SYST 495

Project

Final Report

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

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1.1 Fighter Jet Production Process

Fighter and Attack aircraft are the most exciting machines in the sphere of military power because of their design, speed, and weaponry. The diversity of its category, their evolution through military history, and the modern race to produce the most advanced and lethal fighter and attack aircraft yield a great deal of information and generates more interest than any other category of military aircraft.

In the early 1900s, the airplane emerged, serving as a vital inspection tool during WWI since it was realized to protect the skies over the battlefields. It wasn't until WWII that the fighter aircraft began reaching a level of refinement recognized in today's fighter and attack aircraft. Improved aerodynamics, the monoplane design, engine performance, weapons accuracy and destructive force, and survivability became design factors that worked in tandem to determine an aircraft's effectiveness. Also in this war, fighter aircraft's role varied. The roles of defending the skies from attacking strategic bombers and bomber escort into enemy territory both yielded numerous epic air-to-air confrontations. The role of ground attack of strategic targets and enemy infantry became prominent as well. Furthermore, naval fleet attack and defense by carrier-borne aircraft proved how a country's military could be projected globally (“Combat”).

Today, this category of aircraft is dominated by manufactures in America, Russia, and joint ventures coming out of Europe. As the emphasis appears to be moving toward flexibility of the platform to both protect the skies and eliminate targets on the ground, the multi-role fighter aircraft is being given the most significant attention at this time. The production of these aircrafts with flexibility roles, which can perform multiple tasks with greater accuracy is expensive, complicated, consists a lot of parts and involve many companies to make it reality(“Combat”). The F-35, made from more than 300,000 individual parts from 1,400 suppliers was selected as the case model for this project. The table below displays the production time, number of aircraft built, and average unit cost for the F-35 and earlier fighter jets(Lockheed).

Aircraft	**Production Time**	**# Aircraft Built**	**Average Unit Cost**
F-15	1970 - Present	1198+	F-15A/B : $28M
			F-15 C/D: $30 M (1998)
F-16	1973 – Present	4540+	F-16A/B: $14.6M (1998)
			F-16C/D: $18.8M (1998)
F-117	1981 – 2005	64	$111.2M
F-22	1996 – 2011	195	$150m
F-35	2006 – Present	150	F-35 A: $98M
			F-35 B: $104M
			F-35 C: $116M

Table 1 –Fighter Jets (1970 - Present)

Designed with the overall battle space in mind, the F-35 Lightning II is the most technologically sophisticated multirole fighter built in history. The US government has realized the excessive expenses associated with having different airframes for different aircrafts. For instance the F-22 Raptor, the Harrier Jump Jet and many other aircrafts have different fuselages which makes them have to be built at different factories and multiple projects have to be funded simultaneously. Developing one airframe for many aircraft is usually cheaper, so called economies of scale, then modifying them at the last stages to fit their specific purposes, similar to the customization approach. This is the essence behind the F-35. The intention was to replace the F-16, A-10, AV-18 and F/A-18 (excluding the "Super Hornet" variants) in a cost-effective manner

The program is the Department of Defense's (DOD) largest international cooperative program. DOD has actively pursued allied participation as a way to defray some of the cost of developing and producing the aircraft, and to "prime the pump" for export sales of the aircraft. Eight allied countries—the United Kingdom, Canada, Denmark, The Netherlands, Norway, Italy, Turkey, and Australia—are participating in the F-35 program under a Memorandum of Understanding (MOU) for the SDD and Production, Sustainment, and Follow-On Development (PSFD) phases of the program.

There is a multitude of technologies required for an aircraft to be capable of meeting the needs of the three branches of the US Military, and eight international partners' rivals any fighter jet of in history. There are three versions of the F-35, tailored to the specifications of its end users; the Conventional takeoff version for the Air Force; a carrier-based version for the Navy; and a short takeoff and vertical landing (STOVL) version for the Marine Corps, each equipped with internal technologies that better accomplish their user's goals. Inherently, the development and integration of such advanced technologies with the numerous participants implies many questions and hypothesis. As difficult as it is to predict, cost is a point frequently discussed, to the say the least, in the debate over the F-35. In 2014, the Department of Defense (DOD), a clear stakeholder in the life of the F-35 estimated that the remaining cost for the F-35 purchases, including the cost to complete development, will amount to about $300 billion (in nominal dollars).

