Analysis of the Impact of Enhanced FOD Inspection for the Aircraft Manufacturing Process
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Abstract: Fighter jet assembly is a complex process that involves joining thousands of parts of varying sizes while using a multitude of tools that go through the hands of many aircraft production personnel. As a result, Foreign Object Debris [FOD], is a source of lost assembly time (due to inspections and rework) and increased costs. Aircraft manufacturers are estimated to incur additional direct costs up to $4 billion annually due to FOD inspections and rework. Currently, FOD inspection is conducted by visual inspection. This method is time consuming, error prone, and limited to line-of-sight. This project analyzes the impact of an alternate FOD inspection systems (e.g. X-ray technology and image processing techniques) in terms of FOD occurrence on delivery, time of rework, and aircraft assembly time. The fighter jet assembly simulation showed that the FOD inspection accuracy of 80% is sufficient to maximize assembly plant productivity, exhibiting an average cost savings of $3.6M annually. The simulation proved the key goal of enhancing the probability of detection was to detect these FOD items earlier in the assembly process, in order to decrease the rework hours required per aircraft prior to mating components (45% increase); and decrease the rework hours required post mating.

Keywords: Aircraft Assembly, Foreign Object Debris, FOD, X-Rays, Non-Destructive Evaluation, Discrete-Event Simulation

1. Overview

The F-35, requiring more than 300,000 individual parts from 1,400 suppliers was selected as the case study for this project. Any items that could be lost, misplaced, or forgotten are defined as Foreign Object Debris [FOD]. FOD categories are : panstock (33.6%), consumables (13.71%), manufacturing debris (19.09%), tools/shop aids (8.74%), and trash (24.87%). (Tseng & Guadamuz, 2014) A typical fighter jet production line with 26 assembly stations will experience one FOD event approximately every 5.46 hours. Manual inspections are limited to human capabilities such as line-of-sight, therefore causing a limited search success rate per inspection at 50% (Tseng & Guadamuz, 2014). When FOD is discovered, the assembly must be placed in rework. Analysis of manufacturing data shows that reworks due to FOD adds on average 9.51 hours per FOD event to assembly time, reducing the productivity of the whole plant.

1.1 Fighter Jet Assembly

A typical fighter jet assembly is composed of 21 stations (Figure 1). Throughout each shift personnel on the production line are required to perform FOD searches. FOD search time accounts for between 5 and 10% of total shift time (Lockheed Martin, n.d.). Four assemblies are mated at the Electrical Mate and Alignment System (EMAS). FOD discovered after EMAS adds an additional 46% in rework time and costs.
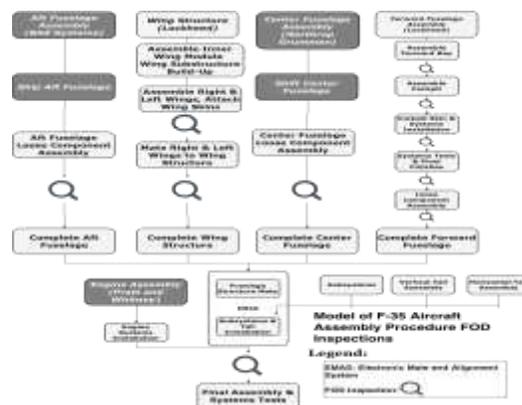
Figure 1. Aircraft Production Displaying Manual FOD Inspection Locations.

1.2 Stakeholder Analysis

- The primary stakeholders when considering the FOD issue, are the Aircraft Manufacturers and production line personnel. Manual inspections incur unnecessary labor costs, and high rework hours, ultimately wasting money: approximately 5-10% of shift time for production line personnel. The customers purchasing these aircrafts are the secondary stakeholders. With the intention of purchasing fighter jets free of FOD, in a time and cost effective manner, manual inspections put a hindrance on them. The 50% detection probability (Tseng & Guadamuz, 2014) increases the probability of deadlines being extended as a result of unexpected FOD post assembly, and increased contract costs as a result of unnecessary time required per aircraft with manual inspection. An

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enhanced FOD inspection system shall decrease the time required per inspection, and for rework hours, ultimately decreasing the total time and cost required per aircraft.

