Design of an Enhanced FOD Inspection System for the Aircraft Assembly Process

BEFORE

Manual Inspection

Foreign Object Debris (FOD)

Reduce:
- Human Error
- Rework Hours
- Inspection Time

AFTER

X-ray Imaging

Differential Imaging

By: Justin Amoyal, Roman Garber, Marwan Karama, Meba Kassahun & Anoosha Koohi

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LOCKHEED MARTIN
We never forget what we're working for...

Agenda

- **Context**
    - **FOD & FOD Inspection**
    - **Aircraft Production**
    - **Stakeholder Analysis**
    - **Problem & Need**
    - **System Requirements**
- Operational Concept/Approach
- Method of Analysis
    - Stochastic Simulation
    - Design of Experiments
- Results
    - Simulation Results
- Business Case Analysis
    - Business Case & Cost Analysis
- Conclusions /Recommendations

FOD Overview

- **Foreign Object Debris (FOD):** A substance, debris or article alien to the aircraft which would potentially cause damage.
  - According to Boeing, FOD costs the aerospace industry **$13 Billion/year** [1]
  - **Manual Inspection** techniques used to combat FOD
  - According to sponsor at Lockheed Martin manual FOD inspections take **5-10% of each shift**
    - FOD Inspections occur at the end of each shift

Classification	Examples
Panstock (33.6%)	Washer, Bolt, Screw, Pin
Consumables (13.71%)	Rag, Cap, Bag, Bottle
Tools/Shop Aids (8.74%)	Wrench, Socket, Hammer
Trash (24.87%)	Plastic Wrap, Used Tape
Manufacturing Debris (19.09%)	Metal Shavings, Rivet Tails

[2]

[1] "FOD Prevention – What is FOD?"', 2013. http://fodprevention.com/fod-information/. Accessed: September 7, 2015.
[2] Tseng, Natalia E and Guadamuz, Mauricio "FOD Prediction in Aerospace Production through Logistic Regression." *Proceedings* of the Industrial and Systems Engineering Research Conference, 2014.

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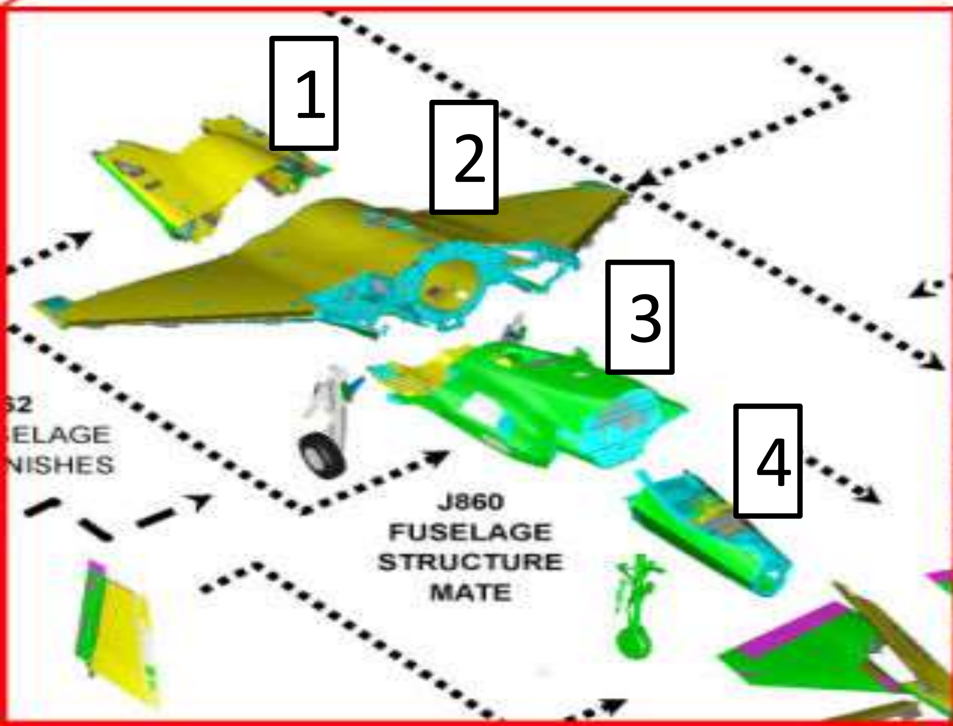
1
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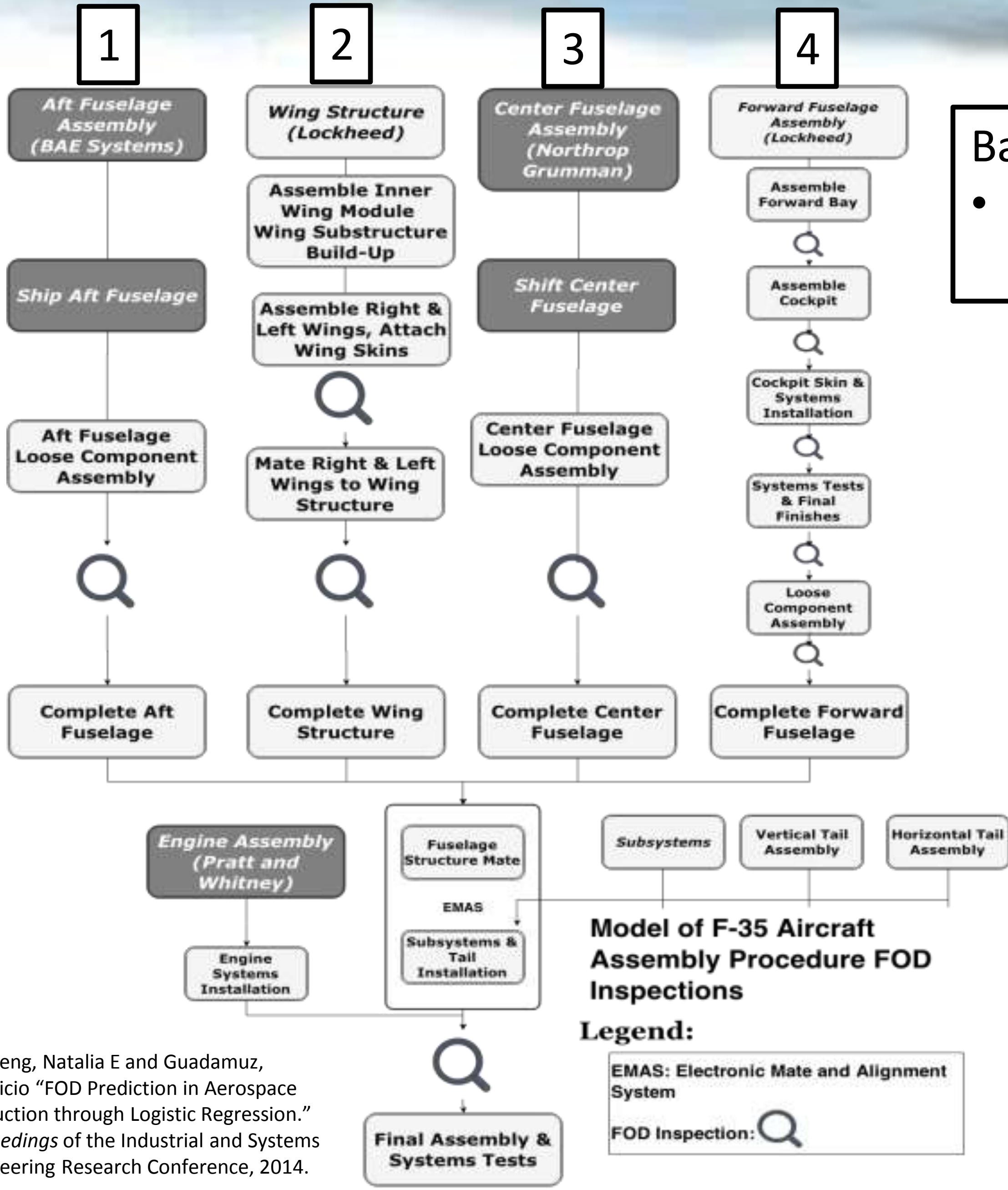
J860
FUSELAGE
STRUCTURE
MATE

F-35 Production



Balanced Assembly Line

- Work in Progress kept to a minimum

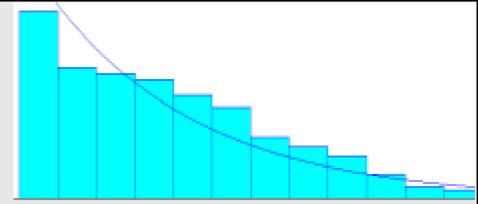
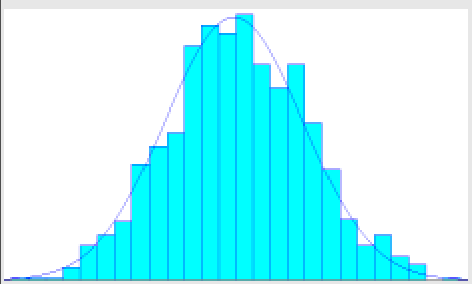
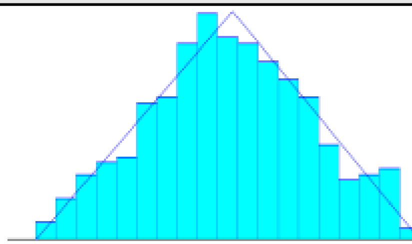
- **Limited to 50% Probability of Detection**[2]
- Total Rework & Repair Times (Hours)
- Inspection Times
- Number of Aircraft Produced
- FOD Present Post Assembly

[2] Tseng, Natalia E and Guadamuz, Mauricio "FOD Prediction in Aerospace Production through Logistic Regression." *Proceedings* of the Industrial and Systems Engineering Research Conference, 2014.

Historical FOD Data

Create Date	Occurences Per Day	Complete Date	Days to Complete	Initiating SWBS	Init Date	Estimated Complete Date	Labor Hours
10/9/97	1.00	10/10/97	1.00	228			0
10/9/97	1.00	10/9/97	0.00	229			0
10/9/97	1.00	10/9/97	0.00	229			0
10/9/97	1.00	10/26/97	17.00	232			0
10/10/97	1.00	10/13/97	3.00	230			0
10/12/97	1.00	10/12/97	0.00	229	8/4/14	3/28/15	0
10/12/97	1.00	10/12/97	0.00	229			0
10/13/97	1.00	10/15/97	2.00	229			41.7831823
10/13/97	1.00	10/13/97	0.00	229	8/5/14		0
10/13/97	1.00	10/14/97	1.00	231			0
10/13/97	1.00	10/13/97	0.00	233	8/5/14		0
10/13/97	1.00	10/28/97	15.00	279			0
10/14/97	1.00	10/15/97	1.00	228	8/6/14		0
10/14/97	1.00	10/14/97	0.00	229			0
10/14/97	1.00	1/22/98	100.00	229			0
10/14/97	1.00	1/22/98	100.00	229			0
10/14/97	1.00	10/15/97	1.00	229			0
10/14/97	1.00	10/20/97	6.00	279			0
10/15/97	1.00	10/15/97	0.00	211	8/7/14	4/4/15	0
10/15/97	1.00	10/15/97	0.00	211	8/7/14	4/4/15	0
10/15/97	1.00	10/30/97	15.00	226	8/7/14		0
10/15/97	1.00	10/30/97	15.00	226	8/7/14		0
10/15/97	1.00	12/2/97	48.00	228	8/7/14	1/31/15	223.367238

Case Study Parameters

Variable	Distribution & Random Number Generator	Distribution Graph
FOD Arrival Rate	Exponential Distribution (λ = 0.0102) $X = -\frac{\ln(1-R)}{0.0102}$ $0 \leq R \leq 1$	
FOD Rework Time	Exponential Distribution (λ = 0.951) $X = -\frac{\ln(1-R)}{0.951}$ $0 \leq R \leq 1$	
Inspection Time	Normal Distribution (MEAN, VAR) For Manual X = INVERSENORMAL(4.2,3.35) For FODXSYS X = INVERSENORMAL(0.42,0.0347)	
Station Process Times	Triangular Distribution (50,60,70) $T = 4 + \sqrt{R(8-4)(6-4)}$ $0 < R < 0.5$ $T = 8 - \sqrt{(1-R)(8-4)(8-6)}$ $0.5 \leq R \leq 1$	

Stakeholder Analysis: Wins & Tensions

Production Line Personnel

Production Line Personnel	Aircraft Production Corporation	
High FOD Inspection hours	High Labor Costs	Labor Costs
High Rework & Repair Hours	High Rework & Repair Costs	Rework and Repair Costs
Many Inspectors Needed	High Labor Costs	Inspection Cost
Experienced with Manual Inspections	Decreased Training Costs	Training Costs

Aircraft Production Corporation

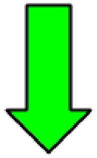
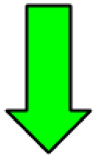
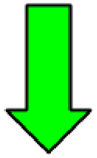
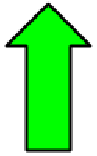
Aircraft Customer

Aircraft Customer	Aircraft Production Corporation	
Missed deadline due to FOD related Rework & Repair	Deadline extensions due to FOD related Rework & Repair	FOD Related Deadline Extensions
FOD is contained at delivery	FOD present at customer delivery	FOD in Final Product
Increased chance of FOD related pilot danger	Decreased Contract Value due to low reliability	Contract Value

Win

Tension

Enhanced Inspection Need

Objective	Increase/Decrease
Total Rework & Repair Hours	
Total Inspection Time	
FOD Present post Assembly	
Number of Aircraft Assembled	

Enhanced Inspection System Requirements

MR #	Requirement Description	
MR.1.0	System shall have a **95% FOD detection rate** in all portions of the Aircraft to support a **production rate of 1 Aircraft/day.**	
	MR.1.1	System shall incorporate **multi-layer visibility,** enabling **95% visibility within assembly components.**
	MR.1.2	System shall **limit human error** by implementing **decision assistance**.
	MR.1.3	System shall reduce the Type II Error, by **detecting 95% of FOD inputted prior to EMAS**.
MR.2.0	System shall reduce **FOD inspection times by 50%** providing an **ROI of 25%**.	
	MR.2.1	System implementation shall reduce the **number of inspections required per Aircraft by 50%.**

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    - **Alternatives – Manual & Enhanced Inspection System**
    - **System Validation and Implementation Alternative Selection**
        - X-Ray Mounting Alternatives
        - Decision Analysis for X-Ray Alternatives
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Design Alternatives & Implementation

1. Manual/Visual Inspection
2. X-Ray imaging & Differential imaging software
   - Automated system with multi-layer view
   - Automated FOD Identification Software-Subject To: Design/Sensor

Pro

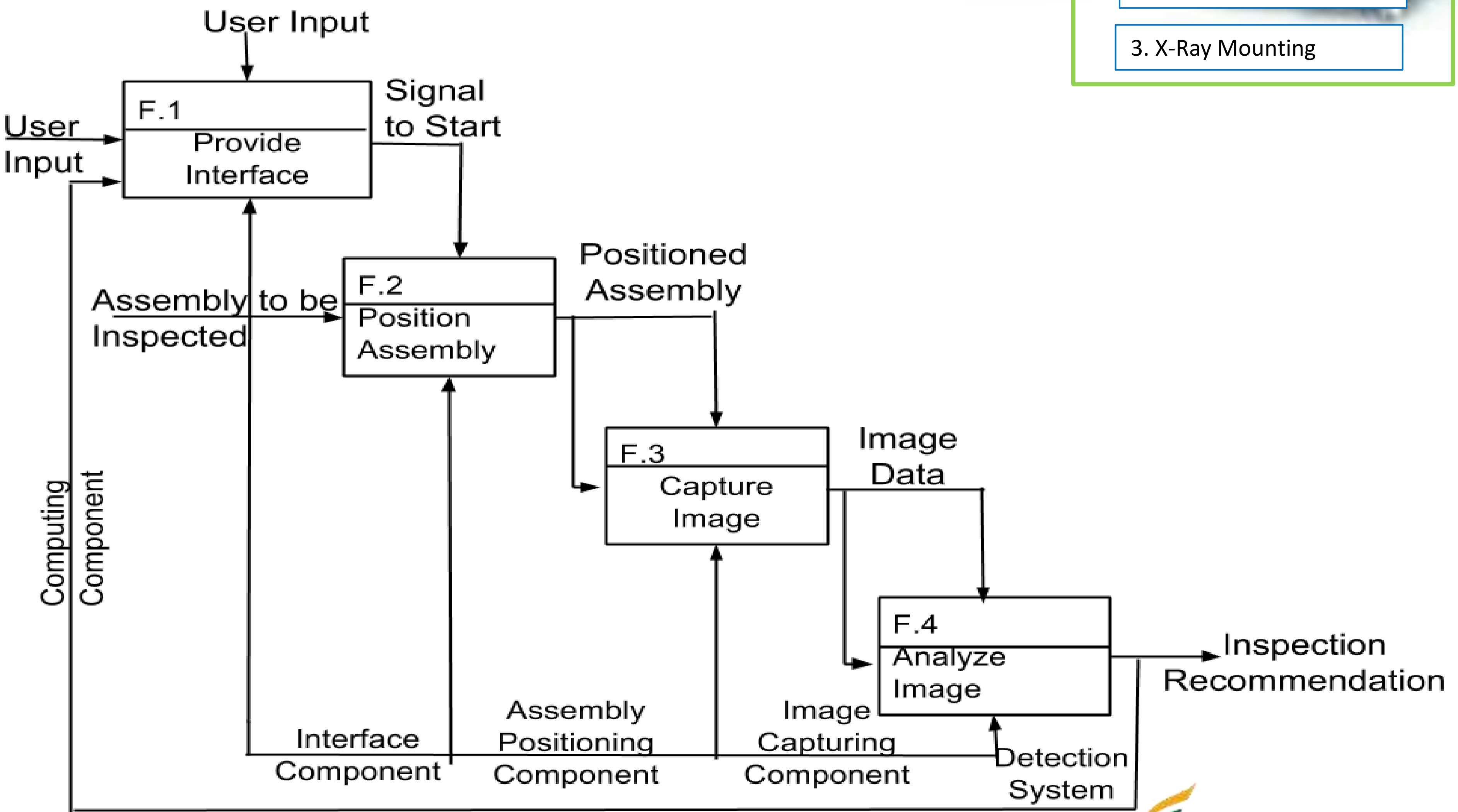
Con

	FOD Detection Probability	Time	Cost
Manual Inspection	- Limited by line of sight - **Solely human decision making** - Prone to Human Error	- Visually Inspect Entire Component	- Hourly rate of additional FOD inspectors - No additional installation cost - Cost of human error
Enhanced Inspection	- Bypass line of sight - Provides penetration of multiple layers - **Computer assisted decision making**	- Faster scan time - X-ray start up time - Image Analysis Time	- Cost to power X-ray system - Installation Cost - Maintenance Cost - Training Cost