Due to the complexity involved in creating the most advanced fighter jet in history, the F-35 production process utilizes the resources of 1400 suppliers nation-wide (Callerame). Main components of the plane are manufactured by three main companies -Northrop Grumman, BAE Systems and Pratt and Whitney then shipped to Lockheed Martin's production facility in Fort Worth, Texas to be mated later. The factory in Fort Worth operates under a "flow-to-tact" manufacturing plan, which can best be described as the movement of component assemblies, from one build station to the next at a rate equal to the delivery rate.

A method called the Fighter Production Process (FPP) was established to separate the production process into two teams – The Factory Flow Team and the Supplier Collaboration and

Development Team. The Factory Flow Team is responsible for preparing and enabling the production line to deliver F35 exact manufacturing standards and predictable tact or cadence time. These standards include meeting expected delivery tempo, proper presentation of parts and materials, and standardizing work. (Document best practices & precisely define parts and tools.) 5000 kits containing 25000 parts are delivered to the F35 flow center where they are put through a robust provisioning process established to ensure regulated flow. Rather than wasting time and having mechanics leave their station to search for parts, time is minimized with the signal for a new kit once the old one is nearing completion (Callerame).

The Supplier Collaboration and Development Team has three main objectives; meeting throughput demands, meeting affordability targets, and reducing supply chain risks. These are accomplished through an in-depth analysis of a supplier's operational capability to deliver consistent quality at a high production rate. The overall cost of the supply chain is reduced through increasing the supplier value-added tasks such as piecework, sub-assembly tasks, and installation ready parts. Primary goals involve reducing lead times, optimizing inventories, and lowering the manufacturing hours required per unit (Callerame).

The production process of this unique and advanced fighter jet kicks off with four stages that occur simultaneously. As the fighter jet advances throughout production other stages are met simultaneously prior to the system reaching the Electronic Mate and Alignment System. (EMAS) These stages mark the initial assembly of the multiple fuselages (Aft, Center, Forward), inner wing module, right and left wings, and nose of the F35. Post-EMAS the aircraft will reach Final Assembly where the engine will be inputted into the fighter jet. Lastly, the aircraft will go to Final Finishes and complete its final tests prior to delivery.