1.3 Problem & Need

Currently FOD inspections are a difficult and timely process, forcing rework and repair, all on the manufacturer's expense. And after all the costs incurred, there remains a possibility of delivering aircraft with FOD, risking the lives of pilots and the reputation of the manufacturer. Thus, there is a clear demand for a method to improve FOD inspection, which will in turn improve time, cost and quality of the aircraft production process.

There is a need to reduce total inspection time, FOD-related repair hours and Aircraft quality upon delivery; for providing unrestricted visual capacity to the inspector, reducing human error by providing computer assisted decision making and ultimately detecting FOD incidents more reliably and earlier in the manufacturing process. Table 1 lists the major set-backs that the visual inspection process suffers, and how those problems need to be addressed.

Table 1. Comparison of Inspection Attributes

Priority	Manual FOD Inspection	Goals of Enhanced FOD Inspection System
Inspection Capabilities	High Potential	Multi-Layer Visibility
Reliability	Subject to Human Error	Automated
Time	Subject to Human Limitations and exhibits variability	Automated with no variability
Detection Location in Manufacturing Process	Same reliability in loactions	Better reliability early in process

2. Concept of Operations

The proposal is to replace the existing manual FOD inspection method with an automated inspection. The proposed system (FODXSYS), shall be designed to meet the limitations by utilizing X-Rays and differential imaging technologies. The X-ray inspection shall be conducted at critical points within the assembly process rather than at each individual station. The X-ray inspection shall take less time than the manual inspection and provide improved accuracy. The primary functionality of the system is to allow for an enhanced FOD inspection through capturing an X-ray image and using image analysis algorithms in order to pin-point FOD within the Aircraft Sub-assembly.

FODXSYS is to be installed at critical locations in production line, specifically before the mating of the aircraft components. The assembly procedure for the fighter Aircraft that is used as the case study in this project. Analysis indicated that the FOD that remain in the craft after the mating of the fuselage structure cause the most severe rework and are more costly. By performing shorter, more efficient FOD inspections at critical locations, the system shall ultimately reduce FOD related costs.

2.1 Functional Decomposition & IDEF.0

Figure 2 depicts the IDEF.0 diagram of FODXSYS's primary function "Inspect for FOD", examining the sub-functions of the system and their interactions, portraying how the system arrives to its output, the Inspection Recommendation.
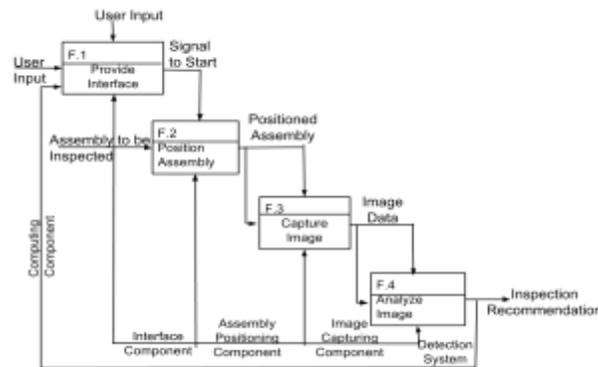
Figure 2. IDEF.0 of System Function F.0 – Inspect for FOD

2.3 Design of the X-Ray System

Analysis of the primary materials, and thicknesses associated with the sub assembly components inspected at each station helped determine a minimum input voltage (220 kilo Volts) required to establish it was possible to scan and detect with 95% accuracy within these components. The penetration depth equation was used to verify that with 220 kV of input voltage, the materials and their associated thicknesses could be penetrated at least 95% through. Although, this established the plausibility of penetrating that deep, verification that FOD items would be clear and visible/detectable once the assembly component had been penetrated was still required.