Enhanced Inspection System IDEF.0

Enhanced Inspection System

1. Differential Imaging
2. X-Ray Component
3. X-Ray Mounting



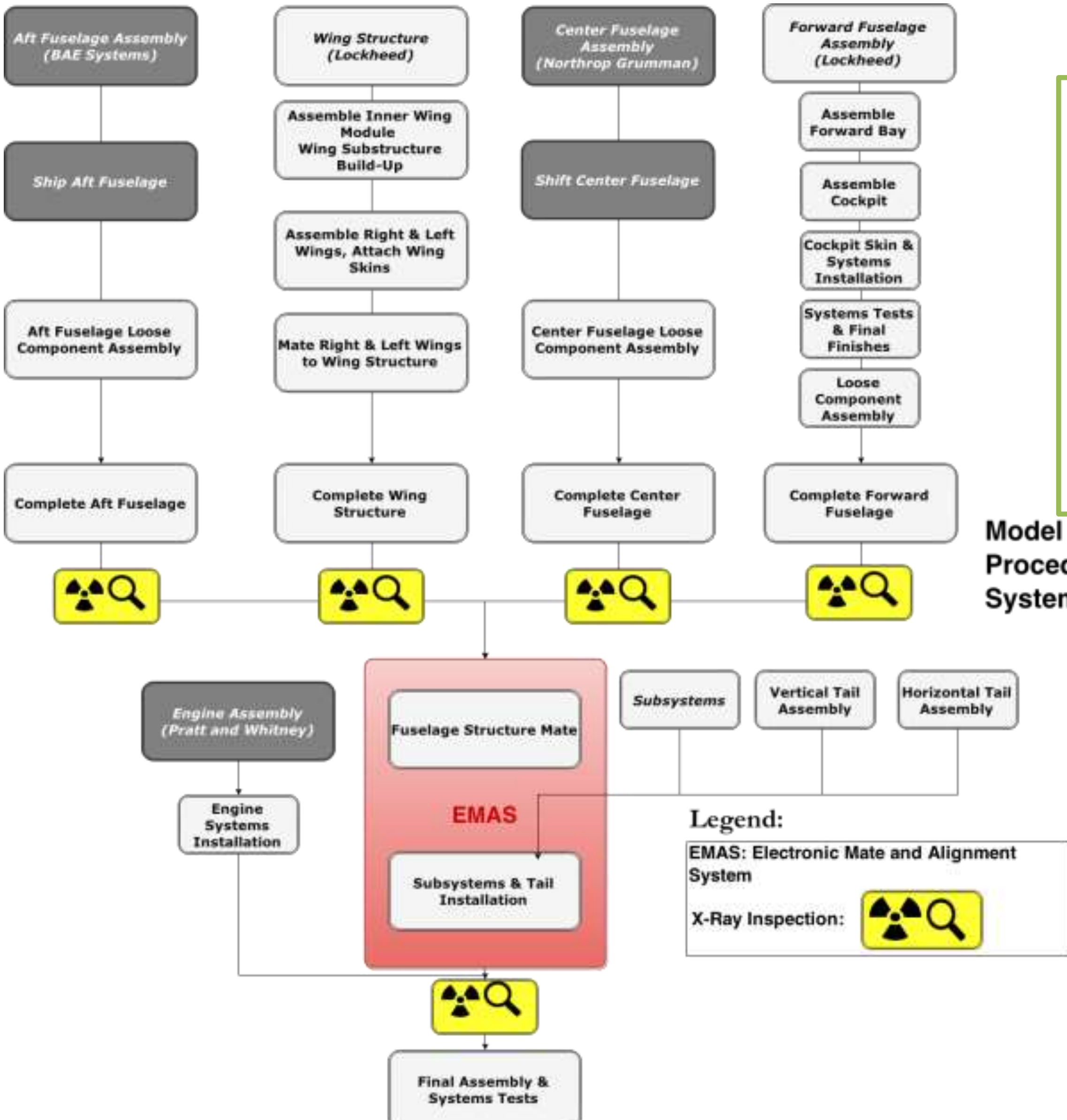
Fighter Jet Assembly with Enhanced Inspection System

Enhanced Inspection System

1. Differential Imaging
2. X-Ray Component
3. X-Ray Mounting

95% Probability of Detection

- Total Rework & Repair Times (Hours)
- Inspection Times
- Number of Aircraft Produced
- FOD Present Post Assembly

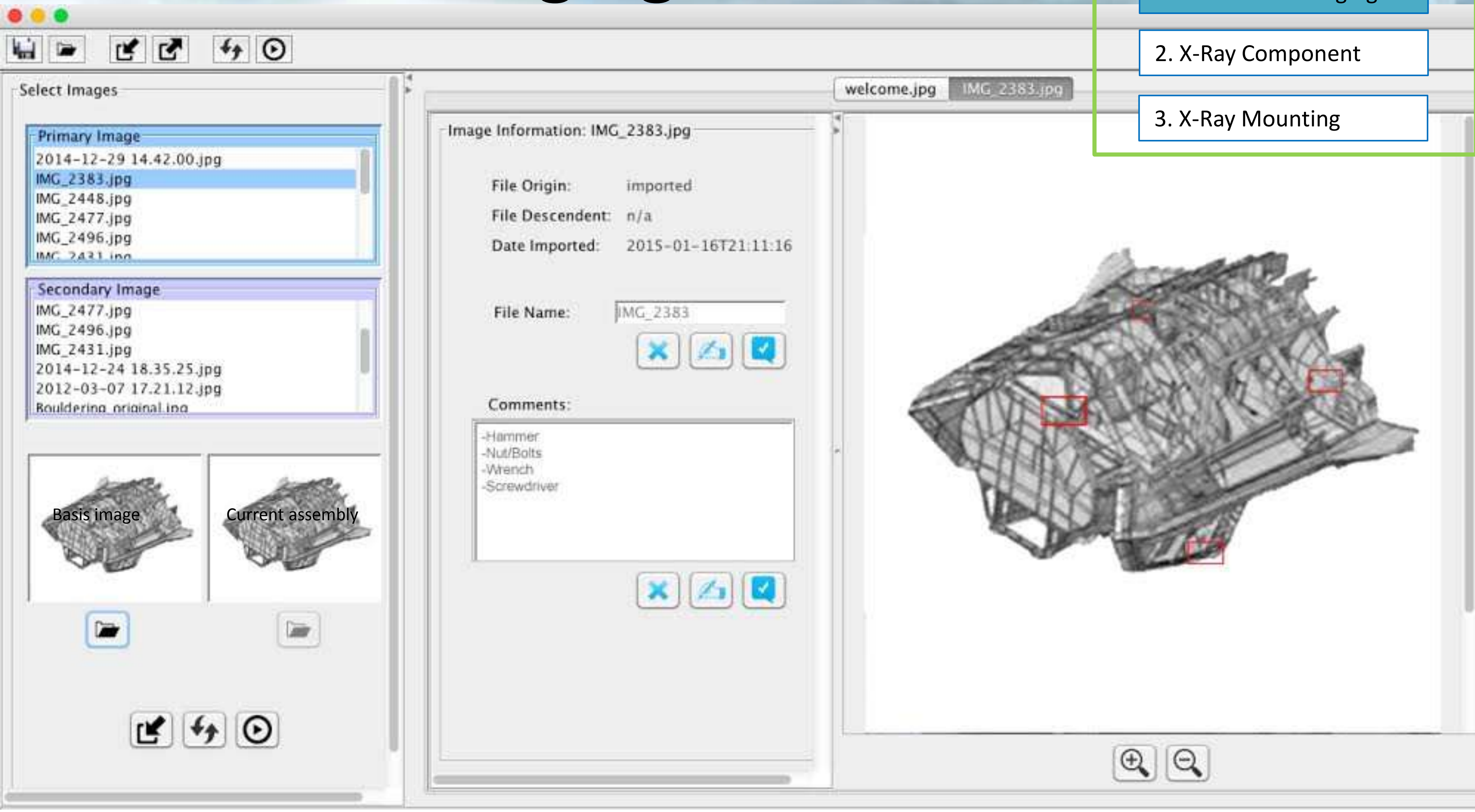


Model of F-35 Aircraft Assembly Procedure Incorporating Proposed System

Differential Imaging

Enhanced Inspection System

1. Differential Imaging
2. X-Ray Component
3. X-Ray Mounting



- Developed by classmate – Don Brody

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X-ray Mounting Alternative

X-ray System	X-ray System	Source	Penetration Power (in steel)	Power Requirement	Scan Speed	Dimensions	Start Up Time	Radiation Dose
	Linear Rail	Backscatter	6.3 mm	250-600 watts	0.185(m^2/s)	DIFFERENT SIZES AVAILABLE	20 min	BASED ON SIZE
	Robotic Arm	Backscatter	6.3 mm	250-600 watts	0.185(m^2/s)	DIFFERENT SIZES AVAILABLE	20 min	BASED ON SIZE
	Gantry	Transmission-Optional Backscatter	400 mm	380-480	9.6(m^2/s)	Length 36.5m Width 3.0m Height 5.0m	15 min	5 mR
	Z-Portal	Backscatter	300 mm	480	9.6(m^2/s)	Width 8.9m Height 6.3m	15 min	5 mR

Detecting FOD Using X-Rays

Thickness/ Component

Material/ Component

Aircraft Components
- Center Fuselage
- Aft Fuselage
- Forward Fuselage
- Wing module

Input Voltage/Device

X-Ray Alternatives
- Robotic Arm
- Gantry
- Z-Portal
- Mobile Search
- Linear Rail System
- ZB Van

Half Value Layer
$$HVL = \frac{0.632}{\mu}$$

X-Ray Intensity
$$I = I_0 e^{-\mu x}$$

Penetration Depth
$$(Thickness)^{HVL}$$

Penetration through assembly component

Signal to Noise Ratio
$$\frac{I_{(s)}\, mean}{\sigma}$$

Visibility within assembly component

Probability of Detection

X-ray Mounting Alternative - Swing Weights

Enhanced Inspection System

1. Differential Imaging
2. X-Ray Component
3. X-Ray Mounting

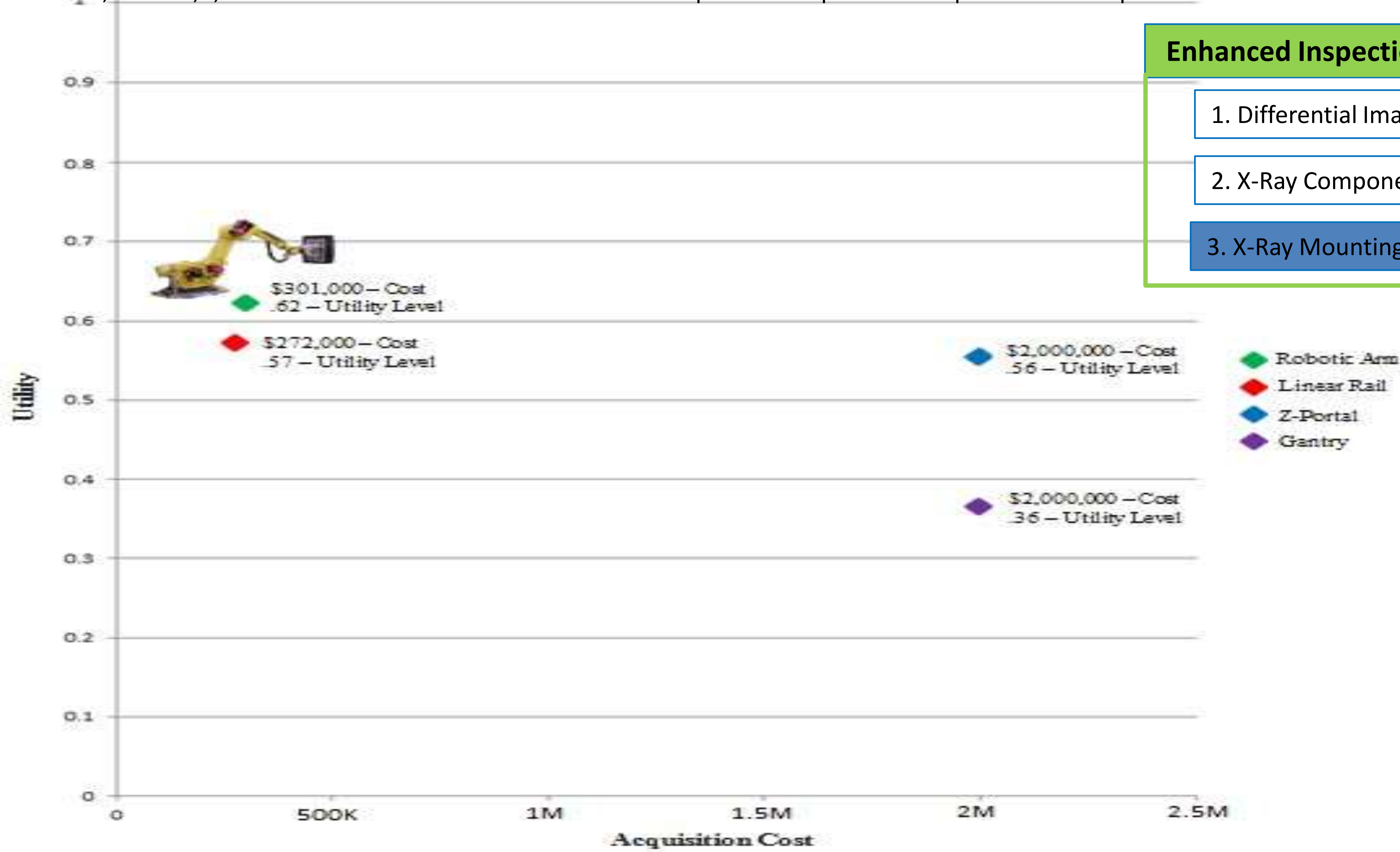
X-ray Mounting Alternative		Average Cost ($)	Average Power Req. (watts)	SNR (Aluminum, Wing)	SNR (Carbon, Wing)	SNR (Aluminum, Fuselage)	SNR (Carbon, Fuselage)	Penetration Depth through Steel (mm)	Start Up Time (min)	Scan Speed (m/s^2)
		$C_{avg\ Cost}$	C_{Power}	C_{SNR}	C_{SNR}	C_{SNR}	C_{SNR}	$C_{Penetration\ depth}$	$C_{start\ up}$	$C_{scan\ speed}$
		$w_{avg\ Cost}$	W_{Power}	W_{SNR}	W_{SNR}	W_{SNR}	W_{SNR}	$W_{Penetration\ depth}$	$W_{start\ up}$	$W_{scan\ speed}$
Weight		.25	.75	.1212	.0909	.3636	.1818	.2424	.25	.75
Preference		Low	Low	High	High	High	High	High	Low	Low
Mounting Alternative	Linear Rail	272,000	550	2.39	3.38	1.97	1.19	6.3	20	0.185
	Robotic Arm	301,000	550	2.39	3.38	1.97	1.19	6.3	20	0.185
	Gantry	2000000	620	2.39	3.38	1.97	1.19	400	15	9.6
	Z-Portal	2000000	480	2.39	3.38	1.97	1.19	300	15	9.6

Mounting Alternative - Utility vs Cost

$$\textit{Utility} = c_{Power}w_{Power} + c_{SNR:A,W}w_{SNR:A,W} + c_{SNR:C,W}w_{SNR:C,W} + c_{SNR:A,F}w_{SNR:A,F} + c_{SNR:C,F}w_{SNR,C,F} + c_{Penetration}w_{Penetration} + c_{Start\ Up}w_{Start\ Up} + c_{Scan\ Speed}w_{Scan\ Speed}$$

Enhanced Inspection System

1. Differential Imaging
2. X-Ray Component
3. X-Ray Mounting



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- Context
- Operational Concept/Approach
- Method of Analysis
- **Method of Analysis**
    - **The Simulation**
        - **Model Boundaries & Simulation Inputs/Outputs**
        - **Simulation Requirements**
        - **FODSim Overview**
        - **Flow & Implementation**
        - **Case Study Variables and Assumptions**
        - **Validation**
    - **Design of Experiments**
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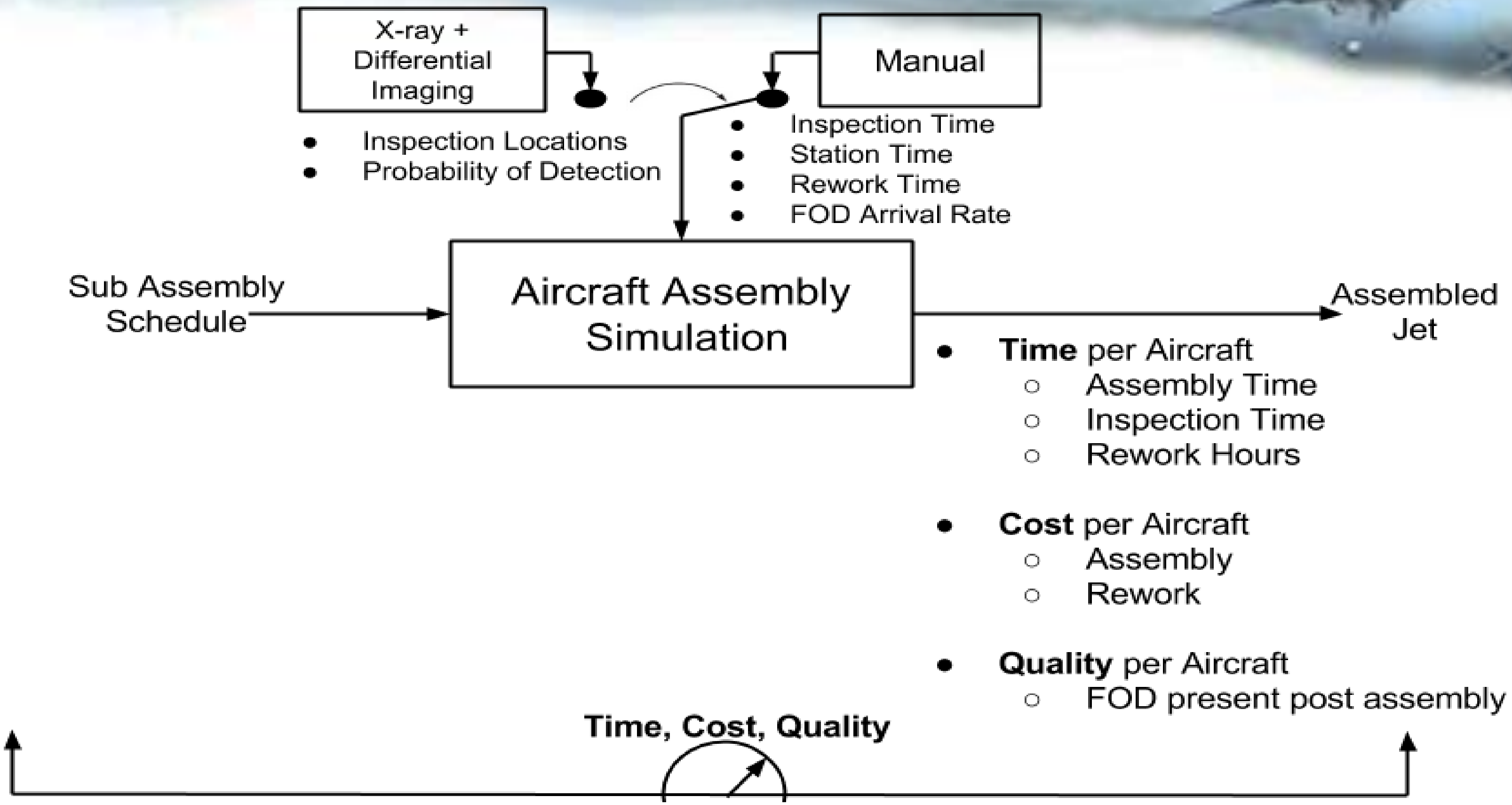
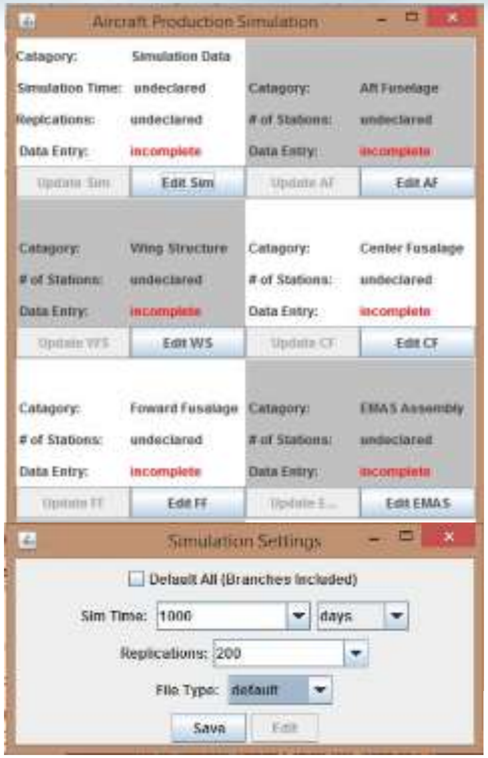
Model Boundaries & Simulation Inputs/Outputs