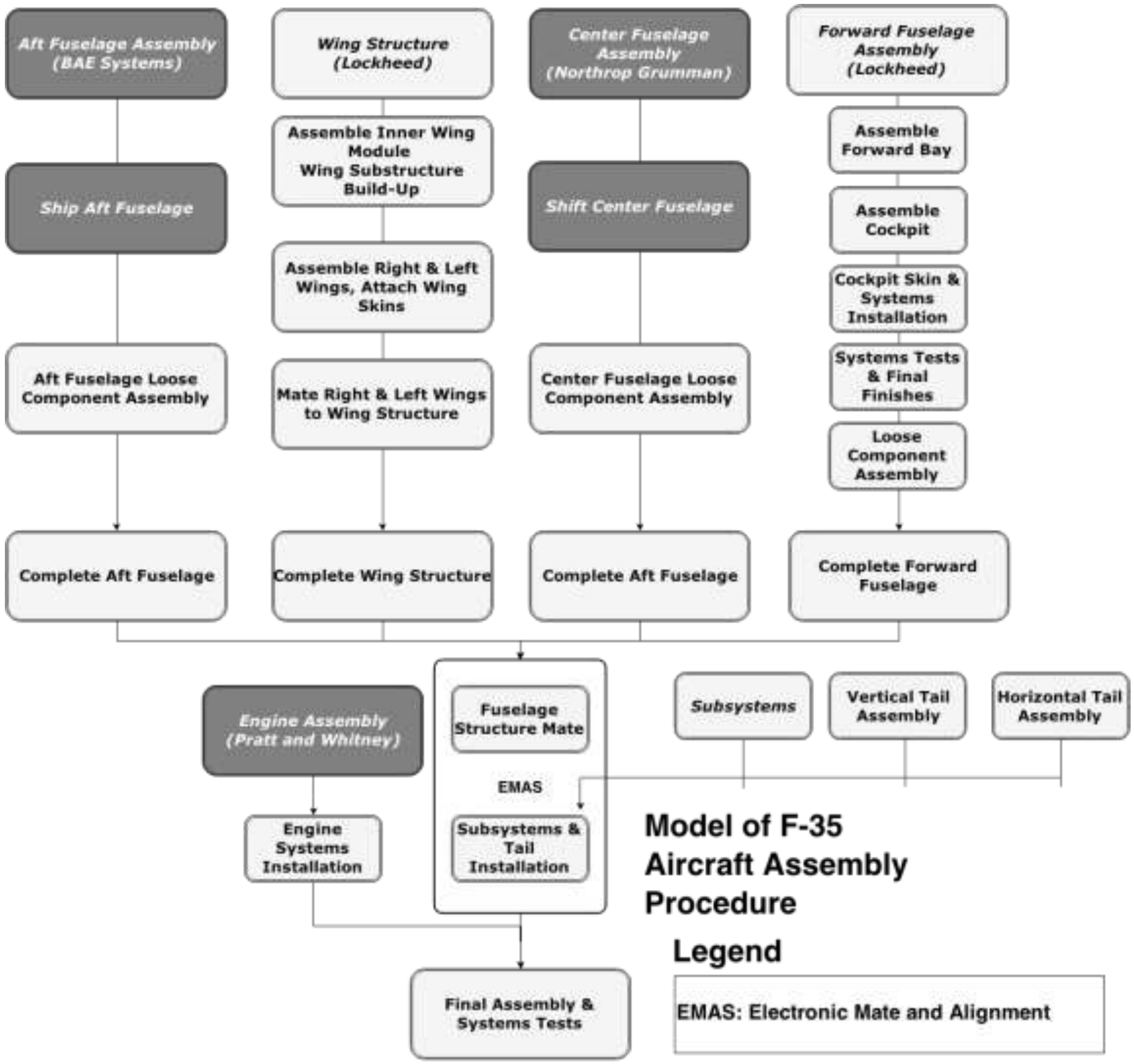


Figure 1: Aircraft Assembly Flow

Based on the facts and assumptions provided below, graphs depicting the varied costs involved in the production process as workers per shift and shifts per day change. Since full rate production will be represented by 1 fighter jet produced per work day, we have run calculations based on how many are being currently produced in an attempt to establish an hour value per stage. 36 aircrafts were produced and delivered in 2013 by Lockheed Martin, so we used that as a base value (Davies & Dildy, 2007, p.249).

- Assumptions:
  - Each stage takes equal amount of time [flow-to-tact manufacturing]
  - 21 working days/month
  - 8 hours/work shift

1.2 FOD Overview

Throughout each of these stages of production there are many complicated procedures that take place, which inherently present an opportunity for foreign object debris (FOD). Foreign object debris refers to any object alien to the craft, with the potential to cause damage to it. Examples of FOD are displayed below and categorized based on their individual likelihood of arrival based on their item classification (Tseng & Guadamuz, 2014).

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

Table 2 - Examples of FOD types and their probability of occurrence

FOD damage is estimated to cost the aerospace industry $13 billion a year ("FOD prevention"). This project focuses on FOD associated with aircraft production, and is thus a primary contributor to this annual FOD cost. To prevent FOD related costs and improve safety, aircraft production corporations put in place a FOD-prevention program that uses to assure a FOD-free product/system. This prevention process is called foreign object elimination (FOE). The current FOE program mainly consists of three main components: Training/ Procedure, prevention, and inspection. (Garber).

The primary objectives of a FOE training program is to increase employee awareness to the causes and effects of FOD, promote active involvement through specific techniques, and stress good work habits through work disciplines. A FOD prevention training Program for employees associated with design, development, manufacturing, assembly, test, operations, repair, modification, refurbishment, and maintenance is required as part of initial job orientation and on a continuing basis (Batchel).

The prevention and inspection components of FOE translate what employees learn on their trainings to their work places. Prevention mainly covers Housekeeping and enforcing rules that applies for each FOD prevention area. Housekeeping mainly refers to the employee usage of deferent techniques and good work habit when it comes to tool handling and cleaning. For instance, employees use Shadowbox, a tool box with specific, marked locations for each tool so that a missing tool will be readily noticeable. Bar coding and paint coding are also used on this process. Furthermore, tether and tote tries are used to keep tools and parts from falling or get forgotten by keeping them with the employee physical body. Furthermore, employees “clean-as-they-go” their work places and storage areas. They clean the immediate are when work cannot continue, after work is completed and prior to inspection. It also applies immediately when work debris has the potential to migrate to an out of sight or inaccessible area and cause damage and/or give the appearance of poor workmanship (Batchel).

The third component of FOD is inspection. Inspection mainly covers searching for FOD, retrieving lost items and report FOD or lost item. The current searching method of FOD is manual, meaning humans carry out visual inspections. These inspections are carried out between each shift as displayed in the Flow diagram below, and are represented by the magnifying glasses.