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2.3.2 Signal to Noise Ratio Calculation

$$I = I_0 e^{-\mu x} \tag{1}$$

$$\text{SNR} = \frac{I_S}{\sigma} \tag{2}$$

The signal to noise ration level is (SNR) compares the level of the desired signal to the level of background noise and is evaluated the equation above (2); where (IS) mean is the mean x-ray intensity over the inspection region of interest is the standard deviation at the inspection region. The SNR was utilized to establish a minimum of 95% visibility of FOD items within the images of the sub assembly components. A signal to noise ratio greater than 1, represents 95% visibility. (Kerur, Thontadarya, & Hanumaiah, B, 1990)

2.4 X-Ray Mounting Alternatives

Table 2. Mounting Alternative Selection

Wing Inspection Solution / X-Ray Mounting Alternative	Cost				Quality										Time				Score
	Average Cost ($)		Average Power Req (watts)		SNR (Aluminum, Wing)		SNR (Carbon, Wing)		SNR (Aluminum, Fuselage)		SNR (Carbon, Fuselage)		Penetration Depth through Steel (mm)		Start Up Time (minutes)		Scan Speed $(\frac{m}{s^2})$		
Weight	.33		.67		.36		.18		.12		.09		.24		.25		.75		
Performance	Low		Low		High		High		High		High		High		Low		Low		
Linear Ral	272K	1	550	.5	2.4	2.4	3.4	3.4	2	2	1.2	1.2	6.3	0	20	0	.19	1	3.3
Robotic Arm	301K	.9	550	.5	2.4	2.4	3.4	3.4	2	2	1.2	1.2	6.3	0	20	0	.19	1	3.3
Gantry	2M	0	620	0	2.4	2.4	3.4	3.4	2	2	1.2	1.2	400	1	15	1	15	0	2.3
Z-Portal	2M	0	480	1	2.4	2.4	3.4	3.4	2	2	1.2	1.2	300	.7	15	1	15	0	3

Different mounting alternatives were considered for each inspection location, all of which provide different benefits and negatives based on the components being scanned at that station. After converting the data points in the X-ray Mounting Alternatives to a 0/1 scale, the swing weights method was used to determine a weighted score that could be ranked in order to establish the optimal X-ray alternative per inspection station. As displayed above, the Linear Rail system achieved the optimal X-ray mounting alternative for both fuselage and wing module inspection stations.

3. Method of Analysis

To evaluate the impact of FODXSYS on the productivity of jet assembly, an aircraft assembly simulator, FODSIM had been developed in Java. By simulating production line labor, FOD inspection, and FOD related rework, it becomes possible to measure both the direct and indirect effects of utilizing FODXSYS.

3.1 Simulation (FODSIM)

Figure 3 below depicts the user inputs, model parameters and the simulation output for FODSIM. The discrete event simulation (FODSIM) models these events throughout the production line for the desired run-time length.
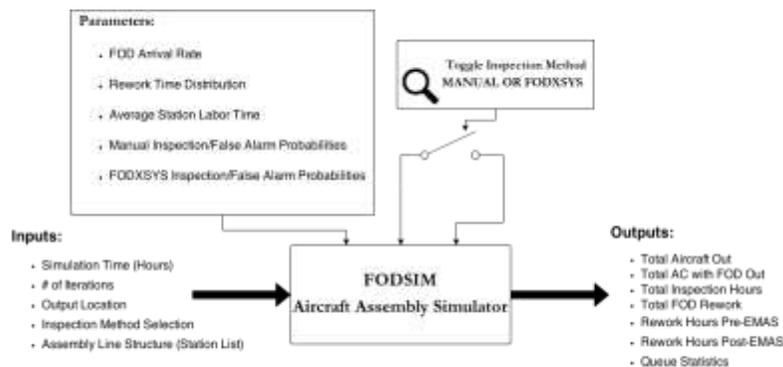
Figure 3. Simulation Parameters & Input/output

3.1.1 Simulation Variables & Parameters

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Parameters for the case study were obtained by fitting provided historical data production data into distributions and then using the inverse cumulative distribution method for random number generation. Equations (3) through (6) are the random number generators created from the parameters where R is a uniform number from 0 to 1.