Input Requirements	Functional Requirements	Output Requirements
• The production flow across Parallel Production lines • Standard Station Production • FOD Occurrences Per Station • FOD Rework and Repair	• Total Simulation Time • A production flow - Station List • A FOD arrival rate • Average Station Time • FOD Detection Rate	• Total # of Aircraft complete by end of Simulation time • Total # of Detected FOD • Total Repair Time • Total Work Time • Total Inspection Time

Stochastic Simulation Tool - FODSIM



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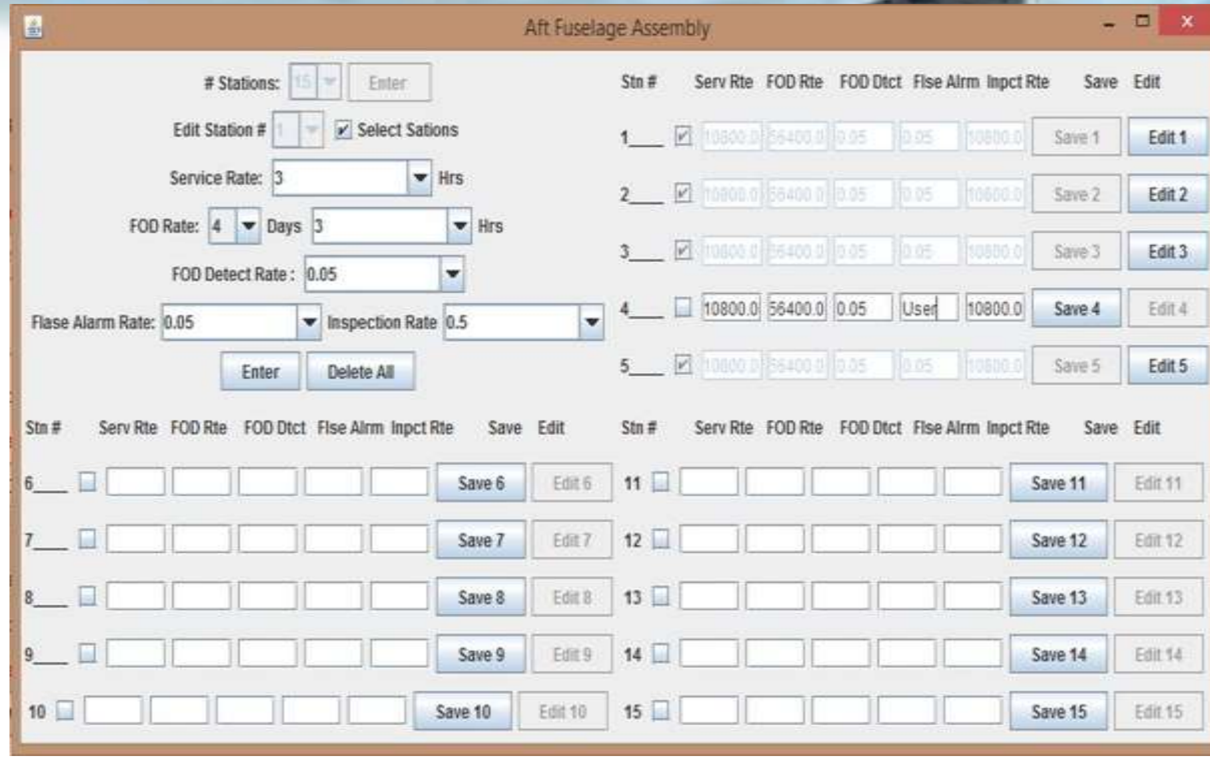


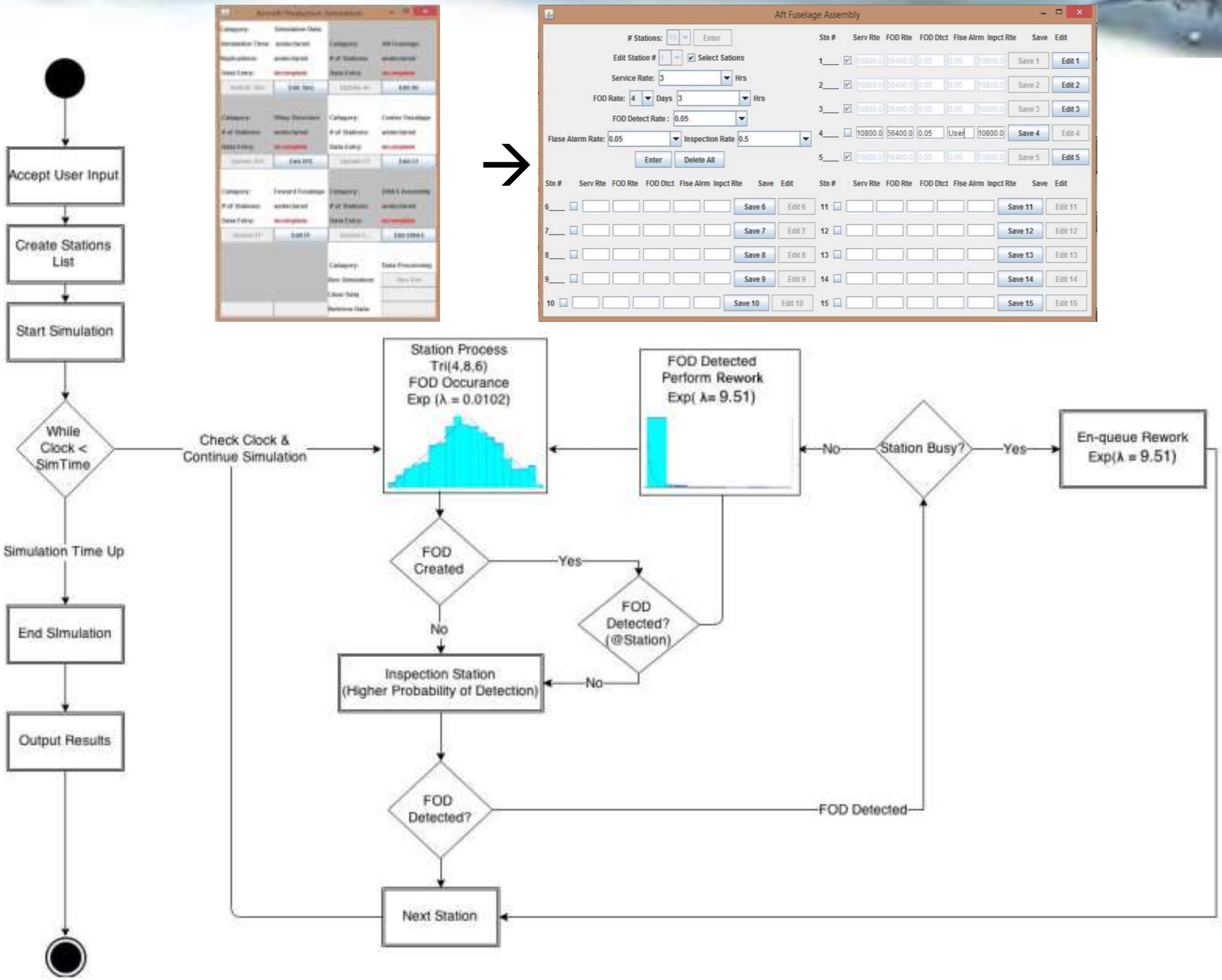
Main Menu	Simulation Settings	Branch Settings	Variables
• Simulation Main Settings • Aft Fuselage Branch • Wing Structure Branch • Center Fuselage Branch • Forward Fuselage Branch • EMAS Assembly	• 2 Default Options • Simulation Time • Simulation Replications • File Location	• Choose how many stations in branch • Can Select Stations with similar parameters • Can Enter Manually or with Drop Down boxes	• Number Stations • Service Rates • FOD Occurrence Rates • FOD Detection Rates • False Alarm Rates • Inspection Rates

Case Study Parameters/Assumptions

- There are **26** total Stations: **21** Assembly (and **5** Inspection Stations with FODXSYS)
  - Process Time modeled by **TRI(50,60,70) hours**
  - FOD Events are based on an arrival Rate **EXP(λ =0.0102)**
  - FODXSYS Inspection time modeled by **Norm(0.42, 0.0347) hours**
  - Manual Inspection time modeled by **Norm(4.2, 3.35) hours**
  - FOD Arrival Rate as Exponential Distribution with λ = 0.0102 FOD Arrivals per Station per Hour
  - FOD Rework Time modeled from Exponential Distribution with **λ = 9.51**

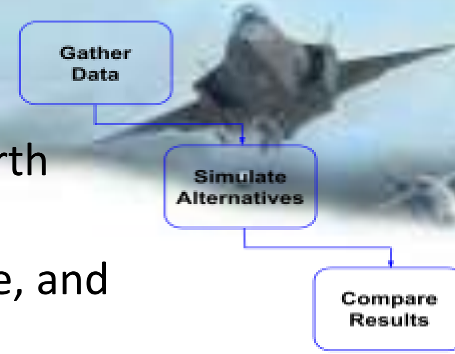
- Inspection Stations and EMAS do not create FOD
- FOD Rework is always performed at the Station that has created the FOD
- FOD Rework time is increased by :
  - **(Station Detected – Station Originated)/ Total Stations + 1) * EXP(λ = 9.51)**
- FOD Inspection decision modeled as Bernoulli Distribution With p = Probability of detection
    - P = 50% for Manual Inspection Station
    - P = 95% for FODXSYS
    - Each Station has a default chance to detect FOD (By Eye) **P = 10%**
- If FOD goes undetected through EMAS, the repair time is increased by another EXP(9.51)

FODSIM Flow Diagram



Design of Experiments

- Generate accurate representation of Lockheed Martin's Ft. Worth
- Create Instantiated architectures for the system
- Instantiated architectures will be compared based on cost, time, and quality



Inputs		Outputs			
FOD Rate	Detection Accuracy	Aircraft Assembled	Aircraft with FOD on Delivery	Total Repair	Average Queue Wait
Low (λ =0.0042)	50%	Number of Aircrafts	Number of Aircrafts	Hours	Hours / Component
Med (λ=0.0102)					
High (λ=0.0260)					
Low (λ =0.0042)	65%				
Med (λ=0.0102)					
High (λ=0.0260)					
Low (λ =0.0042)	80%				
Med (λ=0.0102)					
High (λ=0.0260)					
Low (λ =0.0042)	95%				
Med (λ=0.0102)					
High (λ=0.0260)					

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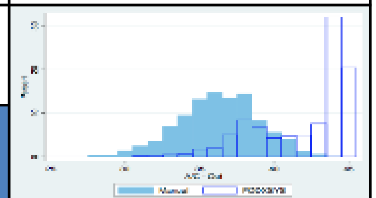
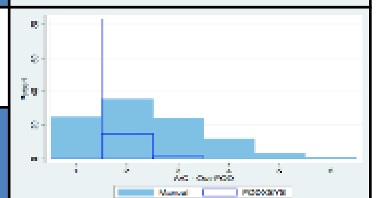
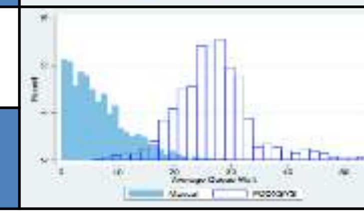
FODSIM Output Analysis FODXSYS vs. Manual

Result	Mean	Probability Distribution
Average Aircraft Assembled (# of Aircraft)	41 36	
FOD Contained Post Assembly (# of Aircraft)	1 2	
Total Labor/Total Aircraft (Hours)	997 1781	

Result	Mean	Probability Distribution
Average Total Repair and Rework Hours	1111 1856	
Average Queue Wait (Hours)	26.9 6.6	

FODXSYS

Manual

- FODXSYS is increasing # of Aircraft Assembled
- Improvement of Quality on Delivery
- Reduction of Total Labor per Aircraft
  - Rework labor reduction
  - Inspection Labor reduction

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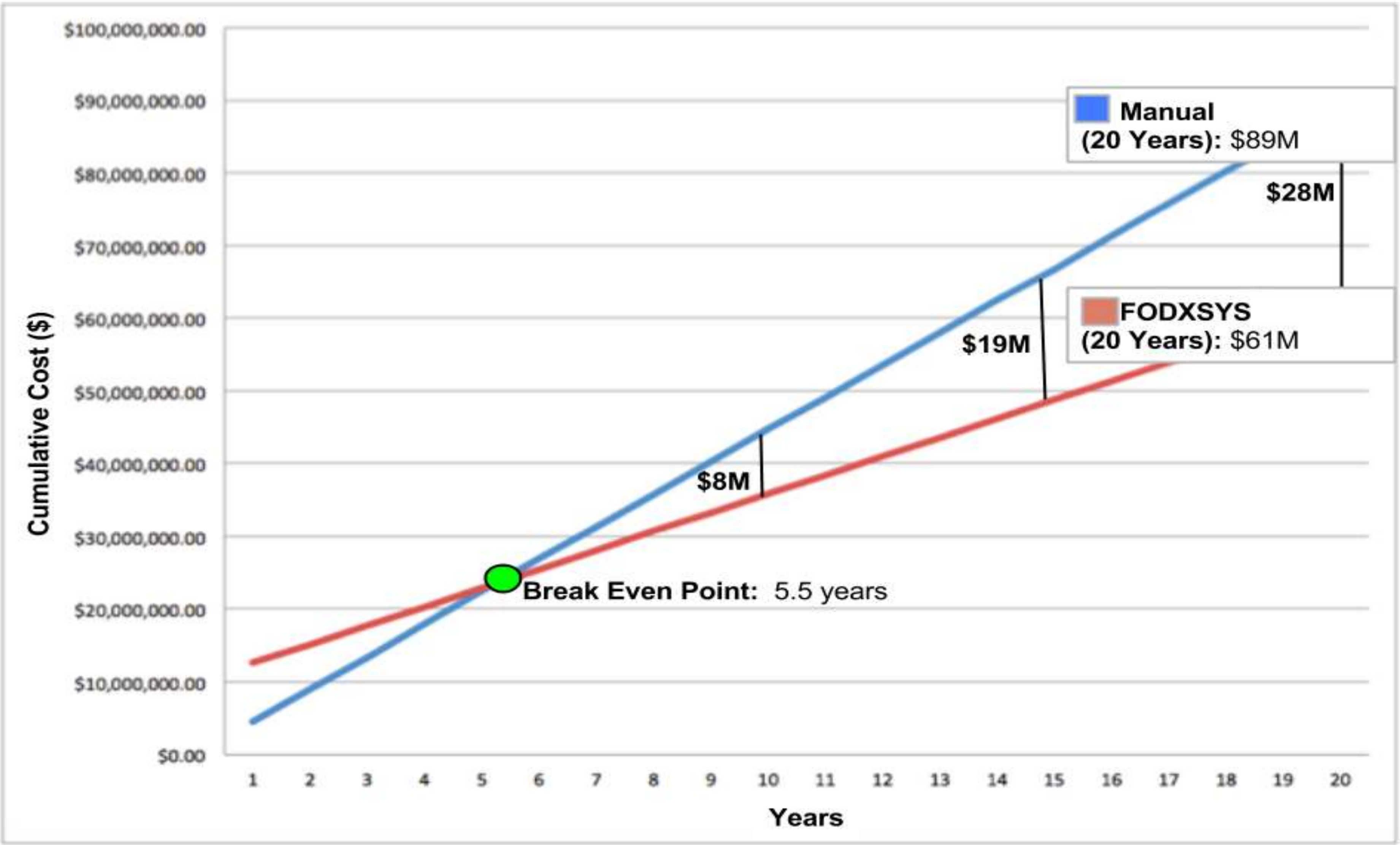
Cost and Business Case Analysis



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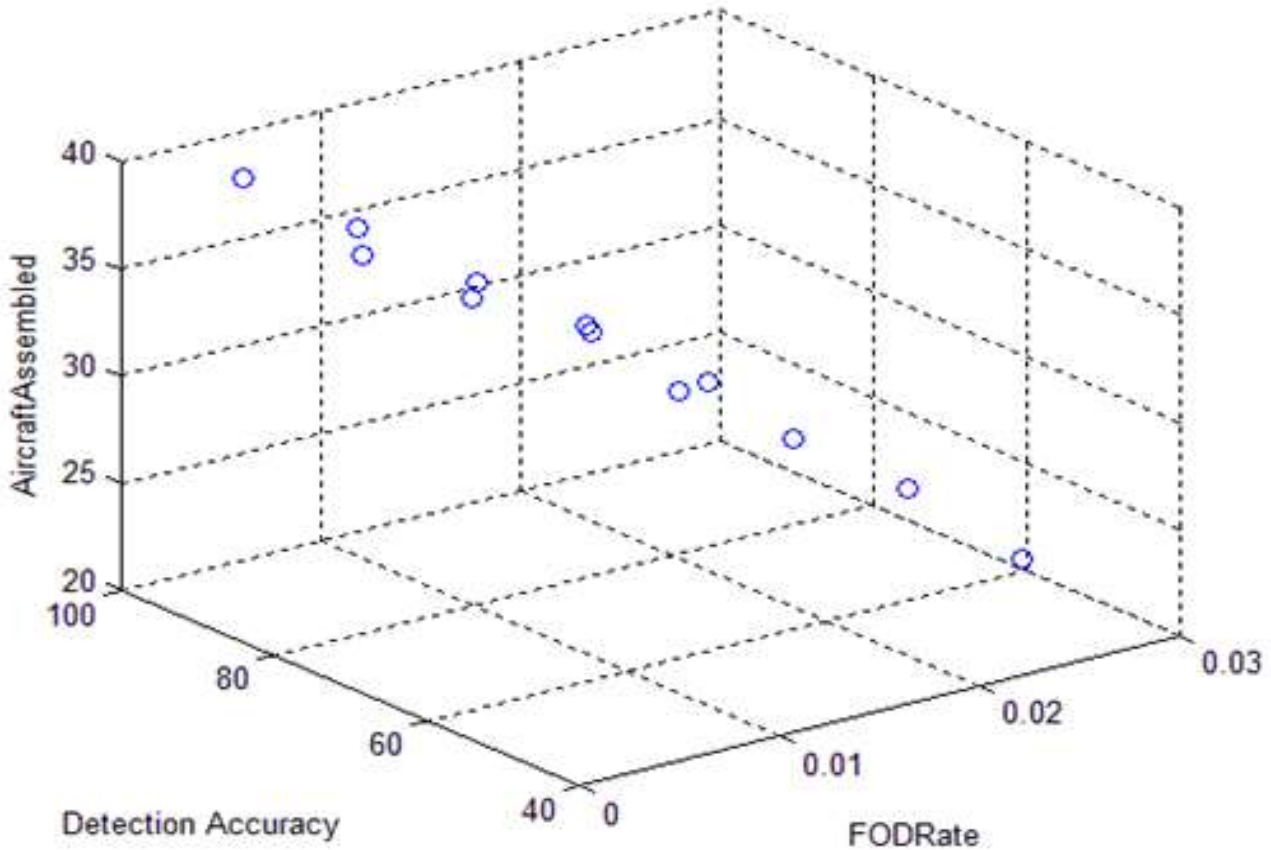
Sensitivity Analysis