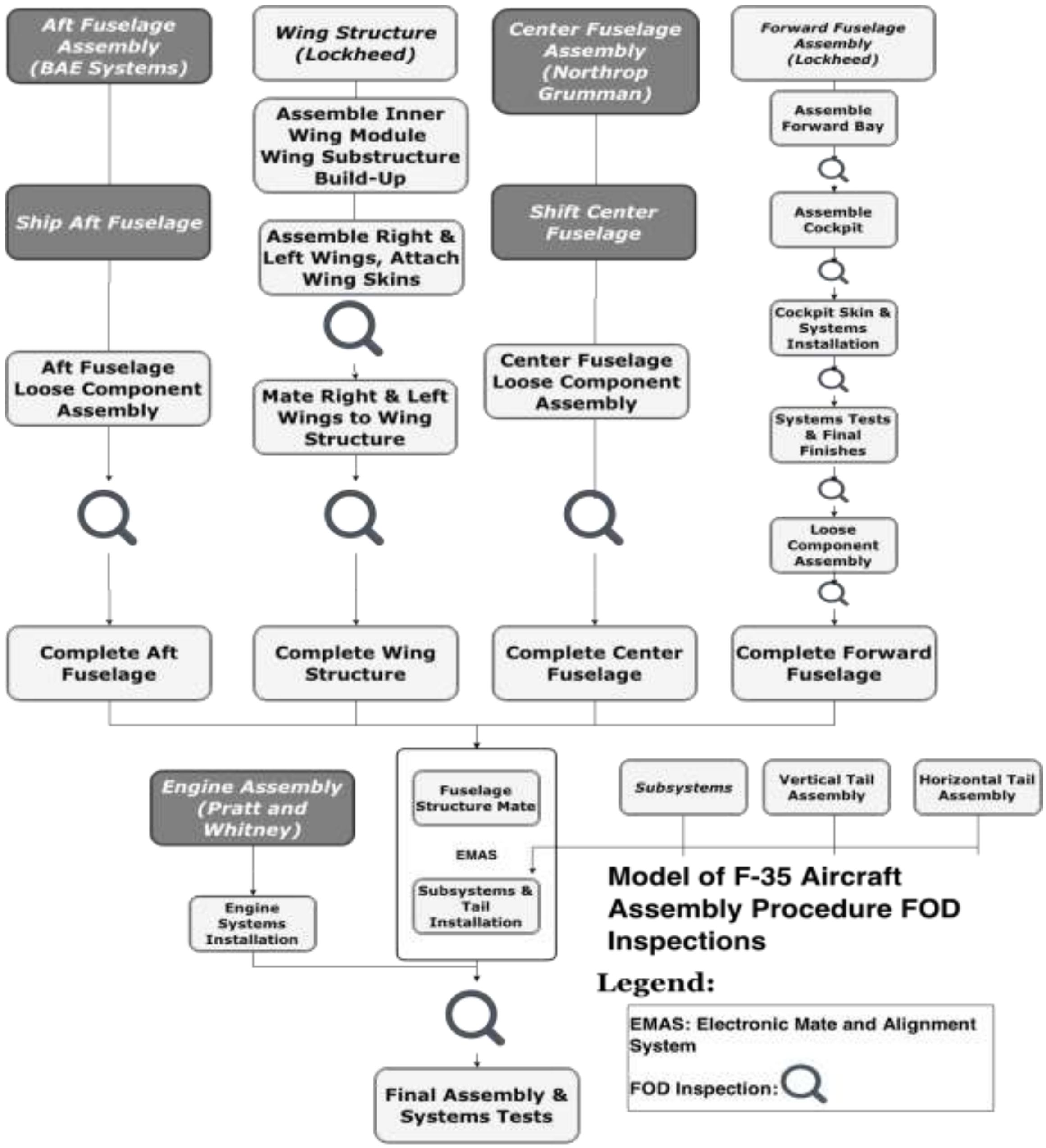


Figure 2: Aircraft assembly flow with Manual Inspection

Any time an item is lost during an assembly; manufacturing, or maintenance task, employees cease activity in the affected area and initiate a search for the item. Continue this search until the item is found or adequate assurances are made that the item is not in the aerospace vehicle or assembly. Searching for such items may require dismantling or nondestructive inspections, including bore scope. If an item cannot be located after a search has been completed, annotate applicable forms with a description of the item and search procedure followed. After finishing this point employees then move to reporting and investigation process. All incidents of actual or potential FOD is reported and investigated (Batchel).

When a FOD incident occurs operations shall immediately cease and an investigation initiated to determine the cause. Corrective action will be required to preclude similar occurrences from happening in the future. Cause may be determined by visual observation, analysis, or by location of the object. A foreign object or tool found during an inspection, audit or abandoned within a FOD sensitive/critical area will be documented using the FOD Incident Report (Butler).