$$X = 4 + \sqrt{R(8-4)(6-4)} \qquad 0 < R < 0.5$$
$$X = 8 - \sqrt{(1-R)(8-4)(8-6)} \qquad 0.5 \leq R \leq 1$$
Station Process Time $\qquad$ (3)

$$X = -\frac{\ln(1-R)}{0.0102} \qquad 0 \leq R \leq 1$$
FOD Arrival Rate $\qquad$ (4)

$$X = -\frac{\ln(1-R)}{0.951} \qquad 0 \leq R \leq 1$$
FOD Rework Time $\qquad$ (5)

$$X = InverseNormal(0.42, 0.0347)$$
Manual Inspection Time $\qquad$ (6)

3.1.2 Simulation Assumptions & Implementation

Model assumptions had been formulated in order to represent the complex fighter jet assembly process production at Ft. Worth.

- There are 26 total Stations: 21 Assembly and 5 Inspection Stations
- FOD Inspection modeled as Bernoulli Distribution with p = 50% for Manual and p = 95% for FODXSYS
- If FOD is detected rework is performed at the Station that the FOD originated in
- FOD that goes undetected through EMAS accumulates in severity by EXP(9.51)
- Inspection Stations do not produce FOD

Figure 4 depicts the flow of the simulation. The subassembly objects will advance through each station, where they are worked on for a duration determined by the Triangular distribution random number generator TRI (4, 6, 8), with a FOD arrival rate modeled by exponential distribution EXP (0.0102), Inspection is modeled as a Bernoulli distribution with p = 50% for manual and 95% for the enhanced system. If FOD is missed, the subassembly will continue forward to the next station naturally, until it is detected at another station. If FOD is detected, it is sent to the originating station to have the rework and repair necessary for it to be completed, which is modeled by EXP (9.51).
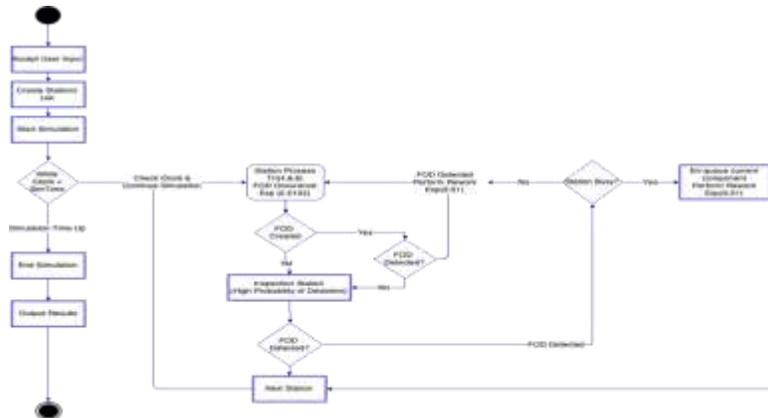
Figure 4. Simulation Flow

4. Results

Results were obtained by running FODSIM for 1000 one-year-long iterations under both manual inspection and FODXSYS. Results on rework and repair hours, total aircraft out, number of aircraft with FOD present at end of production, and the total inspection hours.

Table 4. Simulation Results Summary

Average of 1000 iterations of 1-year long runs	Manual	FODXSYS	% DIFFERENCE
Total Rework & Repair Times (Hours) ↓ Better	6193	4943	22 % ↓ **Decrease from Manual**
Rework & Repair Occurring Pre-EMAS (Hours) ↓ Better	2182	3485	46 % ↑ **Increase from Manual**
Rework & Repair Occurring Post-EMAS (Hours) ↓ Better	4010	1458	93 % ↓ **Decrease from Manual**
Inspection Times (Hours) ↓ Better	791	114	150 % ↓ **Decrease from Manual**

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Total Number of AC Out per Year (Aircrafts)	↑ Better	23	39	48 % ↑ **Increase from Manual**
FOD Present Post Final Assembly (Aircrafts)	↓ Better	4	0.026	197 % ↓ **Decrease from Manual**

