.01 per thousand 1 in 100,000	3	100,000 to 1M
	<_0.001 per thousand 1 in 1,000,000	2	1M to 10 M
Very Low	Failure is eliminated through preventive control	1	0

Process failure modes can be modeled through the "Breakdowns" tab, in Witness simulation software as shown in Figure 8, for process simulation models so that the Process Failure Mode Effect Analysis (PFMEA) can be simulated with probabilistic Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR) affecting cell functionality and capacity [5]. Each cycle in the Multicycle machine is defined as a Functional Requirement and the PFMEA identifies failure modes for each function, establishing a clear linkage. The convention developed is to employ the FR number, i.e. "FR1.2.1.1" and a small letter suffix plus text in the description so that the breakdown is linked to a specific Functional Requirement.

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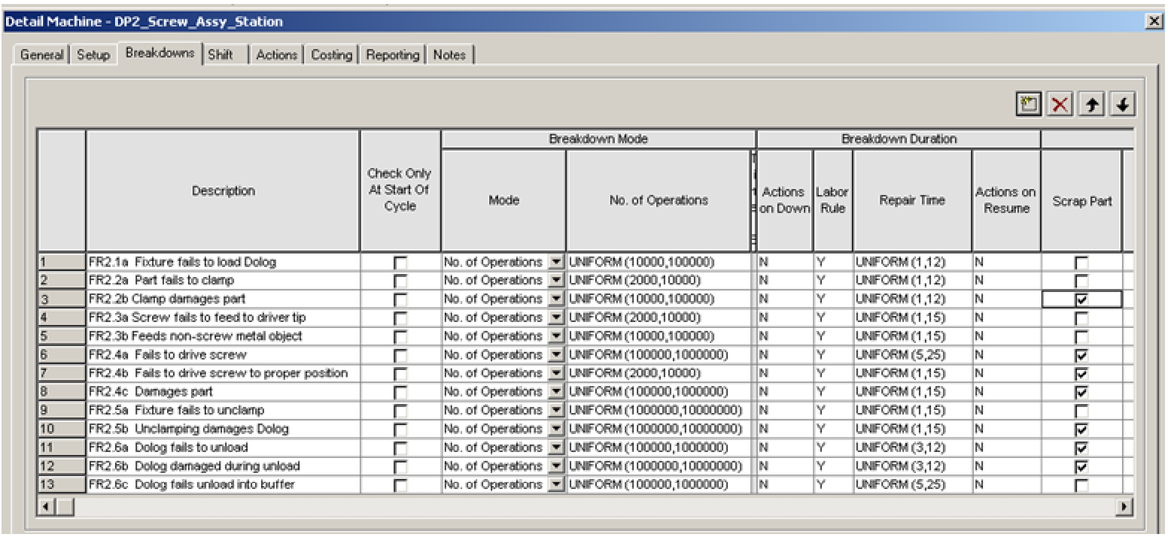
Detail Machine - DP2_Screw_Assy_Station

General | Setup | Breakdowns | Shift | Actions | Costing | Reporting | Notes

	Description	Check Only At Start Of Cycle	Breakdown Mode: Mode	Breakdown Mode: No. of Operations	Breakdown Duration: Actions on Down	Breakdown Duration: Labor Rule	Breakdown Duration: Repair Time	Breakdown Duration: Actions on Resume	Scrap Part
1	FR2.1a Fixture fails to load Dolog	☐	No. of Operations	UNIFORM (10000,100000)	N	Y	UNIFORM (1,12)	N	☐
2	FR2.2a Part fails to clamp	☐	No. of Operations	UNIFORM (2000,10000)	N	Y	UNIFORM (1,12)	N	☐
3	FR2.2b Clamp damages part	☐	No. of Operations	UNIFORM (10000,100000)	N	Y	UNIFORM (1,12)	N	☑
4	FR2.3a Screw fails to feed to driver tip	☐	No. of Operations	UNIFORM (2000,10000)	N	Y	UNIFORM (1,15)	N	☐
5	FR2.3b Feeds non-screw metal object	☐	No. of Operations	UNIFORM (10000,100000)	N	Y	UNIFORM (1,15)	N	☐
6	FR2.4a Fails to drive screw	☐	No. of Operations	UNIFORM (100000,1000000)	N	Y	UNIFORM (5,25)	N	☑
7	FR2.4b Fails to drive screw to proper position	☐	No. of Operations	UNIFORM (2000,10000)	N	Y	UNIFORM (1,15)	N	☑
8	FR2.4c Damages part	☐	No. of Operations	UNIFORM (100000,1000000)	N	Y	UNIFORM (1,15)	N	☑
9	FR2.5a Fixture fails to unclamp	☐	No. of Operations	UNIFORM (1000000,10000000)	N	Y	UNIFORM (1,15)	N	☐
10	FR2.5b Unclamping damages Dolog	☐	No. of Operations	UNIFORM (1000000,10000000)	N	Y	UNIFORM (1,15)	N	☑
11	FR2.6a Dolog fails to unload	☐	No. of Operations	UNIFORM (100000,1000000)	N	Y	UNIFORM (3,12)	N	☑
12	FR2.6b Dolog damaged during unload	☐	No. of Operations	UNIFORM (1000000,10000000)	N	Y	UNIFORM (3,12)	N	☑
13	FR2.6c Dolog fails unload into buffer	☐	No. of Operations	UNIFORM (100000,1000000)	N	Y	UNIFORM (5,25)	N	☐

Figure 8: Process Simulation of Failure Occurrence

Risk and Manufacturing System Performance

Since the early efforts in risk assessment and management in the space program, FMEA has been a static tool, frozen at the time of the analysis. With the employment of probabilistic simulation modeling where frequency of failure occurrence is continually selected from a probability distribution function, a more dynamic approach to FMEA is possible. The effect of these process breakdowns or failures and their impact on process through-put and cost can be assessed in a manner that more accurately reflects the actual manufacturing system. In place of the limitations of the RPN score and ad hoc RPN score thresholds in assessing the impact on manufacturing operations, yield and cost can be characterized. If for example, the Occurrence rank is determined to have been improved through manufacturing process improvements from a “6” to a “5”, the benefit of the improvement effort can be characterized in monetary terms.

4 Conclusions

Manufacturing Systems Design Decomposition, function based Process Failure Mode Effect Analysis and process simulation each, in their own right, can be employed in the improvement of manufacturing operations. The greatest benefit can be achieved through the integration of these three important tools so that the rational process design drives the structure of the functionally modeled PFMEA as well as the structure of the simulation model which includes dynamic simulation of the process failure modes.

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