Employees are trained and certified depending on their clearance level. There clearance level also will determine their access to different FOD prevention area. The FOD prevention area is mainly divided in three parts. FOD awareness areas, FOD control areas, and FOD critical areas (Batchel).

1.2.1 FOD Effects

Figure 3: Effect of FOD

Figure 3 above displays a past incident due to FOD. A simple drill bit forgotten can be detrimental to an aircraft and it’s passengers (Butler).

Aside from the safety hazards associated with FOD, aircraft production corporations are constantly trying to innovate to improve their FOD inspection and detection methods in hopes of reducing production costs related to FOD occurrences. The costs resulting from FOD occurrences have a non-linear relationship with the actual occurrence. Thus, there are some FOD occurrences that cost $0, and require 0 hours of work to prior to advancing in production. An example of this is an employee finding a plastic bag in a subassembly component, and simply removing and reporting it. Yet, there are some FOD occurrences that can result in exceedingly high costs. Typically, due to of long rework & repair hours, and re-ordering of damaged parts. Usually, the further the aircraft is in the production process the longer rework & repair hours required to enable the plane to advance in production. Below a graphic displays the process previously described:

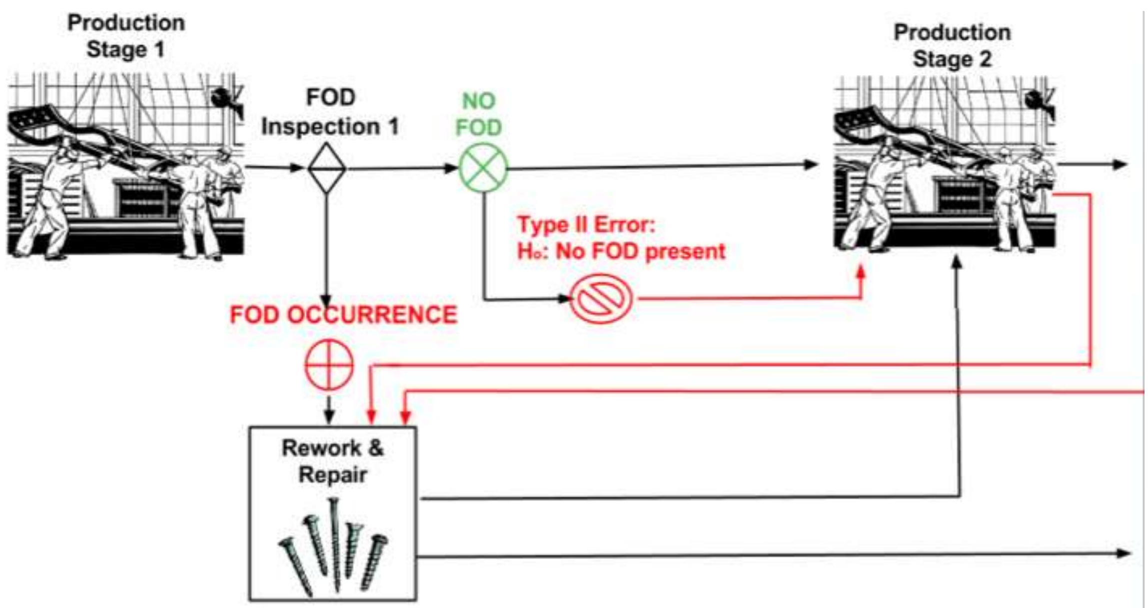


Figure 4: Type II Error Diagram

One can imagine the complexity associated with the job of an aircraft assembly mechanic. While five to ten feet in the air, a multitude of tasks have to be completed using a variety of tools all with the highest focus possible. Working under these conditions provides a huge possibility for a simple bolt or washer to be left behind in a subassembly component. If this does occur there is a chance for the FOD item, in this case the bolt or washer to be detected at the inspection station following the production station where it was inputted. At the inspection station there is a decision to be made, whether or not there is FOD present. If the FOD is caught, the required rework and repair will occur and the sub assembly component will progress through production. Yet, if there is said to be no FOD in the subassembly component, and there is in fact FOD within a Type II Error occurs. This is exactly what are trying to prevent and eventually eliminate in the future. This Type II Error implies high costs as the sub assembly component containing FOD moves further throughout the production process.

Once EMAS (Electrical Mate and Alignment System) is reached the subassembly components begin to be assembled and therefore have to be decomposed if there is a FOD occurrence that cannot be reached within. In an attempt to limit the misdetection and Type II Error rate, different capabilities will be incorporated into the enhanced FOD Inspection System.