Inputs		Outputs			
FOD Rate	Detection Accuracy	Aircraft Assembled	Aircraft with FOD on Delivery	Total Repair Hours	Average Queue Wait
Low (λ =0.0042)	50%	39	3.04	1470	13.6
Med (λ=0.0102)		35	2.42	1726	3.7
High (λ=0.0260)		23	1.72	2058	0.14
Low (λ =0.0042)	65%	38	1.88	1477	13.7
Med (λ=0.0102)		35	2.57	1713	3.6
High (λ=0.0260)		24	0.99	2038	0.15
Low (λ =0.0042)	80%	39	1.01	1466	14.3
Med (λ=0.0102)		35	0.55	1695	4.11
High (λ=0.0260)		24	0.49	2040	0.15
Low (λ =0.0042)	95%	39	1.00	1459	14.5
Med (λ=0.0102)		34	0.55	1722	4.27
High (λ=0.0260)		24	0.47	2048	0.18

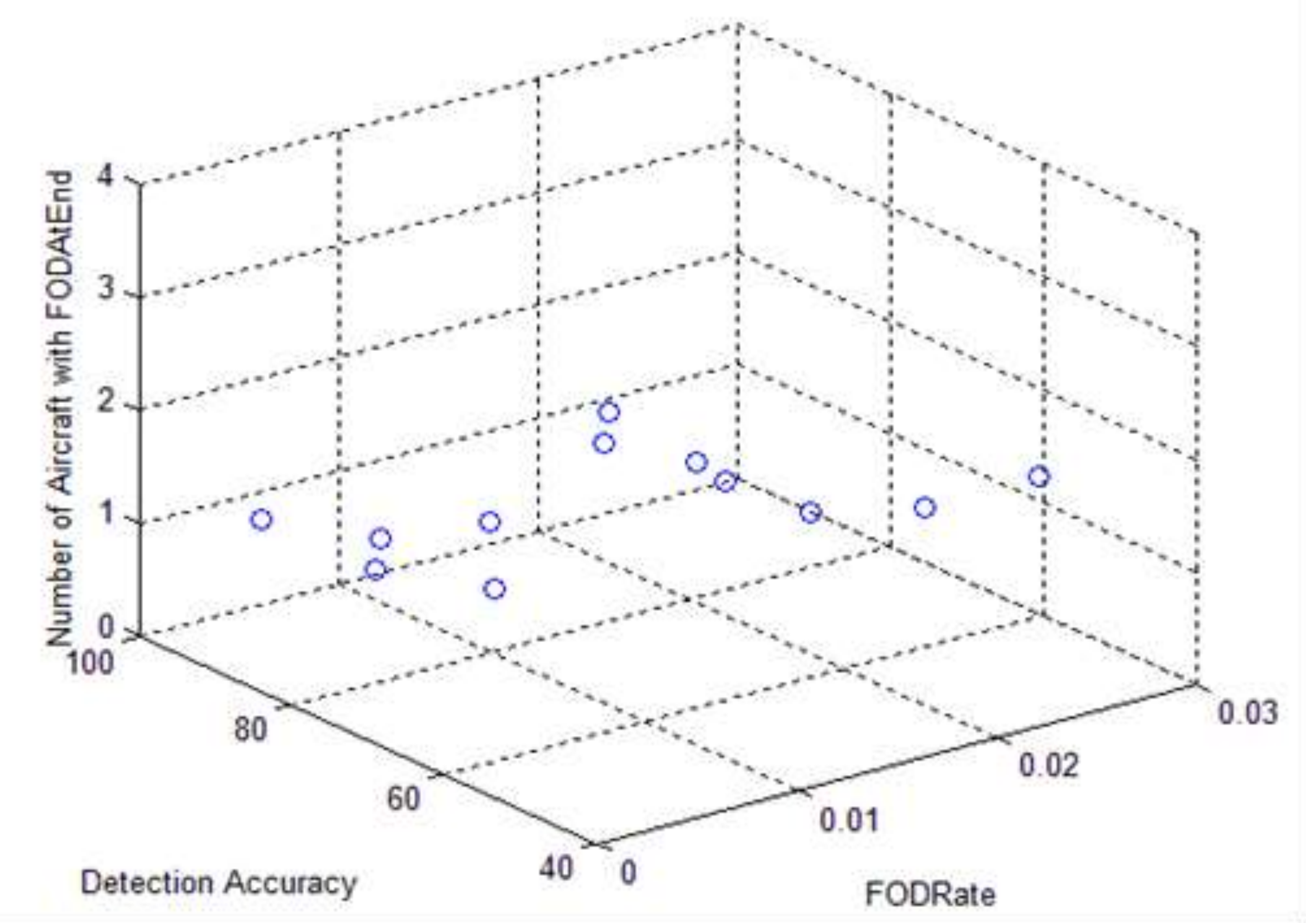
- FOD Rate is the most sensitive parameter of the system – Minor changes lead to significant affects on Total Repair Hours & Aircraft Assembled
- Detection Accuracy > 80% leads to diminishing returns on Quality

Conclusions & Recommendations



- Detection Accuracy > 80% leads to diminishing returns on Quality, and the difference in Pre & Post EMAS Rework & Repair Hours
- Decrease FOD Rate possibly by: Implement new training procedures, establishing more FOD critical areas.

Conclusions & Recommendations



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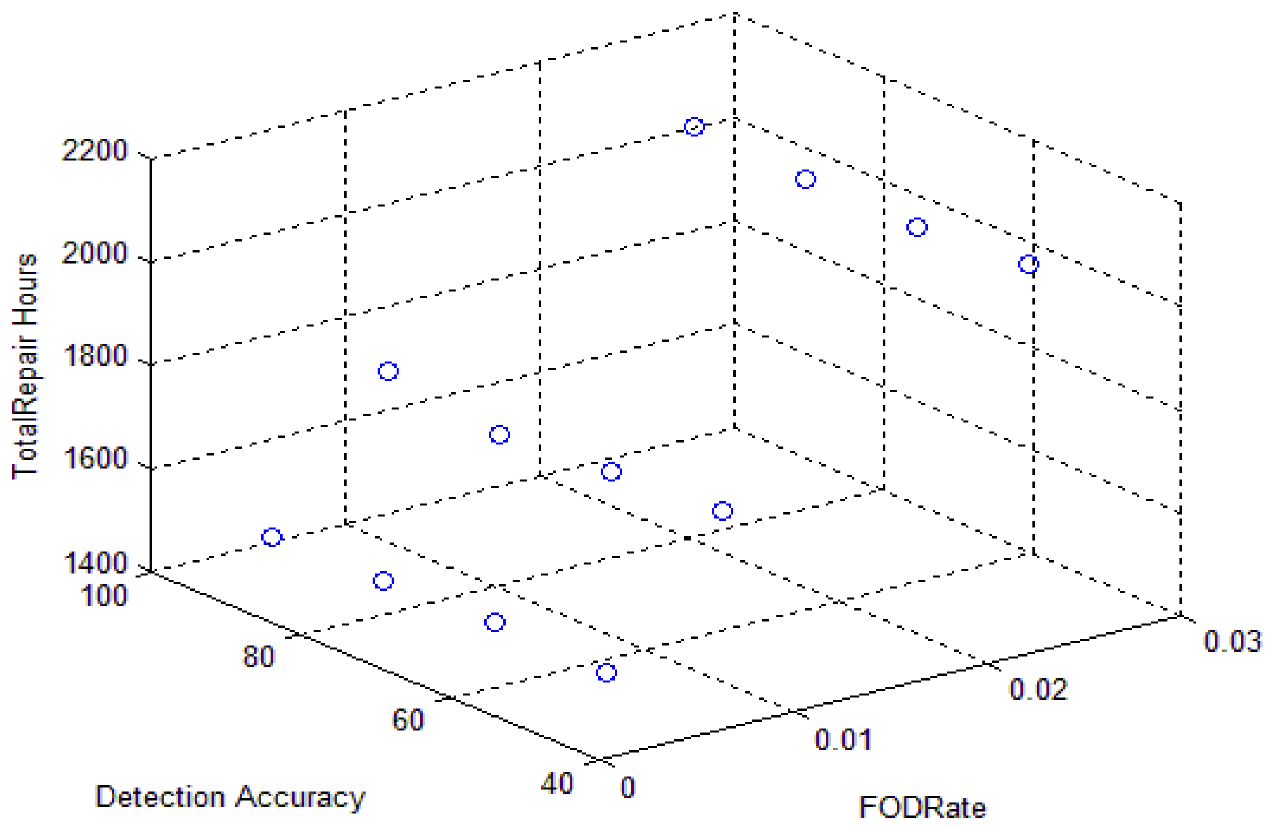
Conclusions & Recommendations



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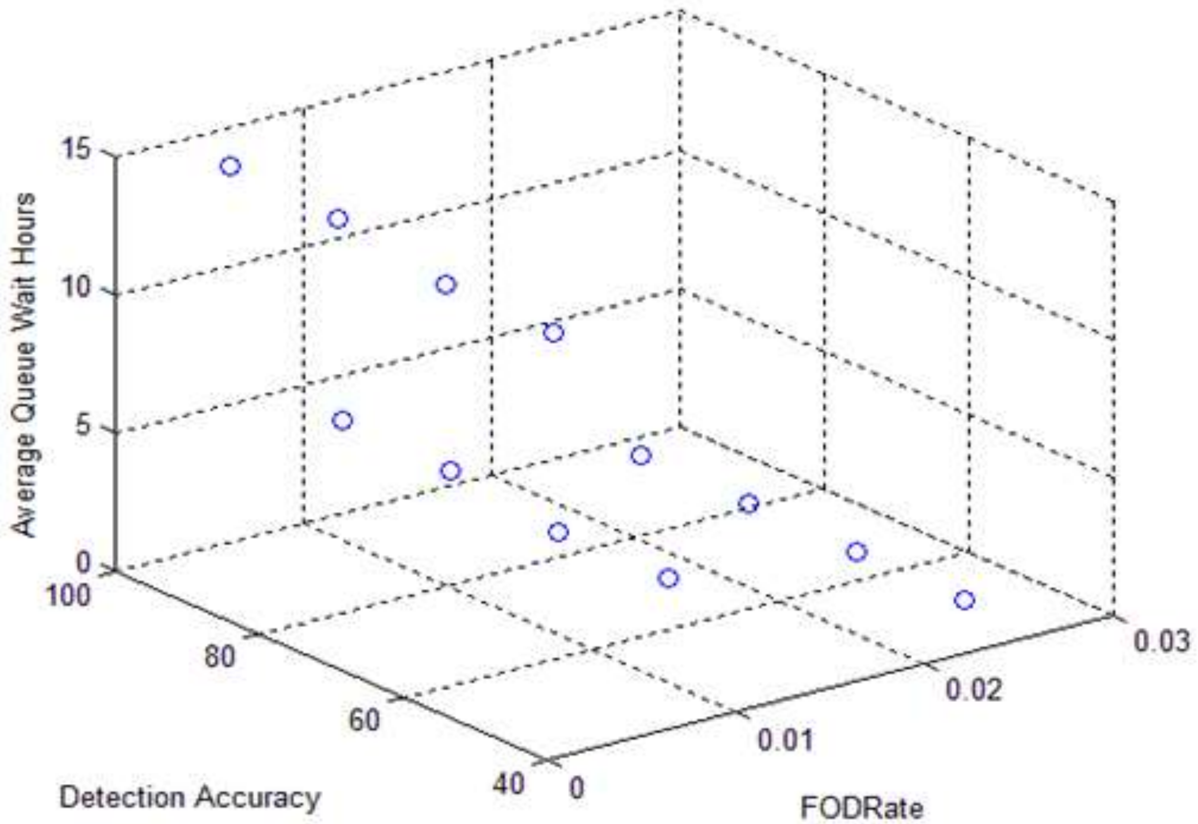
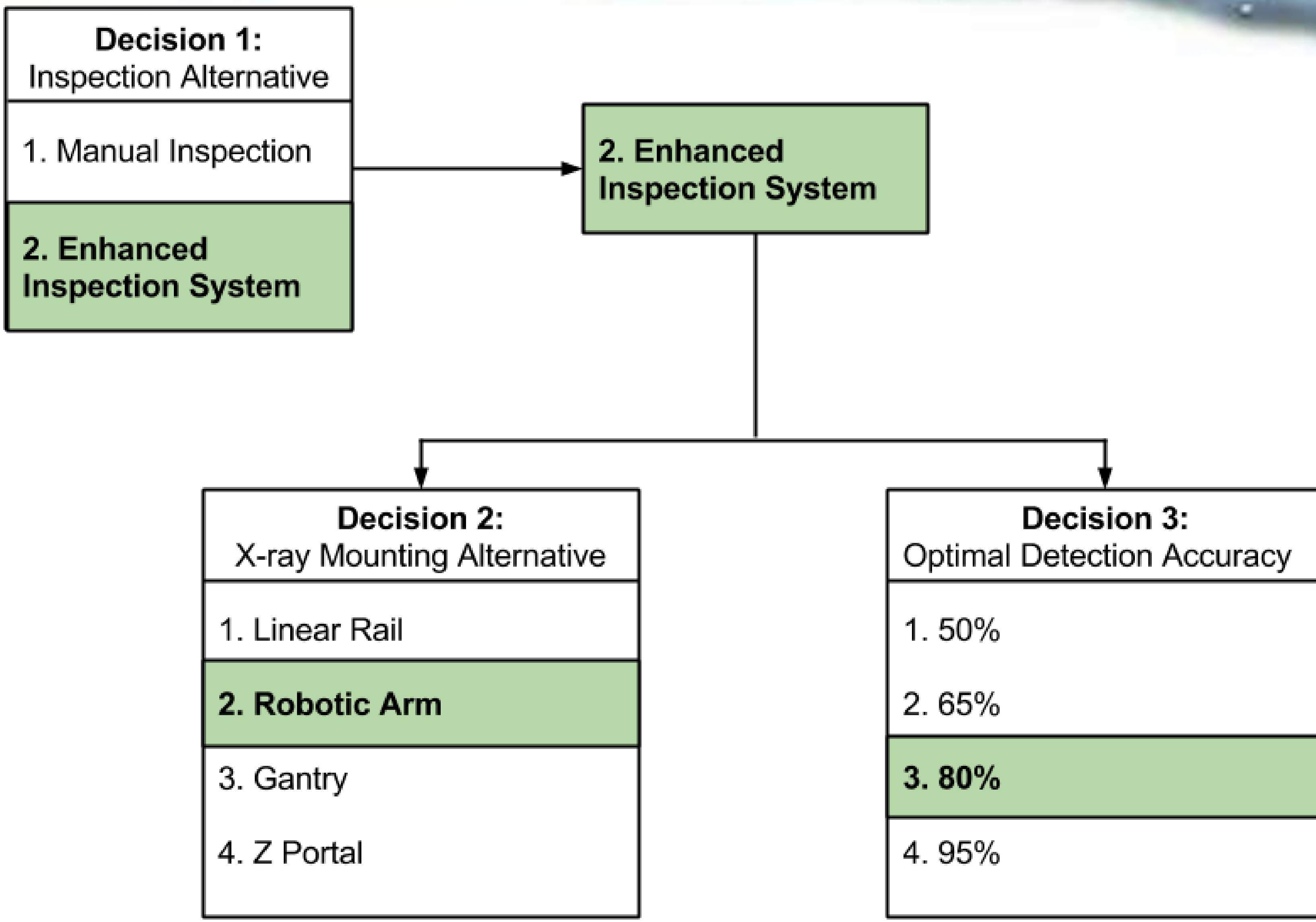
Conclusions & Recommendations



- Detection Accuracy > 80% leads to diminishing returns on Quality, and the difference in Pre & Post EMAS Rework & Repair Hours
- Decrease FOD Rate possibly by: Implement new training procedures, establishing more FOD critical areas.

Final Decisions



Questions?

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Back Up Slides

Simulation Validation

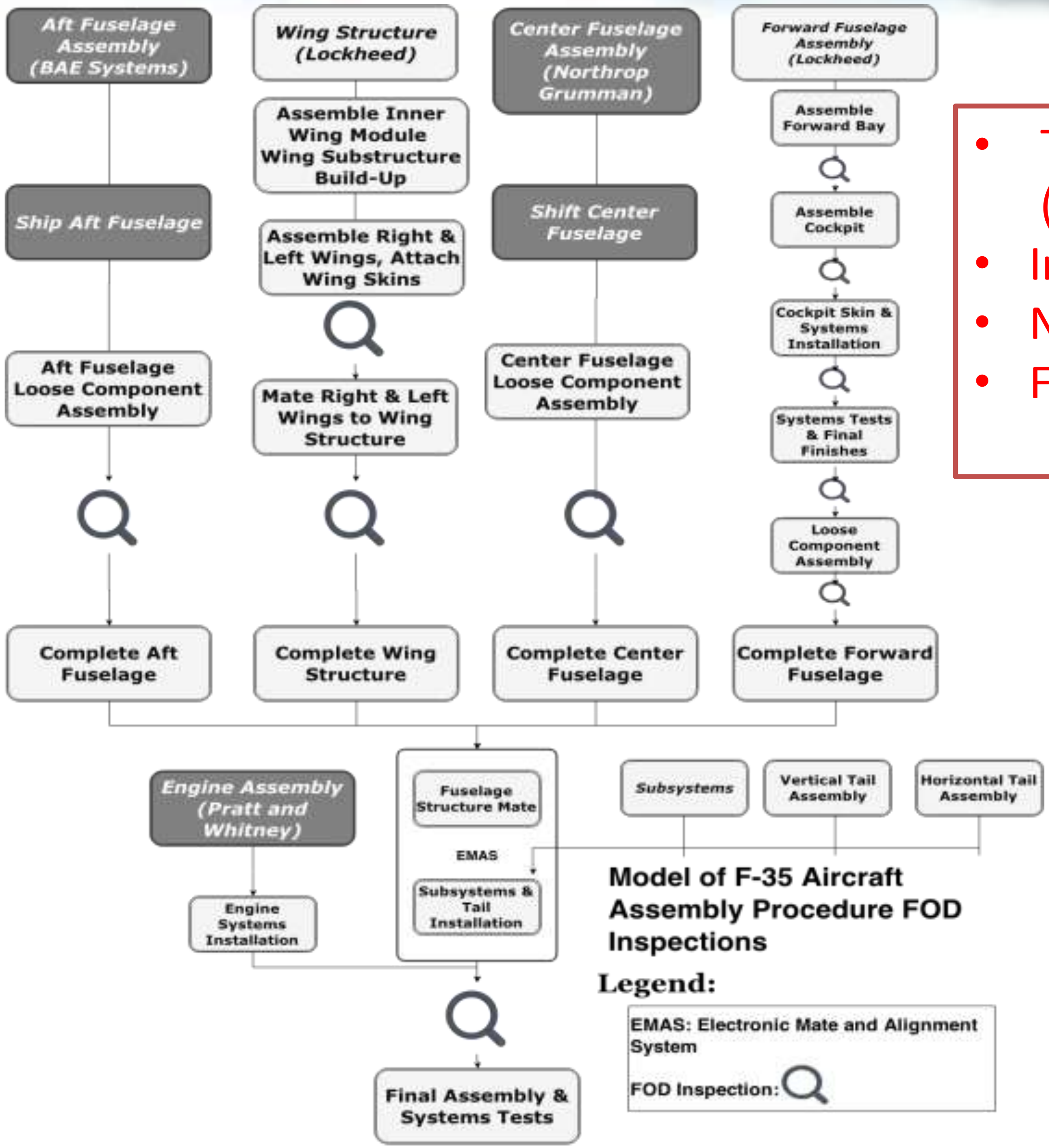
- Tested the Simulation using 4 Validation Tests
  1. Tested Station Process Times – 21 Stations in Series with only one component going from beginning to end with FOD Rate at 0
     - ✓ Test Passed, 130.1253 hours within 3 σ of 126 hours, with σ = 2 hours
  2. Tested FOD Arrival – 21 Stations in Series running continuously for 1 day with FOD Rate at 0.0102
     - ✓ Test Passed, 5.0574 is within 3 σ of 4.40 FOD Arrivals/Day, with σ = 2.959 FOD Arrivals
  3. Tested FOD Arrival – 21 Stations in Series running continuously for 1 day with FOD Rate at 0.183 at one Station and 0 for all others
     - ✓ Test Passed, 4.564 is within 3 σ of 4.40 FOD Arrivals/Day, with σ = 2.959 FOD Arrivals
  4. Tested Rework Time – 21 Stations in Series running continuously for 1 day with FOD Rate at 0.0102, Detection at 100%
     - ✓ Test Passed, 10.817 is within 3 σ of 9.34 Rework Hours/Day, with σ = 34.821 hours

Impact of Detection Errors

- <u>Type I:</u> FOD absent but thought to be present
  - **Manual & FODXSYS:** Assembly Component will be sent to rework station and returned to previous assembly station once it is realized that no FOD is present.