4.1 Rework & Repair Time Analysis

Results indicate that utilizing FODXSYS will reduce Total repair hours by 22%. Figures 5 and 6 depict the distributions of total repair time across the 1000 iterations of manual and FODXSYS at Stations prior to the Aircraft structure mating and post-mating. The figures below show that under FODXSYS, the majority of FOD related repair occurs prior to the mating of the Aircraft, which is occurring due to the higher 95% probability of detection, whilst under the manual inspection, significantly higher repair hours are witnessed post-mating of the aircraft. This can be attributed to the fact that FOD missed after the Aircraft has been mated becomes more severe by EXP (9.51).
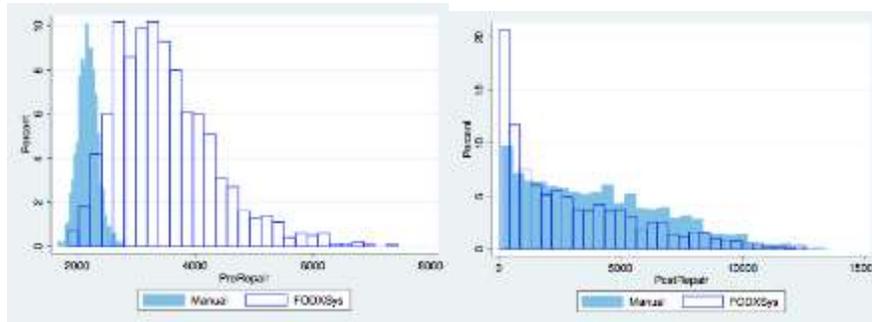
Figures 5 and 6 - Distribution of Total Repair hours results across 1000 iterations Pre-MAS and Post-EMAS

4.2 Production Flow and Aircraft Quality Analysis

In addition to reducing the rework time, FODXSYS reduces the total time as well as variability of inspection time, Figure 7(a) depicts the distribution of Inspection hours of FODXSYS versus manual. Manual inspection time exhibits variability due to differences in inspection styles and procedures across inspectors, whilst FODXSYS provides more objective and concrete inspection times that are calculated through the X-ray scan time. Together, the production line experiences reduced labor hours as depicted in Figure 7 (b).

(a)   (b)
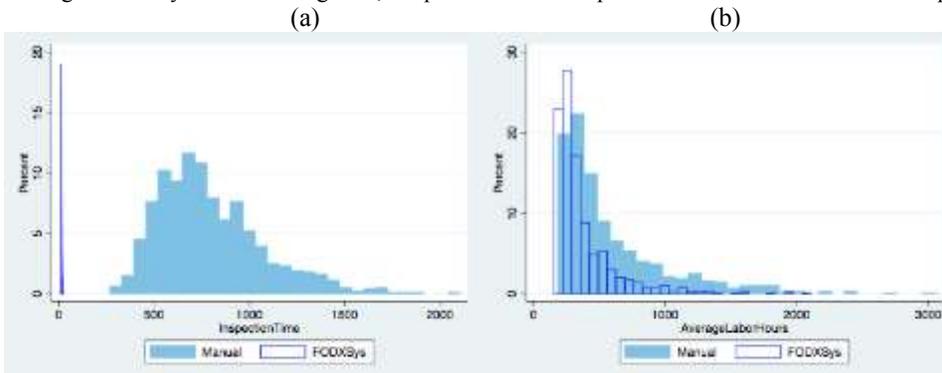
Figures 7 Distributions of Total Inspection Time (a) and Labor Hours (b) across 1000 iterations

A higher number of aircraft per year long iteration can be outputted due to the decrease in required repair hours, and at a higher quality upon delivery due to the increased probability of FOD detection. Figures 8 and 9 depict the number of aircraft produced and the number of aircraft delivered with FOD under FODXSYS and manual inspection.