1.3 Manual FOD Inspection Probability Distributions

With the help of our sponsor from Lockheed Martin, we attained a historical FOD data set; which included FOD occurrences over a yearlong period. (Due to proprietary data restrictions this data is not connected to the F-35 or any other specific aircraft) A subset of this data was included below:

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

Table 3 - Historical FOD Data Set

- Create Date – Date that this FOD occurrence was reported
- Occurrences Per Day – Number of FOD occurrences reported that day
- Complete Date – Date that the rework was successfully completed
- Days to Complete – Number of Days required for the rework of this specific FOD occurrence
- Initiating SWBS – The SWBS station in which the FOD was detected
- Estimated Complete Date – Date the rework for this specific FOD occurrence is expected to be completed
- Labor Hours – The labor hours required for the rework of this specific FOD occurrence

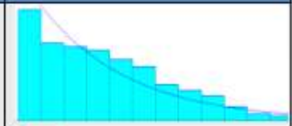
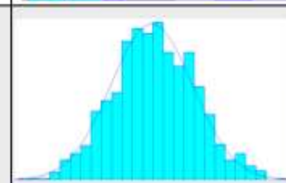
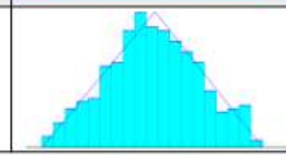
Variable	Distribution & Random Number Generator	Distribution Graph
FOD Arrival Rate	Exponential Distribution (λ = 0.0102) $X = -\ln(1-R)/0.0102$ $0 \leq R \leq 1$	
FOD Rework Time	Exponential Distribution (λ = 0.951) $X = -\ln(1-R)/0.951$ $0 \leq R \leq 1$	
Inspection Time	Normal Distribution (MEAN, 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) $T = 4 + \sqrt{R(8-4)(6-4)}$ $\quad 0 < R < 0.5$ $T = 8 - \sqrt{(1-R)(8-4)(8-6)}$ $\quad 0.5 \leq R \leq 1$	

Table 4 – Manual Inspection Distribution

- FOD Arrival Rate – Determined using the total number of occurrences per day shown in the historical FOD data set
- FOD Rework Time – Determined using the labor hours per occurrence shown in the historical FOD data set
- Inspection Time – Used a multiple with the Station Process Time based on the 5-10% of Shift Time attributed to the manual inspections by our sponsor.
- Station Process Time – Determined based on the 36 Aircraft produced in 2014

1.4 Stakeholders & Objectives

The primary stakeholders associated with FOD and aircraft assembly are the production line personnel and the aircraft manufacturers. Manual inspections incur unnecessary labor costs as a result of the constant inspections taking place after each station and 5-10% of shift time (J. Dorrell, personal communication, 2014). associated with each inspection. This strategy is time consuming and repetitive. Unexpected FOD events can have ripple effects that reach the aircraft customers, depending on the severity of the FOD occurrence. New parts may have to be ordered, or rework may have to be conducted in order to fully complete the assembly of the aircraft, requiring unexpected time, therefore postponing deadlines as a result.