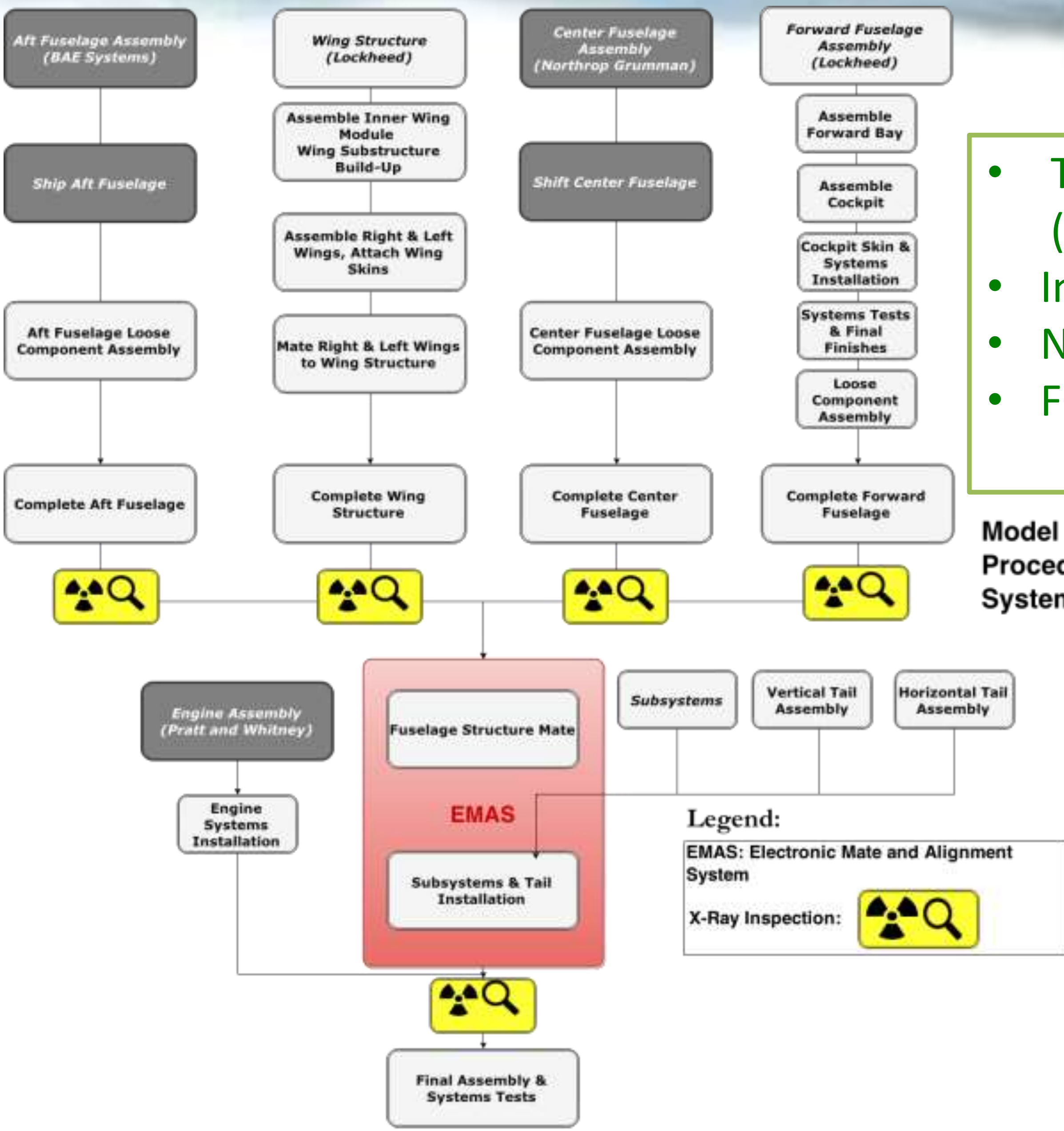
- <u>Type II:</u> FOD present but thought to be absent
  - **Manual:** Compounding **50%** probability of detecting the item based on number of stations following.
  - **FODXSYS:** Individual **95%** probability of inspection at the inspection station following the mating of the assembly components

F-35 Production



- Total Rework & Repair Times (Hours)
- Inspection Times
- Number of Aircraft Produced
- FOD Present Post Assembly

Jet Fighter Production with FODXSYS



- Total Rework & Repair Times (Hours)
- Inspection Times
- Number of Aircraft Produced
- FOD Present Post Assembly

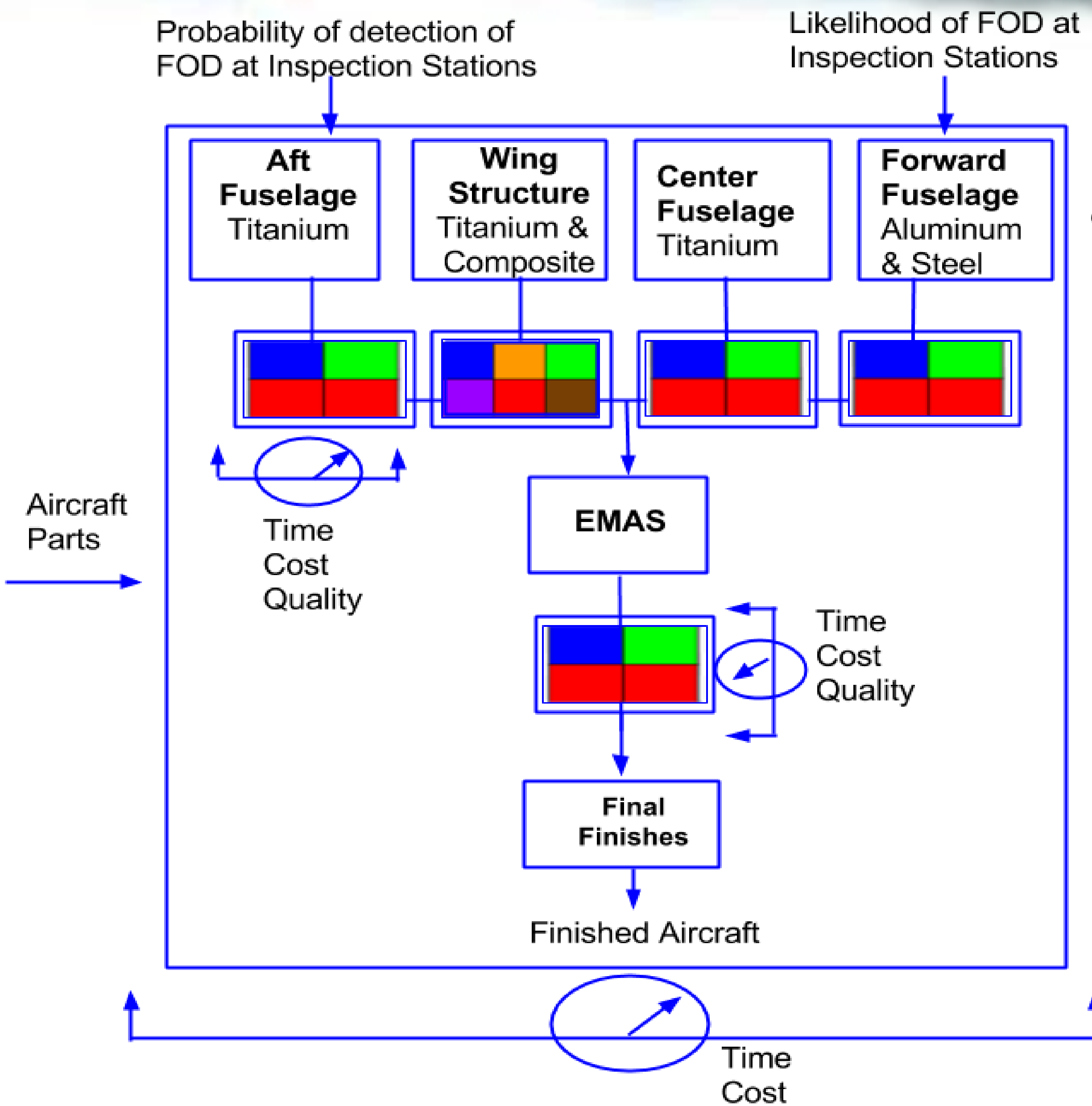
Model of F-35 Aircraft Assembly Procedure Incorporating Proposed System

Differential Imaging – Pseudo Code

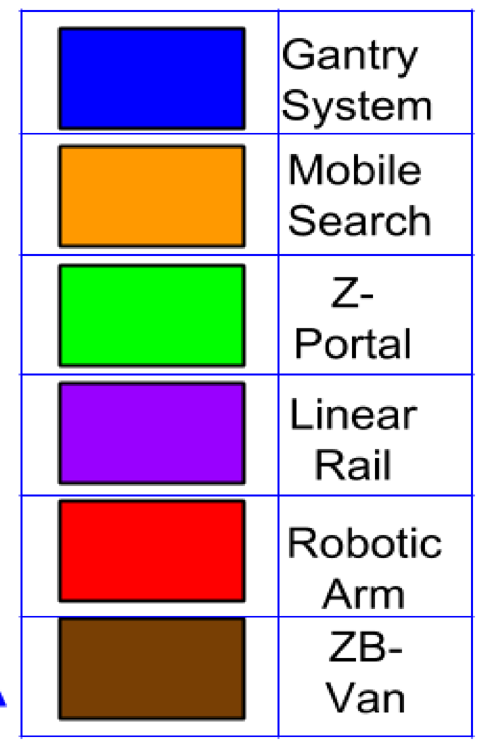
Code	Pseudo Code

<pre>for(int i = 0; i < width; i+= interval) {
    for(int j = 0; j < height; j+= interval) {
        int primaryPx = primary.getRGB(i, j);
        int secondaryPx = secondary.getRGB(i,j);
        int r1 = (primaryPx >> 16);
        int g1 = (primaryPx >> 8) & 0xff;
        int b1 = (primaryPx) & 0xff;
        int r2 = (secondaryPx >> 16);
        int g2 = (secondaryPx >> 8) & 0xff;
        int b2 = (secondaryPx) & 0xff;
 	
        if((Math.abs(r1-r2) + Math.abs(g1-g2) +
                Math.abs(b1-b2))/3.0/255.0 > (10 * difference)) {
 	
            if(++diffCount > 10) {
 	
                if(xStart == 0 && yStart == 0) {
                    xStart = i;
                    yStart = j - 10;
                }
 	
                else {
                    xEnd = i;
                    yEnd = j;
                }
            }
        }
    }
}</pre>
	<pre>offset determined by user
	width = min width of two images
	height = min height of two images
	
	for i = 0 to width, increment by offset
	    for j = 0 to height, increment by offset
	        get RGB value of of primary image pixel at (i,j)
	        get RGB value of secondary image pixel at (i,j)
	
	        totalDiff+= (Math.abs(r1-r2) + Math.abs(g1-g2) + Math.abs(b1-
	        b2))/3.0/255.0;
	    end for
	end for
	
	difference = average difference of the two images
	
	if (difference == 0)
	    return
	
	else
	    for i = 0 to width, increment by offset
	        for j = 0 to height, increment by offset
	            get RGB value of primary image at pixel (i,j)
	            get RGB value of secondary image at pixel (i,j)
	
	            if (pixel difference is > 10 * average difference)
	                if (this is the first difference > 10 * average)
	                    mark xStart and yStart
	                else
	                    mark xEnd and yEnd
	        end for
	    end for
	end else</pre>

Different X-Ray considered per Assembly



- X-Ray Alternative Color will appear if 98% penetration depth requirement is satisfied



Penetration Depth Example

Enhanced Inspection System

1. Differential Imaging
2. X-Ray Component
3. X-Ray Mounting

$$HVL = \frac{0.6328}{\mu}$$

$$P = (thickness)^{HVL}$$

Aircraft Sub-Assembly	Material (Highest Density)	Thickness (inch)
Center Fuselage	Steel	4″

X-Ray Machine	Power (Watt)
Gantry	300

$$\frac{Penetration\ Depth}{Aircraft\ Sub\_Assembly\ Thinckness} = \frac{P}{T} = \frac{3.8}{4} = 95\%$$

SNR and X-Ray Tube Voltage

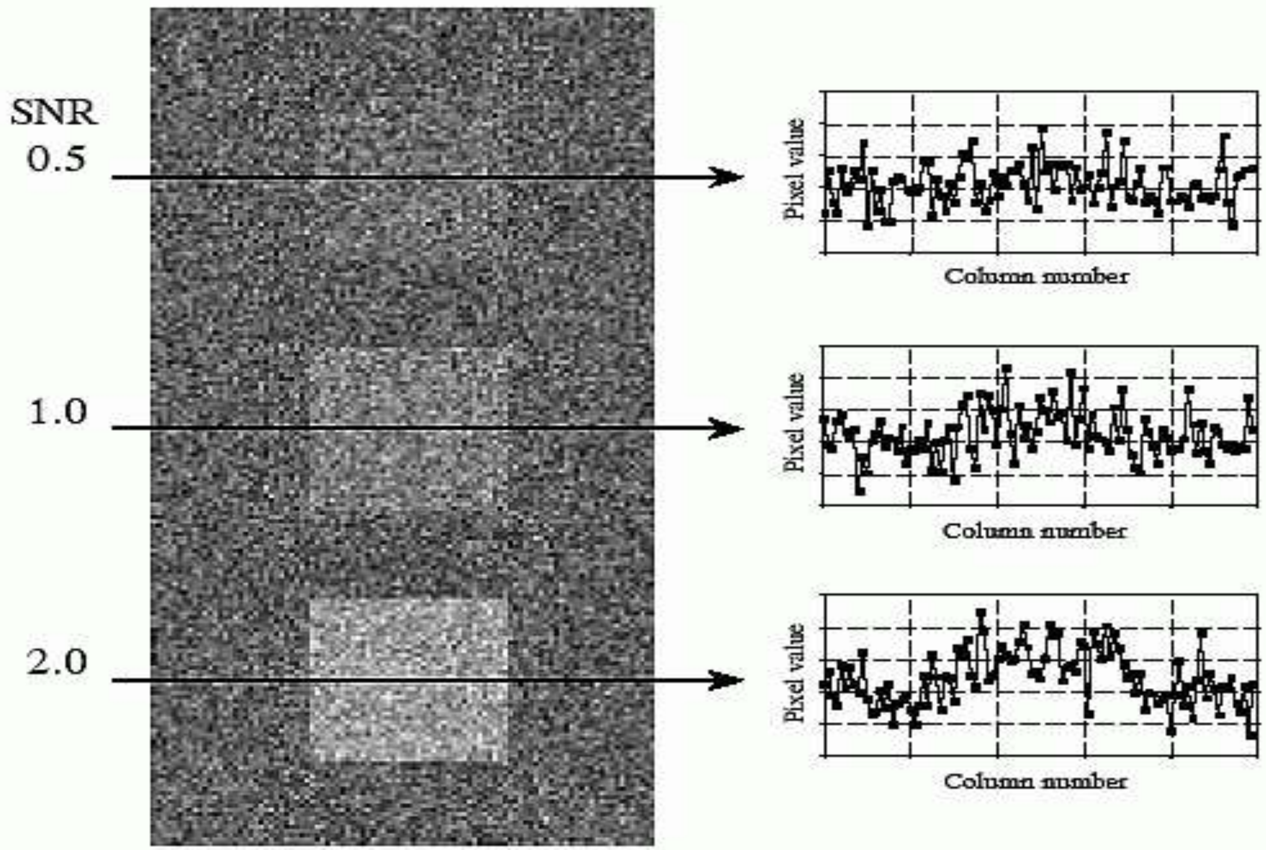


FIGURE 25-8
Minimum detectable SNR. An object is visible in an image only if its contrast is large enough to overcome the random image noise. In this example, the three squares have SNRs of 2.0, 1.0 and 0.5 (where the SNR is defined as the contrast of the object divided by the standard deviation of the noise).

Enhanced Inspection System

1. Differential Imaging
2. X-Ray Component
3. X-Ray Mounting

X-Ray Intensity

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

Signal to Noise Ratio

$$\frac{I_{(s)}\,mean}{\sigma}$$

Alternatives Estimated SNR in Wing and Fuselage

Wing Modulus (Carbon μ=0.02)

X-Ray Alternative	Mean Intensity (Is)	Signal to Noise Ration (SNR)
Ganntry,MobileSearch,Linear Rail, Robotic Arms	23.37287	3.338981

SNR >1

Wing Modulus (Aluminum, μ=0.05)

X-Ray Alternative	Mean Intensity (Is)	Signal to Noise Ration (SNR)
Ganntry,MobileSearch,Linear Rail, Robotic Arms	16.69936	2.385622

SNR >1

Fuselage (Carbon μ=0.02)

X-Ray Alternative	Mean Intensity (Is)	Signal to Noise Ration (SNR)
Gantry,MobileSearch,Linear Rail, Robotic Arms	18.77461	2.682088

SNR >1

Fuselage (Aluminum, μ=0.05)

X-Ray Alternative	Mean Intensity (Is)	Signal to Noise Ratio (SNR)
Gantry,RoboticArm,MobileSearch,Linear Rail,	10.7419	1.534557