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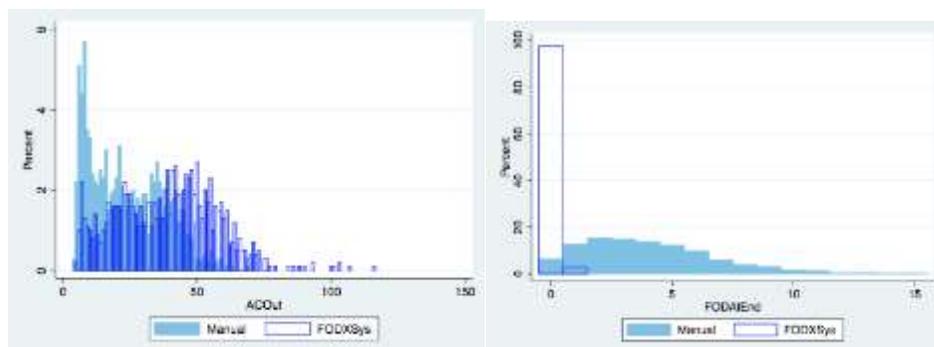
Figures 8 and 9 - Distributions of Number of AC assembled and Number delivered with FOD for 1000 simulation runs

4.3 Business Case Results and Analysis

Converting the hours data outputted from FODSIM to cost data enabled monetary analysis to be conducted. Average wage rates were estimated for aircraft assembly personnel, including inspectors, mechanics, and engineers; along with the number of each required per stage. Ultimately, enabling the number of personnel per stage, the wage of each, and hours required per each to be multiplied and summed to output the total cumulative cost for each run of FODSIM and compare the results of the two alternatives, FODXSYS and Manual.

4.3.1 Return on Investment & Break-Even Analysis

There are 5 critical locations where the inspections will take place, using FODXSYS, therefore, $10,000,000 as an initial investment was required since we chose to use the highest priced X-ray alternative ($2,000,000) to compensate for unexpected costs related to the X-ray equipment. The break-even point can be seen in Figure 11 above at approximately 3.5 years; this represents the point at which the savings from FODXSYS will drive its cumulative cost down to that of Manual Inspection. Profit can be expressed as cumulative; 5 years after implementation, $7M is expected to be saved; 10 years after $26M is expected in cumulative savings.

5. Conclusions

FODXSYS successfully addresses the majority of the issues that are associated with the manual-visual inspection method through by-over-coming line-of-sight visibility restrictions and increasing probability of FOD detection to 95%. In addition, simulation results indicated that FODXSYS will improve aircraft assembly efficiency by reducing total inspection hours as well as FOD-related rework hours by shifting majority of the rework required prior to the mating of the Aircraft.

However, sensitivity analysis indicates that, if increasing the probability of FOD detection to approximately 80% is possible, the method of inspection is irrelevant. Under the current FOD occurrence rate, achieving 80% inspection accuracy, regardless of the inspection method is sufficient due to the fact that there are diminishing returns after. Figure 12 depicts simulation results for rework hours and aircraft quality upon delivery, between different probabilities of detection for the manual method alongside FODXSYS. The graph indicates that the cost and quality of FODXSYS can only be achieved by the manual system through dramatic improvement to the probability of detecting FOD.
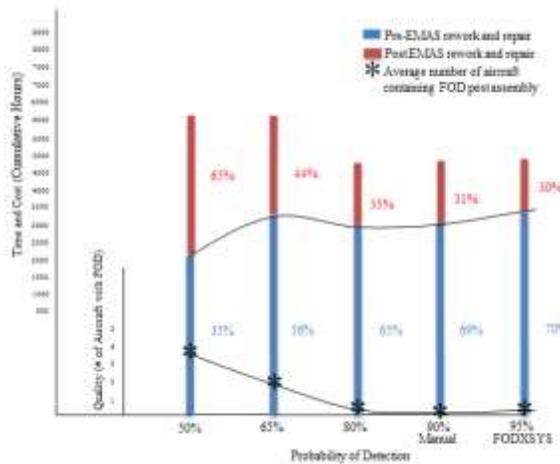
Figure 12. Time/Cost/Quality Sensitivity Analysis – Manual VS FODXSYS

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