1.5 Stakeholder Wins and Tensions

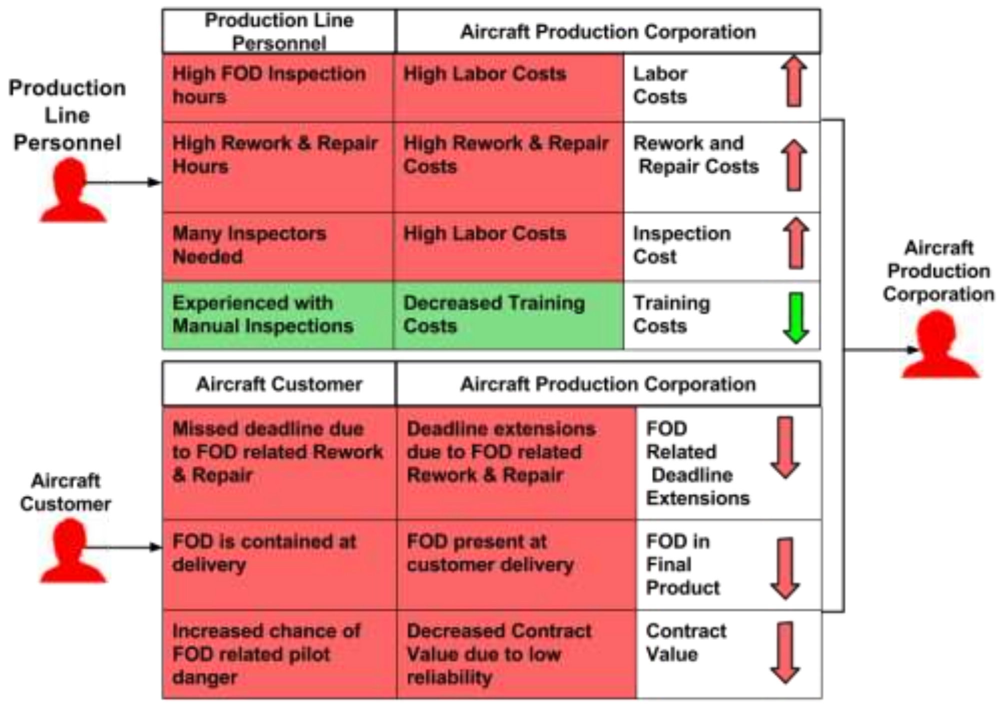


Figure 5: Stakeholders wins and tensions

- *Production Line Personnel*
    - Aircraft Production Corporation responsible for paying production line personnel to conduct constant FOD inspections.
    - The limited probability of a successful inspection cause FOD to be missed throughout initial inspections and detected later in the assembly process forcing assembly components to be decomposed to reach the area containing the FOD; ultimately causing unnecessary rework hours.
    - Inspections occur after each shift, thus many personnel are required to conduct these inspections when their time could be better utilized.
    - Production Line Personnel are already experienced in FOD Inspections, and are even possibly certified; therefore no more training is necessary for current employees under the current inspection technique.

- *Aircraft Customers*
  - The limited probability of detecting FOD promotes the frequency of unexpected FOD occurrences. If there is a severe FOD event that occurs late in the assembly process long hours may be necessary to safely repair the component; if this occurrence is close enough to a deadline it could have to be pushed back as a result of the safety concerns associated.
  - FOD contained upon delivery is detrimental to the reputation of Aircraft Production Corporations and dangerous for the Aircraft Customers. Delays and large Expenses also come as a result of the craft having to be sent back to have the issue repaired, decomposing and repairing the actual issue, and then shipped back to the Customer.
  - The limited probability of detection increases the probability of FOD items being overlooked even in the final product; thus presenting the increased chance of danger to the pilots.

2.0 Problem & Need

2.1 Gap Analysis

The current FOD inspection and prevention methods are not cost effective or efficient in relation to the aircraft production process. These methods, relying on line-of-sight, are time consuming (5-10% shift time), costly ($13B per year) and subject to errors (i.e. 50% FOD remains undetected after inspection (Tseng & Guadamuz, 2014). Due to the fact that the current processes are manual and take place during the shift there it is likely for human error to occur. This includes a fatigued employee overlooking a damaged part, a tool being misplaced, specific area searching due to probable FOD areas, and other possibilities.

Operating under the current inspection technique, delays are caused late in the production process when FOD is detected at the concluding stages. These delays are primarily attributed to decomposing the plane and rework/repair. When a FOD issue occurs late in the production process, that aircraft must be withdrawn from the current stage, decomposed, and then inputted back into a stage where the issue can be repaired. Inherently, the mechanics currently operating at that stage must stop what they are currently working on and attempt to fix the issue at hand. Added costs are implied at each stage that re-work occurs, along with component damage, re-ordering of parts from suppliers, wait-time, and employee wages.

Since the F-15 was built in 1970 the average unit flyaway costs for fighter jet has rose from $28 million to $150 million. With costs required for purchasing these fighter jets constantly growing, the emphasis on preventing damage to them is constantly rising. Yet, over time as the complexity of these fighter jets is constantly increasing the complexity of the FOD Inspection techniques have remained constant, still manual. Therefore, there is a gap between the complexity of fighter jet production and the FOD Inspection techniques. This can be easily seen on the graph below:

2.2 Problem Statement

The limited probability of a successful manual FOD inspection has contributed to the $13 billion annually attributed to FOD damage ("FOD prevention"). Humans carry out manual inspection at each station thus line of sight poses as a restriction. Within each inspection there is a high potential for human error as a result of distractions, fatigue, and bias. After conducting the same inspection daily, humans become accustomed to applying higher focus to areas where they expect to find FOD and therefore less into the other areas. FOD occurrences also affect the customer; unexpected rework and repair hours delay the assembly process therefore postponing deadlines.

2.3 Need Statement

The current FOD inspection and prevention methods are outdated, and unreliable. Inspecting the aircraft manually at each stage of production is inefficient in relation to time, and is presents the application of human error. Production line personnel are under-utilized, and unnecessary costs are created as a result of the Type II error previously discussed. Below we have displayed many of the issues and consequences with the current manual inspection system and the solutions and associated benefits with an enhanced FOD Inspection System.