SNR >1

System Pass Minimum Detectability Requirement

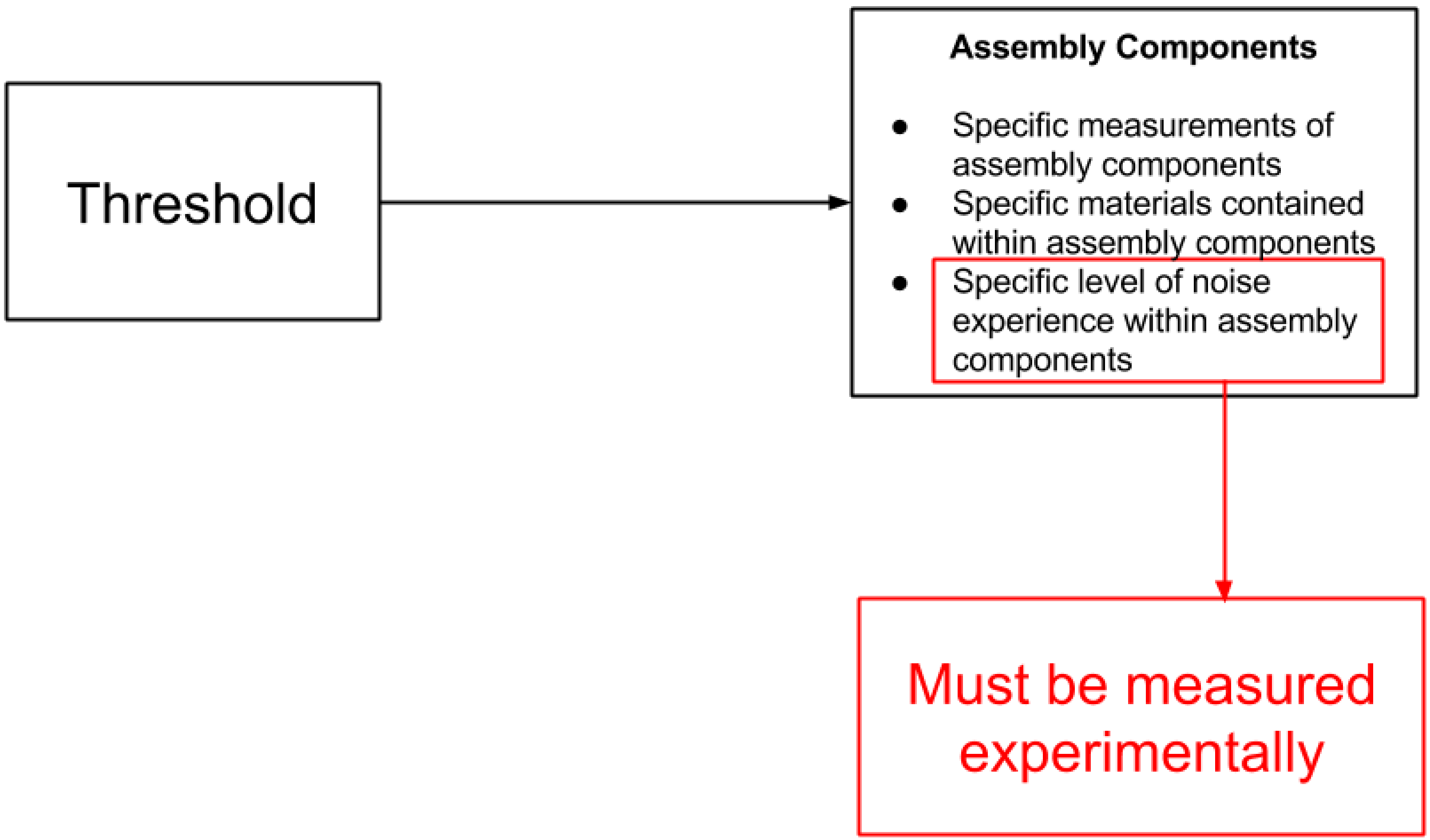
Enhanced Inspection System

1. Differential Imaging
2. X-Ray Component
3. X-Ray Mounting

Robotic Arm SNR Calculation

X-Ray alternative	x-ray tube voltage(kv)	distance to Object(mm)	Mean x-ray backscatter intensity(I)	Standard deviation Of noise	SNR
Robotic Arm	225	20	320	7	6.53

Signal To Noise Ratio

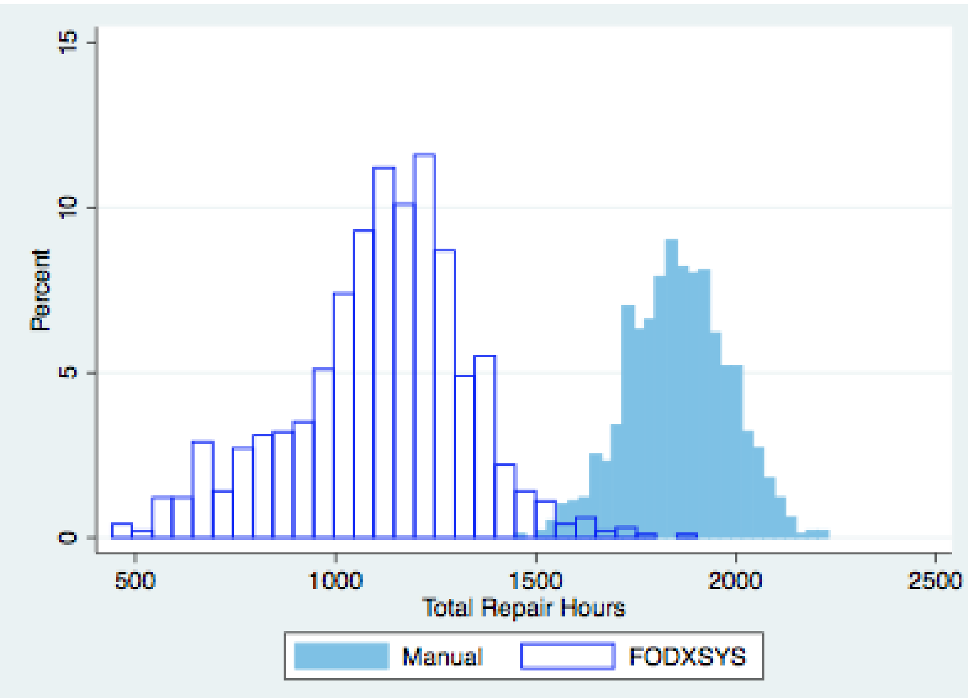


Results Summary

FODSIM RESULTS ---------------------------- ALTERNATIVE MEANS:	AVERAGE REPAIR (HOURS) ($\bar{x}$, σ)	AVERAGE QUEUE WAIT (HOURS) ($\bar{x}$, σ)	AIRCRAFT WITH FOD ON DELIVERY (# AIRCRAFT) ($\bar{x}$, σ)
MANUAL	**1856 , 124**	**6.60 , 5.50**	**2.4 , 1.11**
FODXSYS	**1111 , 220.26**	**26.9 , 6.68**	**0.3 , 0.42**

FODSIM RESULTS ---------------------------- ALTERNATIVE MEANS:	AVERAGE AIRCRAFT ASSEMBLED (# OF AIRCRAFT) ($\bar{x}$, σ)	AVERAGE INSPECTION TIME PER STATION (HOURS) ($\bar{x}$, σ)	AVERAGE TOTAL LABOR / AIRCRAFT ASEEMBLED ($\bar{x}$, σ)
MANUAL	**36 , 2.7**	**1041 , 30.4**	**1780 , 138**
FODXSYS	**41 , 3.1**	**208 , 30.0**	**1020 , 77.8**

Total Repair Hours Dist.

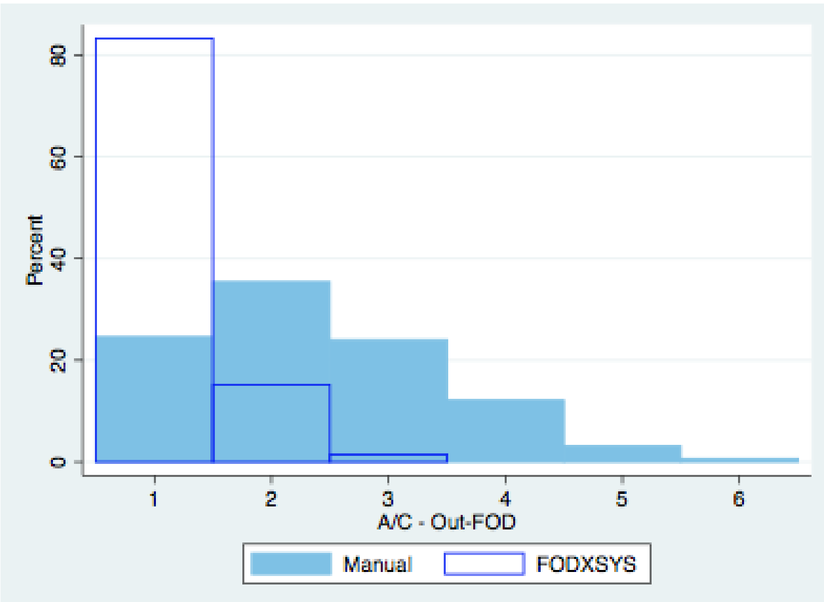



```
. ttest TotalRepairHours , by(Dummy) unequal

Two-sample t test with unequal variances
------------------------------------------------------------------------------
   Group |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
       0 |    1000    1856.014    3.921163    123.9981    1848.319    1863.709
       1 |    1000    1111.299    6.965323    220.2629    1097.631    1124.968
---------+--------------------------------------------------------------------
combined |    2000    1483.657    9.237125    413.0968    1465.541    1501.772
---------+--------------------------------------------------------------------
    diff |            744.7146      7.9932                729.0362     760.393
------------------------------------------------------------------------------
    diff = mean(0) - mean(1)                                      t =  93.1685
Ho: diff = 0                     Satterthwaite's degrees of freedom =  1574.41

    Ha: diff < 0                 Ha: diff != 0                 Ha: diff > 0
 Pr(T < t) = 1.0000         Pr(|T| > |t|) = 0.0000          Pr(T > t) = 0.0000
```

Aircraft Assembled Containing FOD Dist.

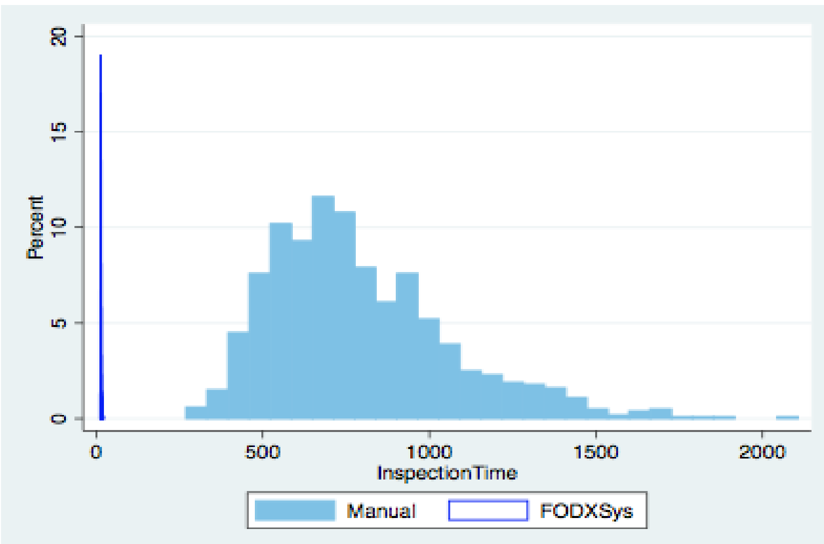



```
. ttest ACOutFOD , by(Dummy) unequal

Two-sample t test with unequal variances
------------------------------------------------------------------------------
   Group |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
       0 |    1000       2.359    .0351761    1.112365    2.289973    2.428027
       1 |    1000       1.182    .0133811     .423149    1.155742    1.208258
---------+--------------------------------------------------------------------
combined |    2000      1.7705    .0229604    1.026819    1.725471    1.815529
---------+--------------------------------------------------------------------
    diff |               1.177    .0376352                1.103167    1.250833
------------------------------------------------------------------------------
    diff = mean(0) - mean(1)                                      t =  31.2739
Ho: diff = 0                     Satterthwaite's degrees of freedom =   1282.2

    Ha: diff < 0                 Ha: diff != 0                 Ha: diff > 0
 Pr(T < t) = 1.0000         Pr(|T| > |t|) = 0.0000          Pr(T > t) = 0.0000
```

Inspection Hours Dist.

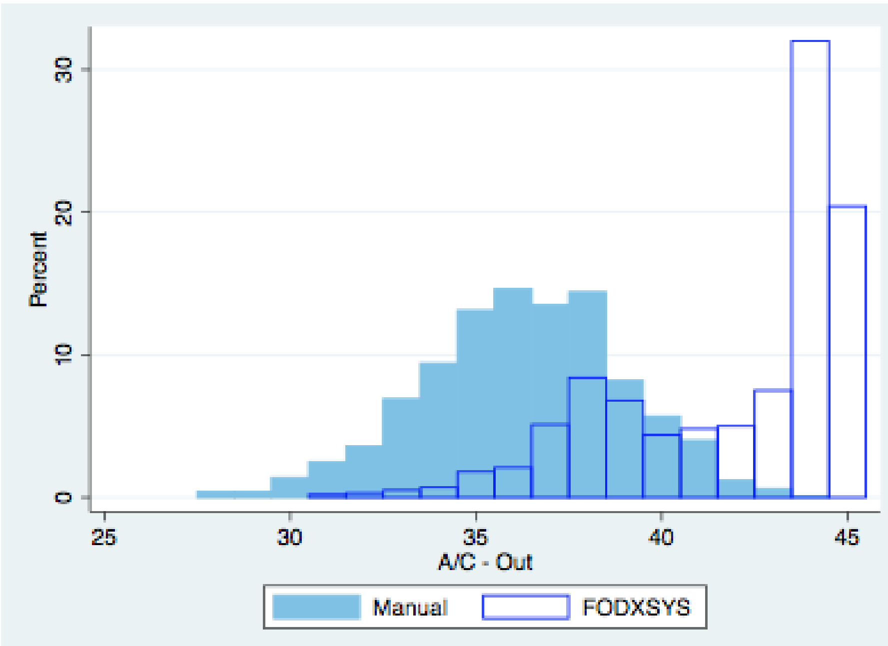



```
. ttest InspectionHours , by(Dummy) unequal

Two-sample t test with unequal variances
------------------------------------------------------------------------------
   Group |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
       0 |    1000    28114.16    26.00748    822.4289    28063.12    28165.19
       1 |    1000     208.269    .9499945    30.04146    206.4048    210.1332
---------+--------------------------------------------------------------------
combined |    2000    14161.21    312.3464    13968.55    13548.65    14773.77
---------+--------------------------------------------------------------------
    diff |            27905.89    26.02483                27854.82    27956.96
------------------------------------------------------------------------------
    diff = mean(0) - mean(1)                                      t =  1.1e+03
Ho: diff = 0                     Satterthwaite's degrees of freedom =  1001.67

    Ha: diff < 0                 Ha: diff != 0                 Ha: diff > 0
 Pr(T < t) = 1.0000         Pr(|T| > |t|) = 0.0000          Pr(T > t) = 0.0000
```

Aircraft Assembled Dist.

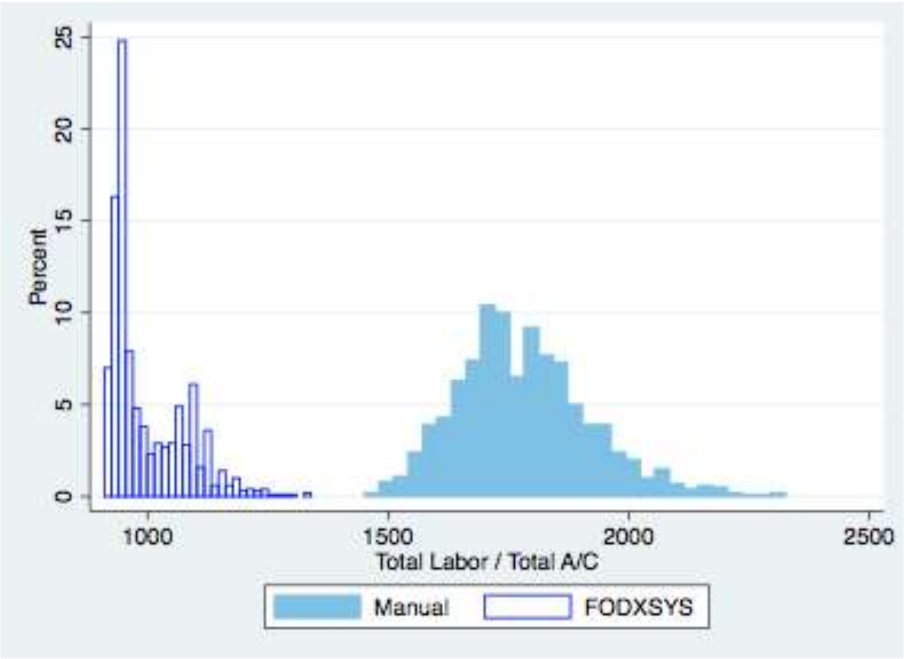



```
. ttest ACOut , by(Dummy) unequal

Two-sample t test with unequal variances
------------------------------------------------------------------------------
   Group |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
       0 |    1000       36.28    .0858194    2.713847    36.11159    36.44841
       1 |    1000      41.991    .0984307    3.112653    41.79785    42.18415
---------+--------------------------------------------------------------------
combined |    2000     39.1355    .0913249    4.084174     38.9564     39.3146
---------+--------------------------------------------------------------------
    diff |             -5.711    .1305893               -5.967108   -5.454892
------------------------------------------------------------------------------
    diff = mean(0) - mean(1)                                      t = -43.7325
Ho: diff = 0                     Satterthwaite's degrees of freedom =  1961.58

    Ha: diff < 0                 Ha: diff != 0                 Ha: diff > 0
 Pr(T < t) = 0.0000         Pr(|T| > |t|) = 0.0000          Pr(T > t) = 1.0000
```

Total Labor Hours/AC Dist.




```
. ttest TotalLaborTotalAC , by(Dummy) unequal

Two-sample t test with unequal variances
```

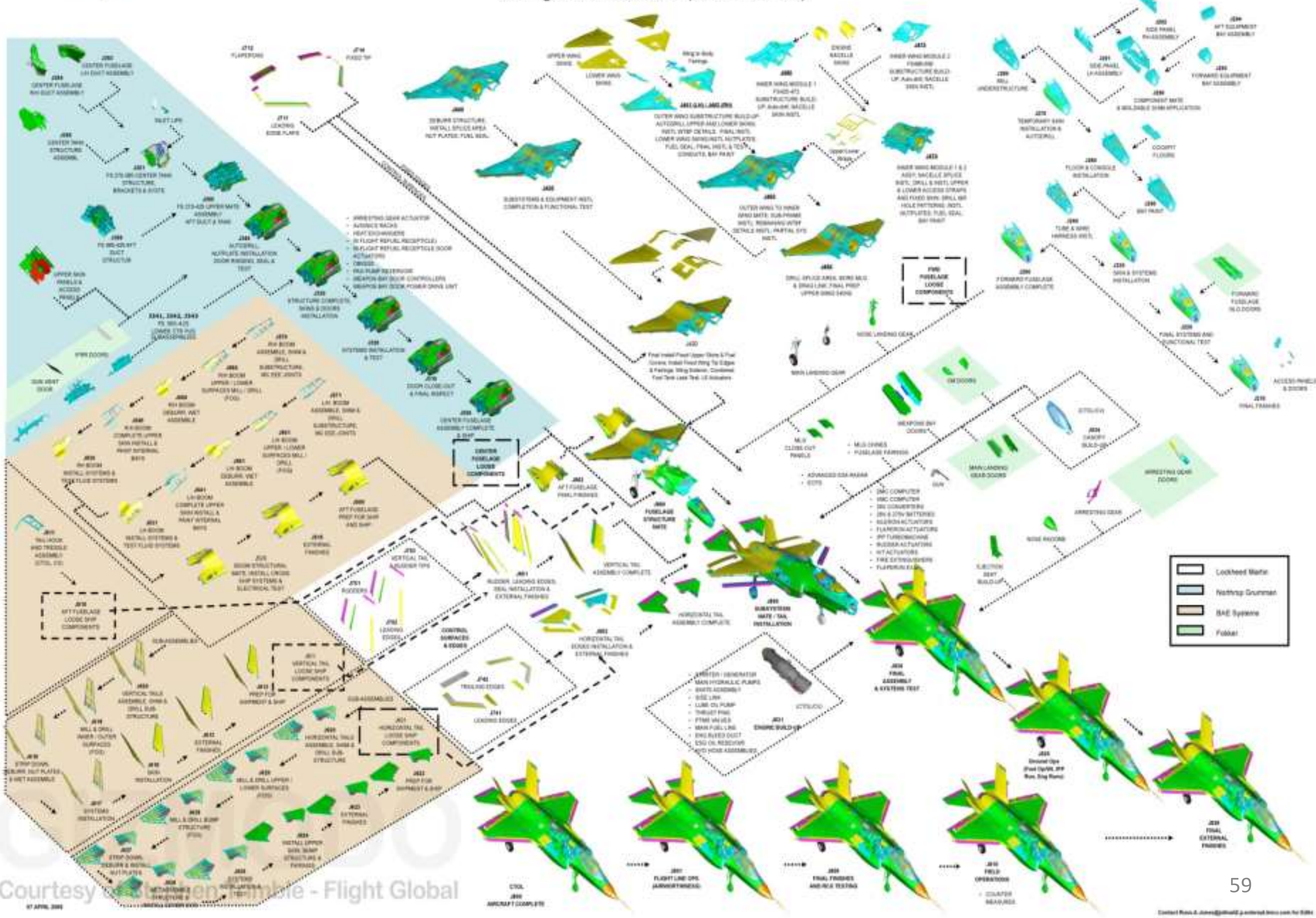
Group	Obs	Mean	Std. Err.	Std. Dev.	[95% Conf.	Interval]
0	1000	1781.483	4.391462	138.8702	1772.866	1790.101
1	1000	997.8388	2.459183	77.7662	993.013	1002.665
combined	2000	1389.661	9.117604	407.7517	1371.78	1407.542
diff		783.6445	5.033142		773.7721	793.5169

```
    diff = mean(0) - mean(1)                                      t = 155.6969
Ho: diff = 0                     Satterthwaite's degrees of freedom =  1569.46

    Ha: diff < 0                 Ha: diff != 0                 Ha: diff > 0
 Pr(T < t) = 1.0000         Pr(|T| > |t|) = 0.0000          Pr(T > t) = 0.0000
```

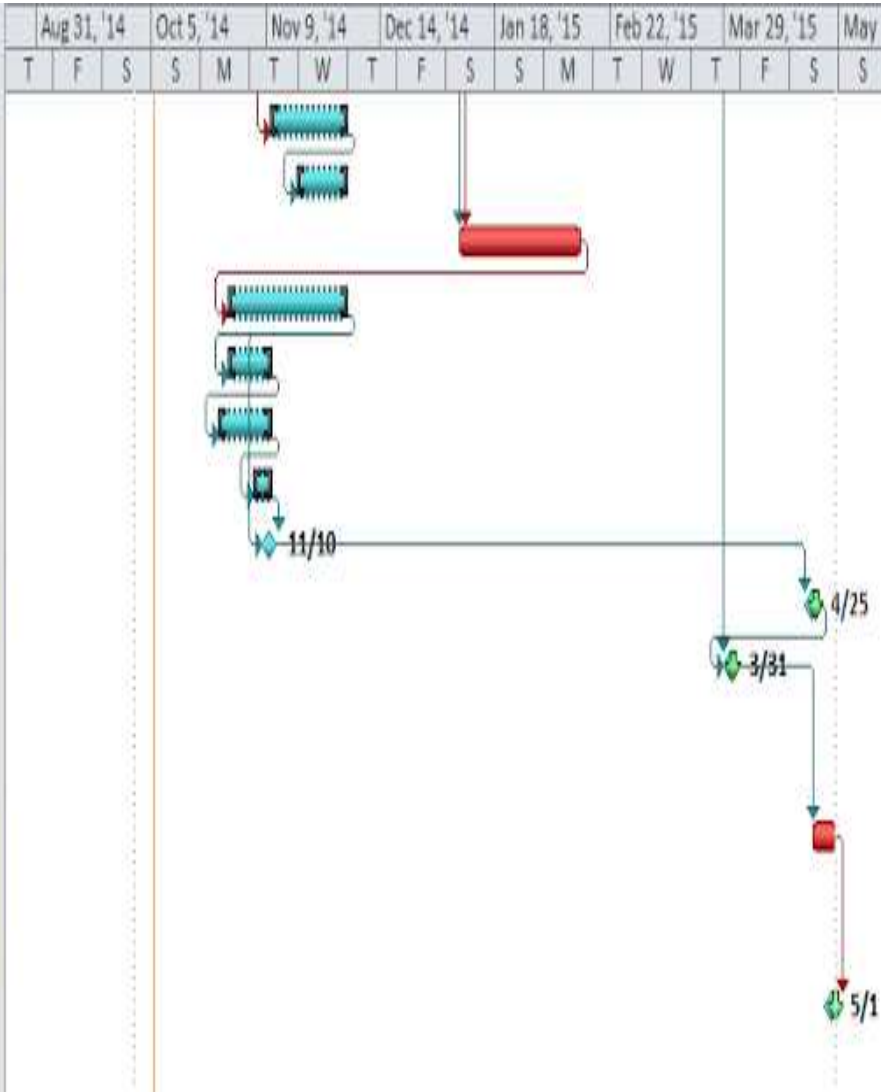
CTOL SWBS MANUFACTURING SEQUENCE FLOW

Configuration 240A-4.7 (2AF:1 and On)



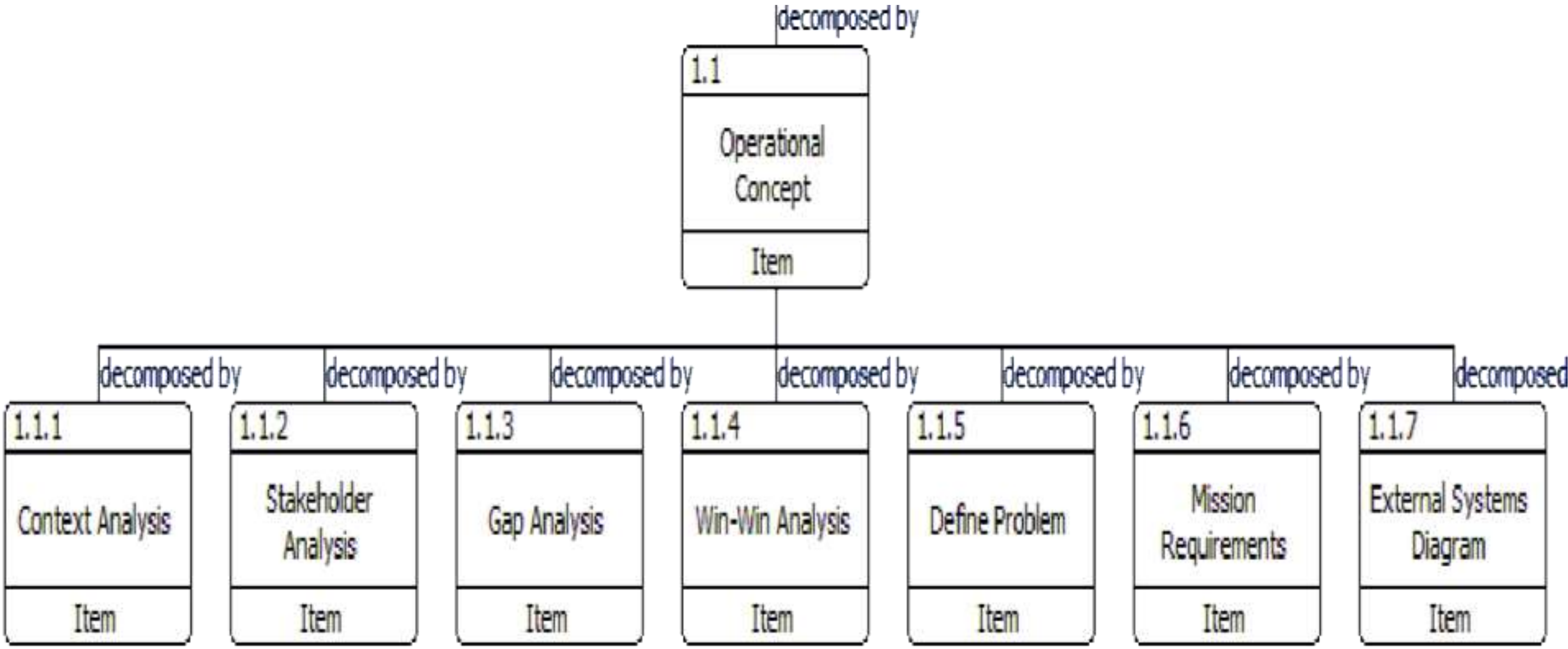
Project Timeline & Critical Path

	Task Name	Duration	Start	Finish	Predecessors	Successors
47	Finalize Final Presentation	18 days	Mon 11/10/14	Wed 12/3/14	46	48
48	Proposal Final Presentation Due	12 days	Tue 11/18/14	Wed 12/3/14	47	
49	Draft Conference Paper Due	27 days	Wed 1/7/15	Thu 2/12/15	45,46	50
50	Draft Poster Due	27 days	Tue 10/28/14	Wed 12/3/14	49	51,54
51	SIEDS Conference Rehersal	10 days	Tue 10/28/14	Mon 11/10/14	50	52
52	SIEDS Abstract Draft	12 days	Sat 10/25/14	Mon 11/10/14	51	53
53	Finalize SIEDS Abstract	4 days	Wed 11/5/14	Mon 11/10/14	52	54
54	SIEDS Abstract Submission	0 days	Mon 11/10/14	Mon 11/10/14	50,53	55
55	SIEDS Conference	0 days	Sat 4/25/15	Sat 4/25/15	54	56
56	General Donald R. Keith Memorial Cadet Capstone Conference Registration	0 days	Tue 3/31/15	Tue 3/31/15	29,39,42,55	57
57	General Donald R. Keith Memorial Cadet Capstone Conference Draft Presentation	6 days	Sat 4/25/15	Fri 5/1/15	56	58
58	General Donald R. Keith Memorial Cadet Capstone Conference	0 days	Fri 5/1/15	Fri 5/1/15	57	



Critical Tasks	Foreseeable Risks	Mitigation Routes
1.Define Requirements	1a. Receiving definitive feedback from Lockheed Martin 1b. Verification of specific requirements from lack of quantitative data.	1a: Define requirements based on the capabilities of the system with correlation to the goals and objectives of Lockheed Martin 1b. Use "dummy variables" in simulation and verify requirements based on output
2. Times for Production Stages	2a. Data not received from LMCO in sufficient time	2a. Ask for average times per stage from Lockheed Martin and apply a random number generator as a multiplier to obtain multiple data points
3. Times for FOD Inspection	3a. Data not received from LMCO in sufficient time	3a. Ask for average FOD inspection times per stages or position 3aa. Establish a percentage of time per shift spent searching and apply this to the simulation
4.Retrieve Costs of Different X-RAY System Alternatives	4. Failure to receive data from X-RAY vendors.	4a. Estimate costs from available research
5. Establishing Distributions of discrete events	5a. Dependent upon receiving data in a timely fashion	5a: Establishing "dummy variables" will enable our team to run multiple simulations, graph the output and establish these distributions 5aa. Obtaining these averages from Lockheed Martin

WBS 1.1



decomposed by
1.1
Operational Concept
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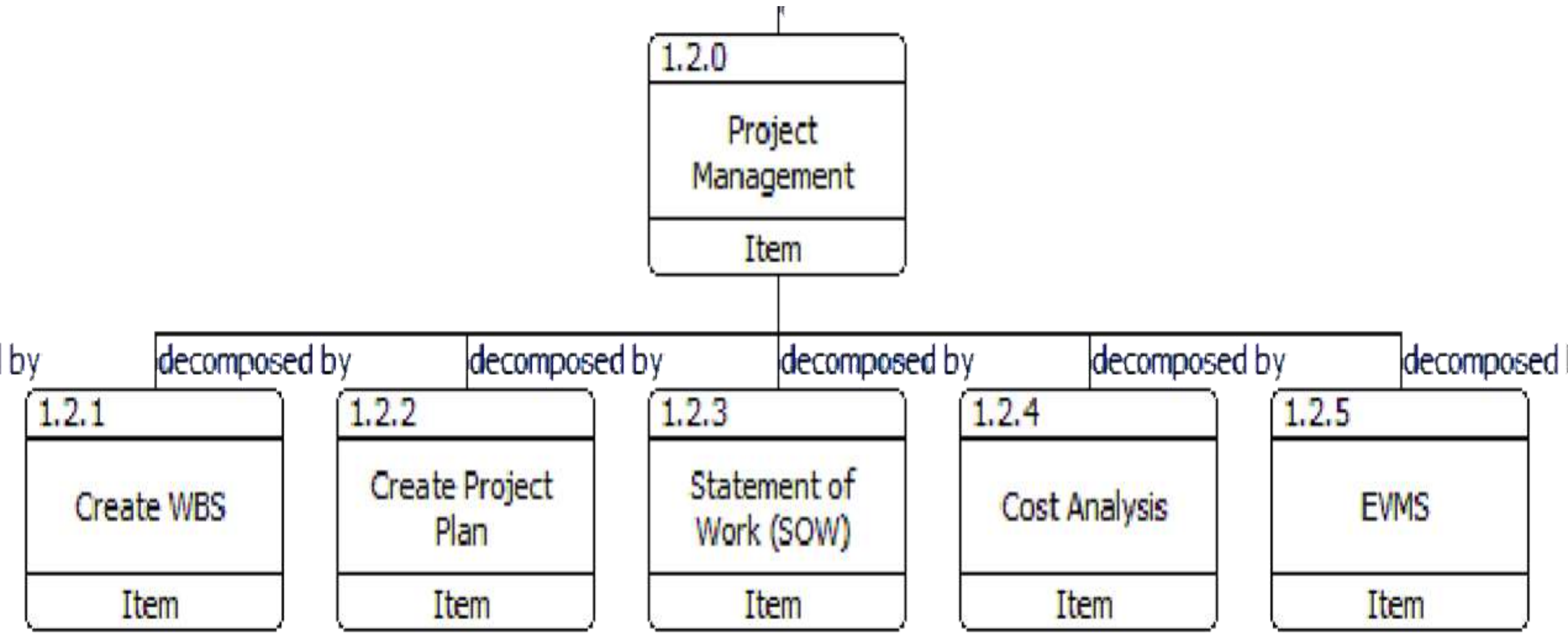
1.1.1
Context Analysis
Item
1.1.2
Stakeholder Analysis
Item
1.1.3
Gap Analysis
Item
1.1.4
Win-Win Analysis
Item
1.1.5
Define Problem
Item
1.1.6
Mission Requirements
Item
1.1.7
External Systems Diagram
Item

WBS 1.2



1.2.0
Project Management
Item
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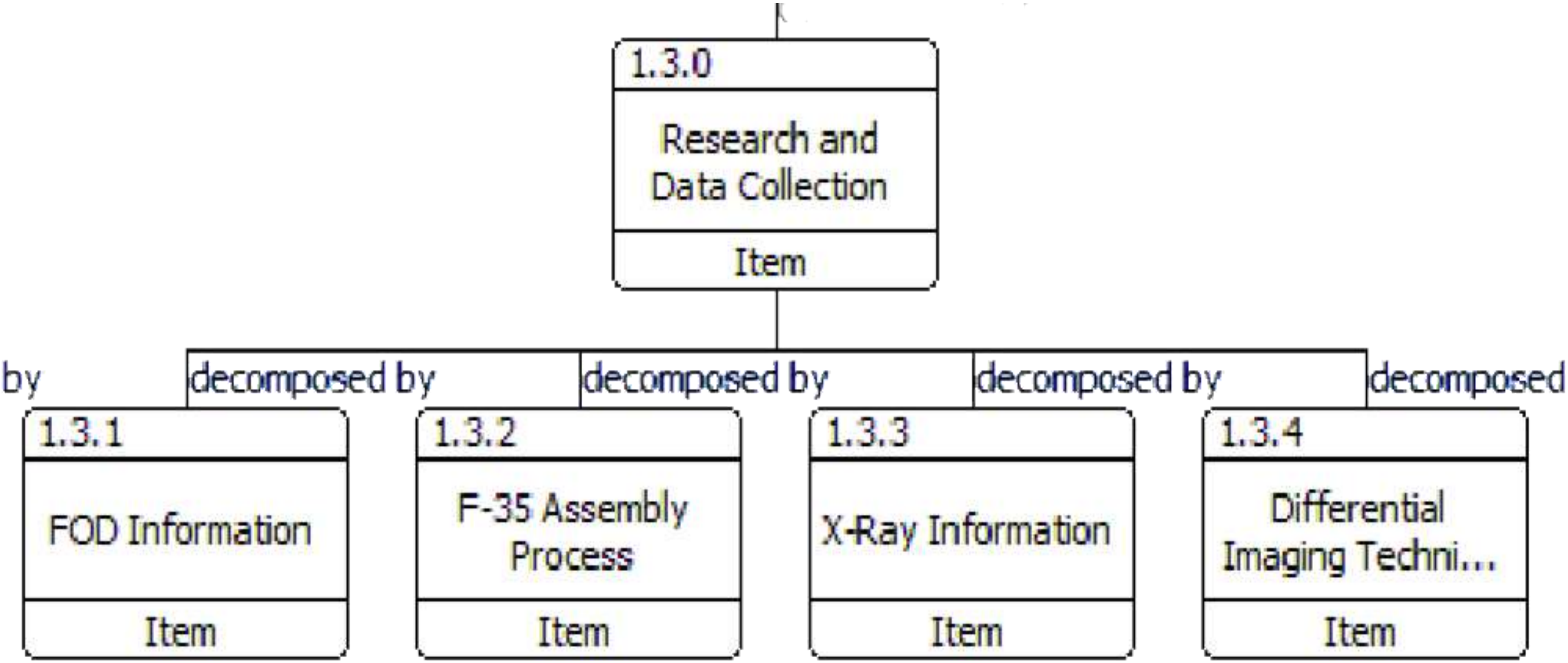
decomposed by
decomposed by
decomposed by
1.2.1
Create WBS
Item
1.2.2
Create Project Plan
Item
1.2.3
Statement of Work (SOW)
Item
1.2.4
Cost Analysis
Item
1.2.5
EVMS
Item

WBS 1.3



1.3.0
Research and Data Collection
Item
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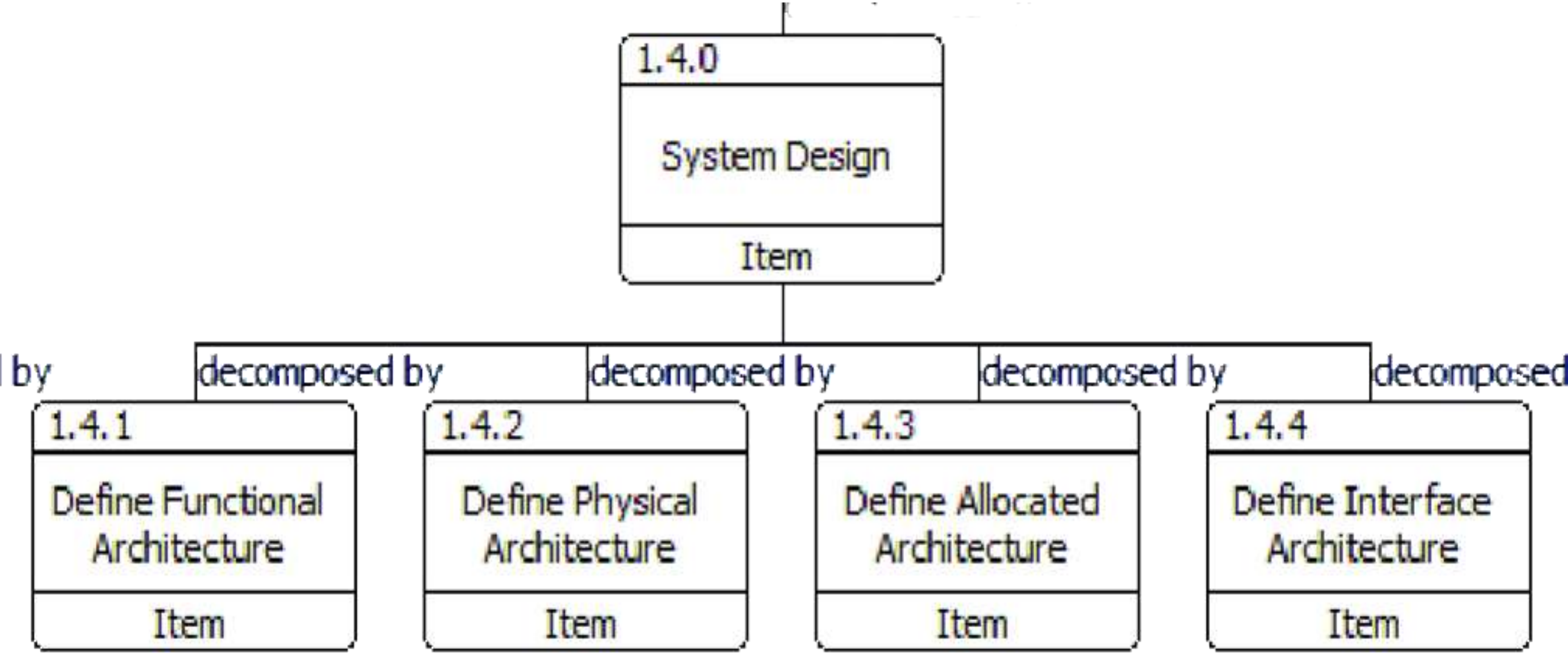
decomposed by
decomposed by
decomposed
by
1.3.1
FOD Information
Item
1.3.2
F-35 Assembly Process
Item
1.3.3
X-Ray Information
Item
1.3.4
Differential Imaging Techni...
Item

WBS 1.4


1.4.0
System Design
Item
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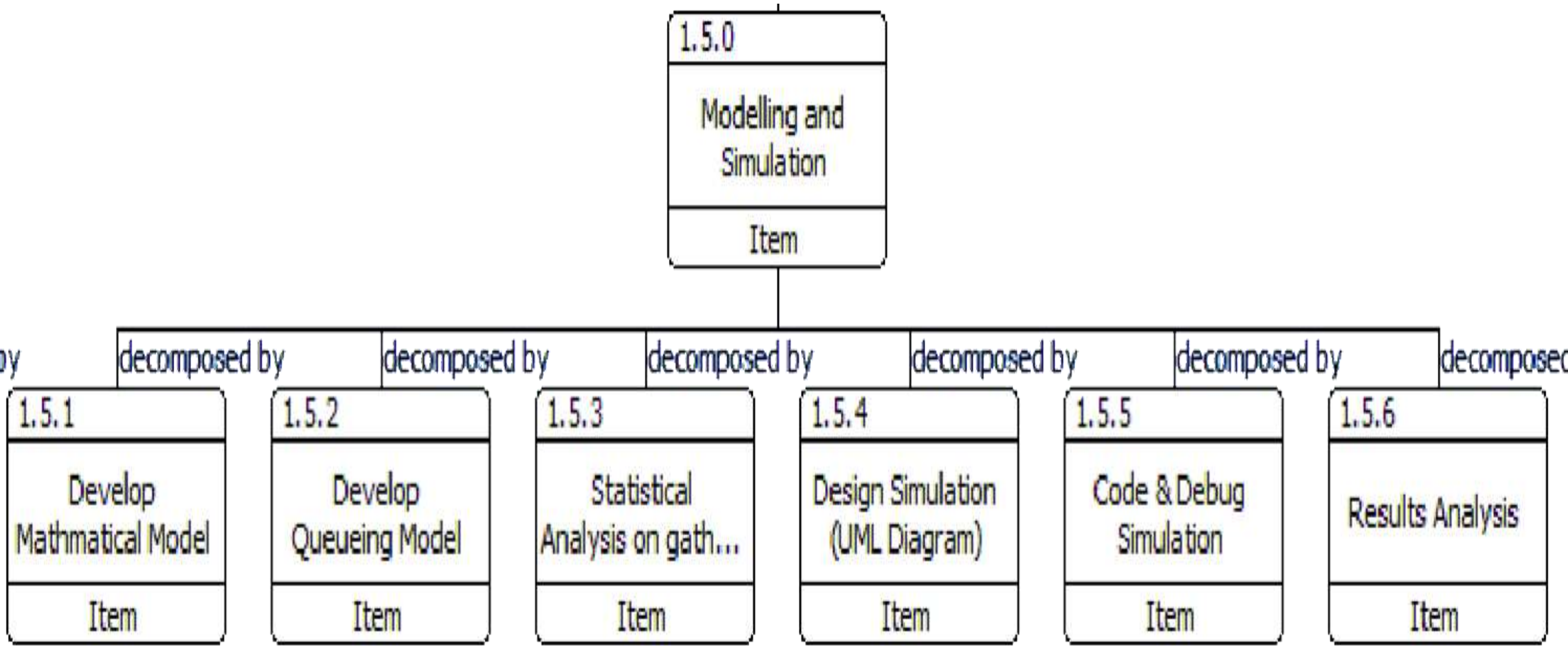
decomposed by
decomposed by
decomposed by
1.4.1
Define Functional Architecture
Item
1.4.2
Define Physical Architecture
Item
1.4.3
Define Allocated Architecture
Item
1.4.4
Define Interface Architecture
Item

WBS 1.5


1.5.0
Modelling and Simulation
Item
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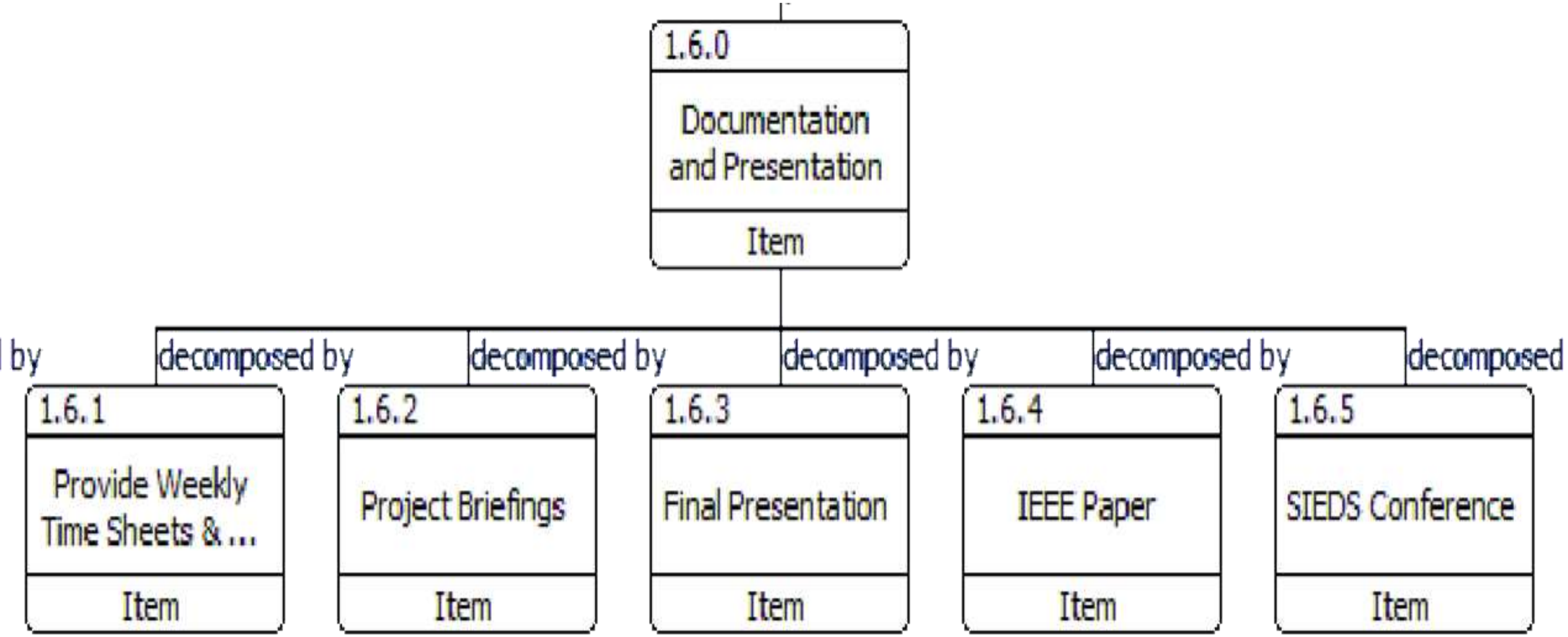
1.5.1
Develop Mathmatical Model
Item
1.5.2
Develop Queueing Model
Item
1.5.3
Statistical Analysis on gath...
Item
1.5.4
Design Simulation (UML Diagram)
Item
1.5.5
Code & Debug Simulation
Item
1.5.6
Results Analysis
Item

WBS 1.6


1.6.0
Documentation and Presentation
Item
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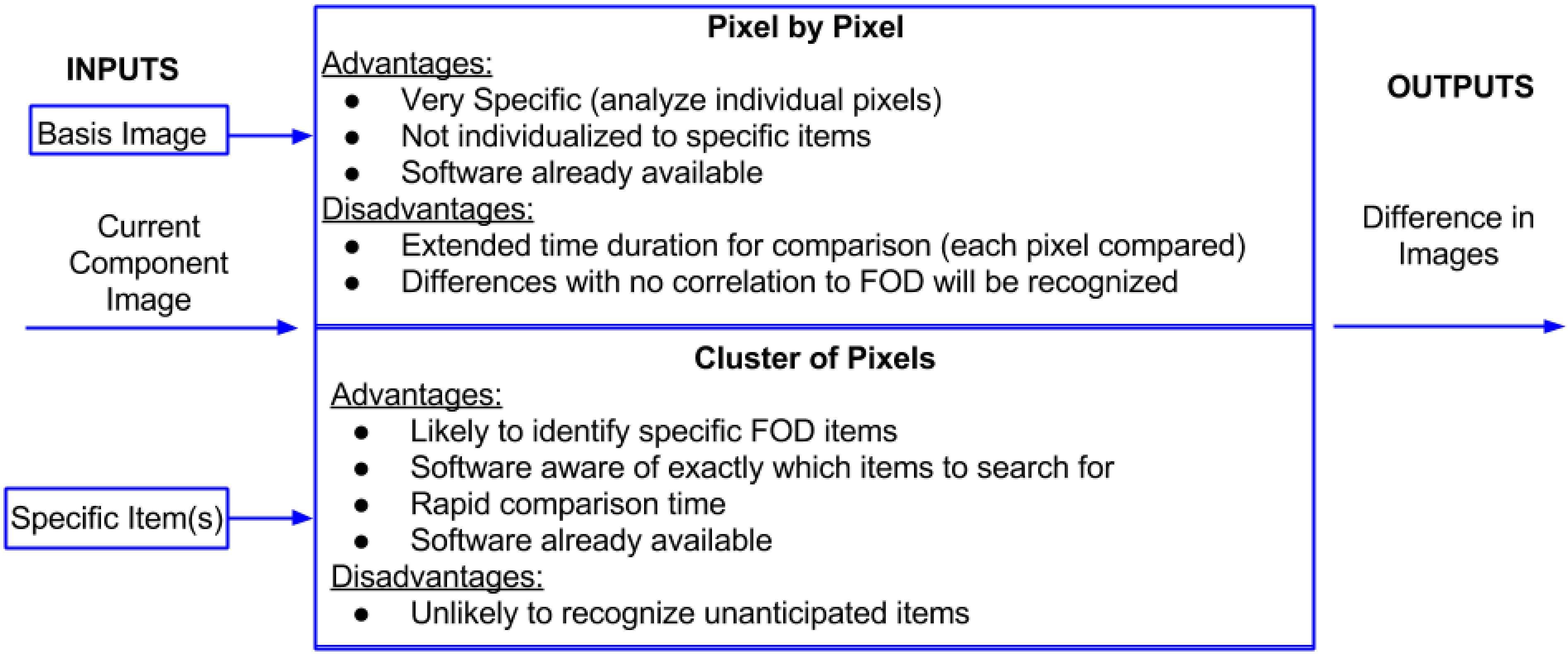
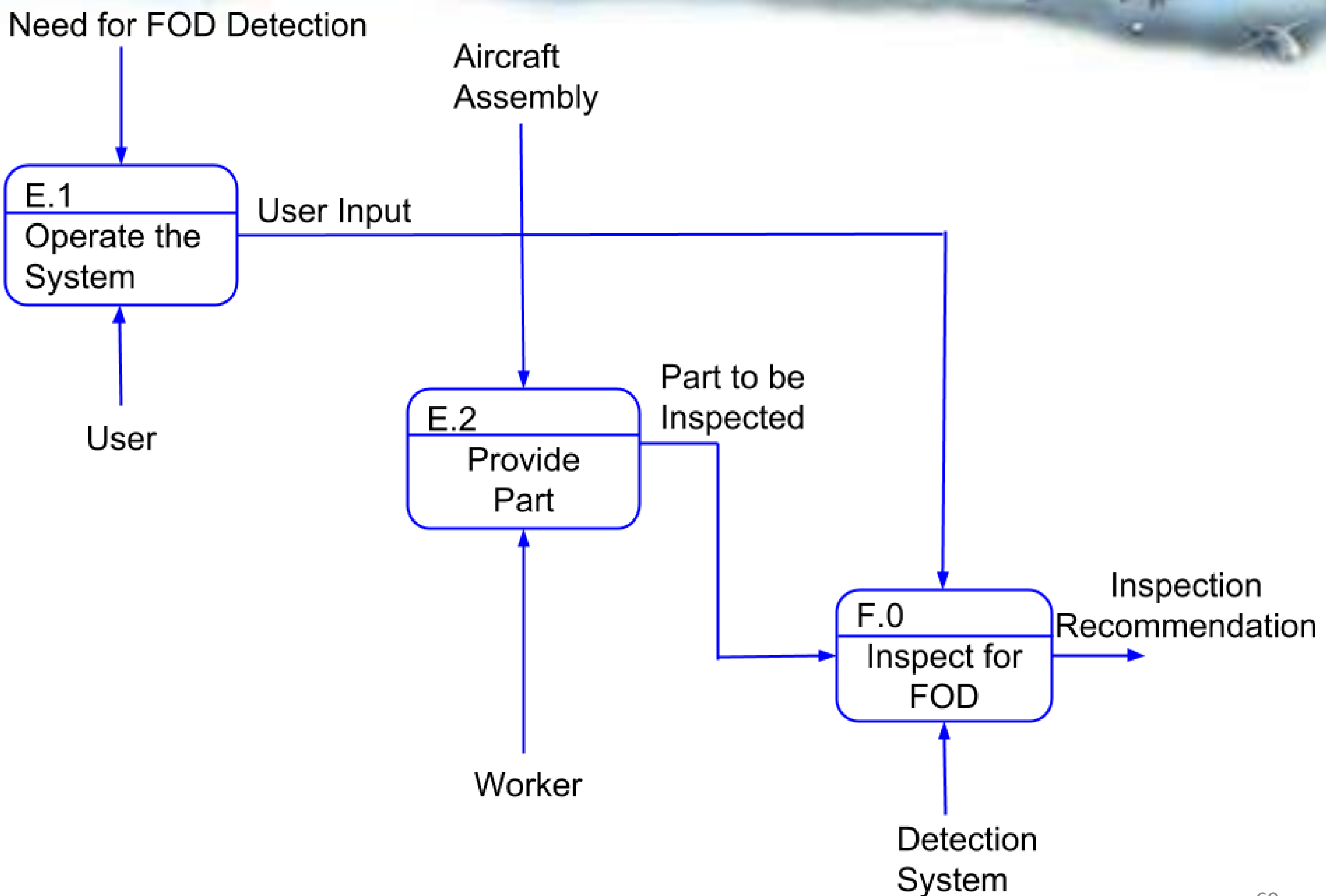
1.6.1
Provide Weekly Time Sheets & ...
Item
1.6.2
Project Briefings
Item
1.6.3
Final Presentation
Item
1.6.4
IEEE Paper
Item
1.6.5
SIEDS Conference
Item

Alternate Differential Imaging

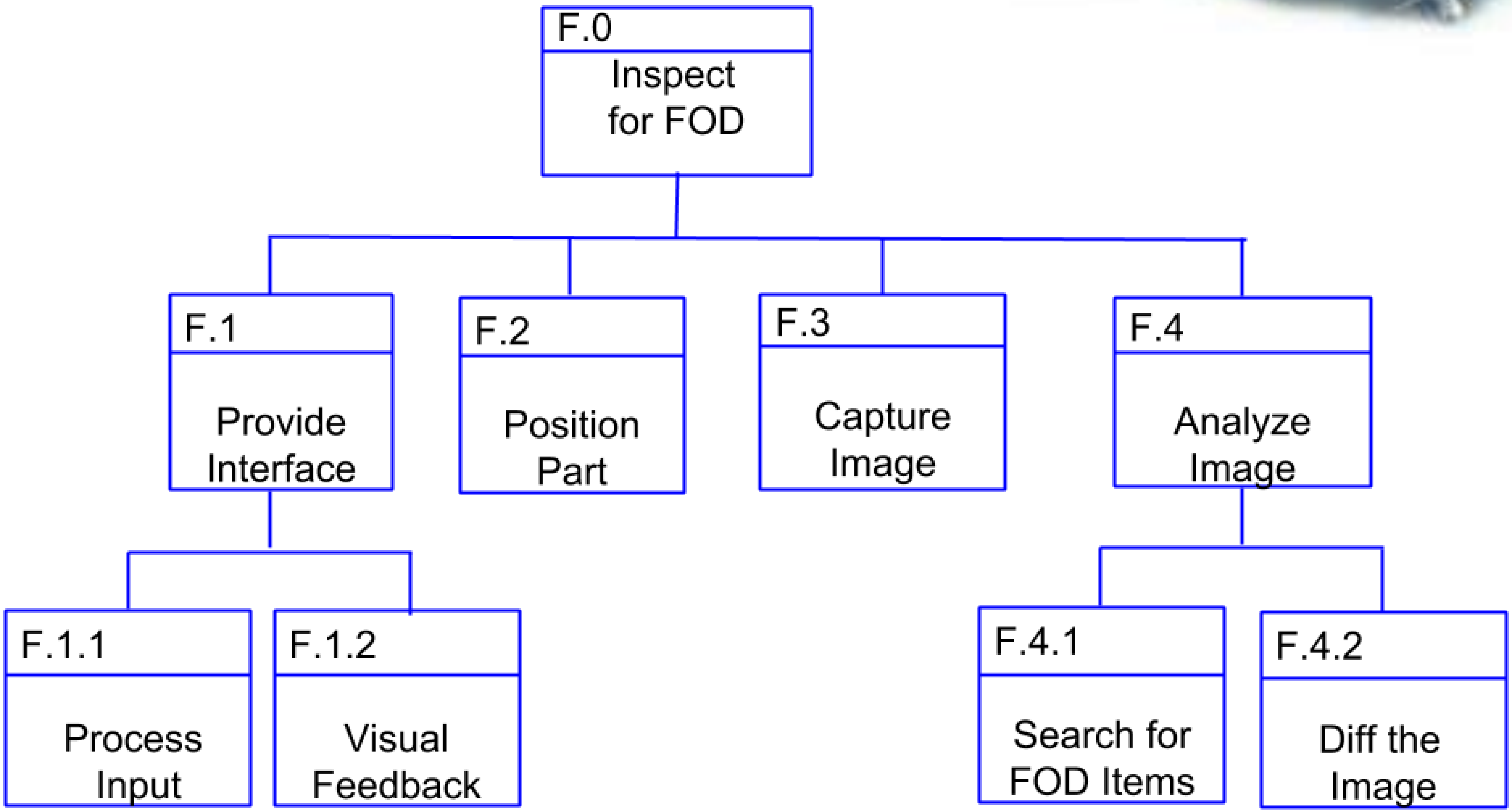


Differential Imaging provides the operator with a means of assistance in identifying the FOD items after the Aircraft Components have been scanned and the images are being compared.

External Systems Diagram



FODXSYS Functional Architecture



Problem & Need

Problem

Manual Inspection Process →

Issues	Consequences
Limited to top layer visibility	Increased Production Cost
Possibility of Human Error	Possibility of FOD related pilot casualties
Manual inspection is not time effective	Decreased Production Rate Deadline Issues
Increased Rework & Repair Hours as a result of inspection reliability	Increased Rework & Repair Costs

Need

Enhanced Inspection Process →

Solutions	Benefits
Multi-layer visibility capability	Detect FOD hidden within layers
Eliminate possibility of Human Error	Decreased chance of Aircraft delivery containing FOD
Decrease FOD Inspection time	Decreased Inspection Costs
Increased Probability of Detection	Decreased FOD related Rework & Repair Costs