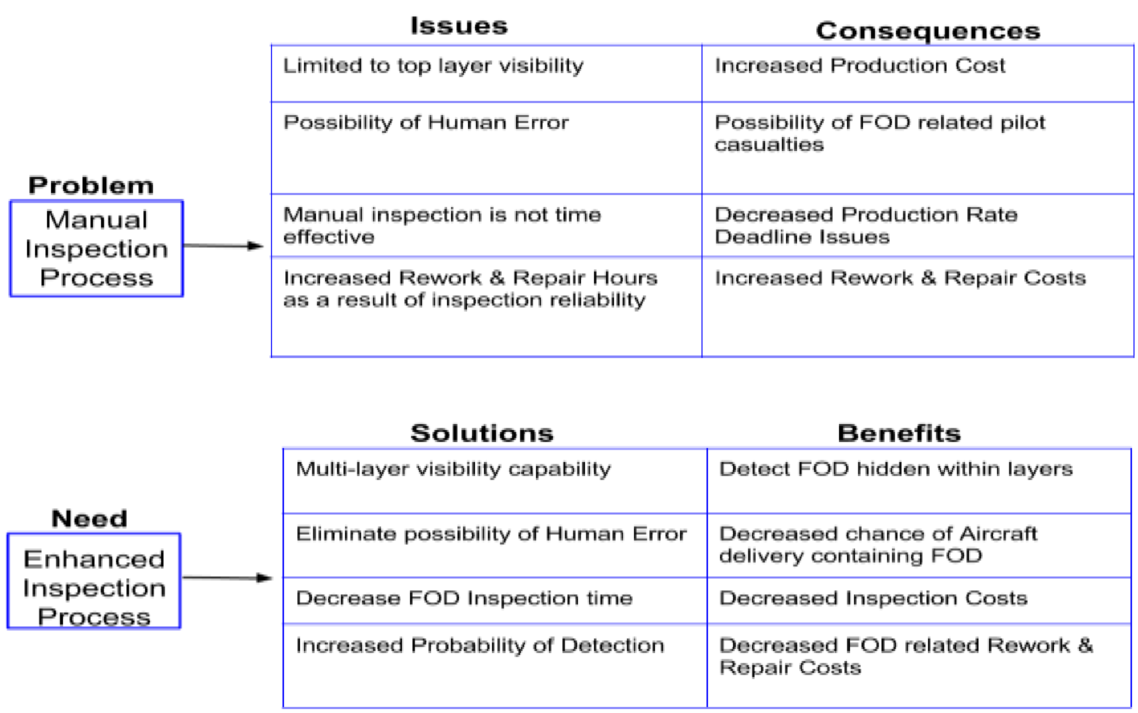


Figure 6: Problem and need

2.4 Enhanced Inspection System Requirements

With assistance from our sponsor at Lockheed Martin the following Enhanced Inspection System requirements were derived.

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%.**

Table 5 – Enhanced Inspection System Requirements

3.0 Concept of Operations & System Alternatives

3.1 Implementation & Design Alternatives

The Enhanced Inspection System proposed will combine X-Ray technology along with differential imaging software. The table below depicts the pros and cons between the enhanced and manual inspection using three measurements: FOD detection probability, time and cost.

	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

Table 6 - Manual Inspection Vs Enhanced Inspection

Since humans solely carry out the manual inspections, the inspectors are limited by line of sight and limited to human decision making. Therefore it increases room for human error when deciding where to search, or deciphering what is and what is not FOD. On the other hand, the Enhanced inspection system uses X-ray technology to penetrate through multiple layers bypassing the line of sight, enabling detection throughout all layers of the aircraft assembly component. Furthermore, using differential imaging software, an inspection recommendation will be made to the personnel responsible for the inspection. Differential imaging software is compares two images either pixel by pixel or by skipping a portion of pixels (i.e. – every other pixel) and detects differences between them. Therefore, serving as a means to limit human error, by assisting the inspector with a recommendation.

The enhanced inspection system incorporates the inspection stations at critical points throughout the assembly process as shown in the diagram below. The rework hours required per aircraft can be decreased if FOD is detected before the subassembly's are mated together, since taking apart the aircraft in order to clear FOD has severe time and monetary costs associated with it. The model below depicts the same production stages of the F-35 discussed in the context, yet, now with the implementation of the enhanced inspection stations rather than the manual inspection stations.

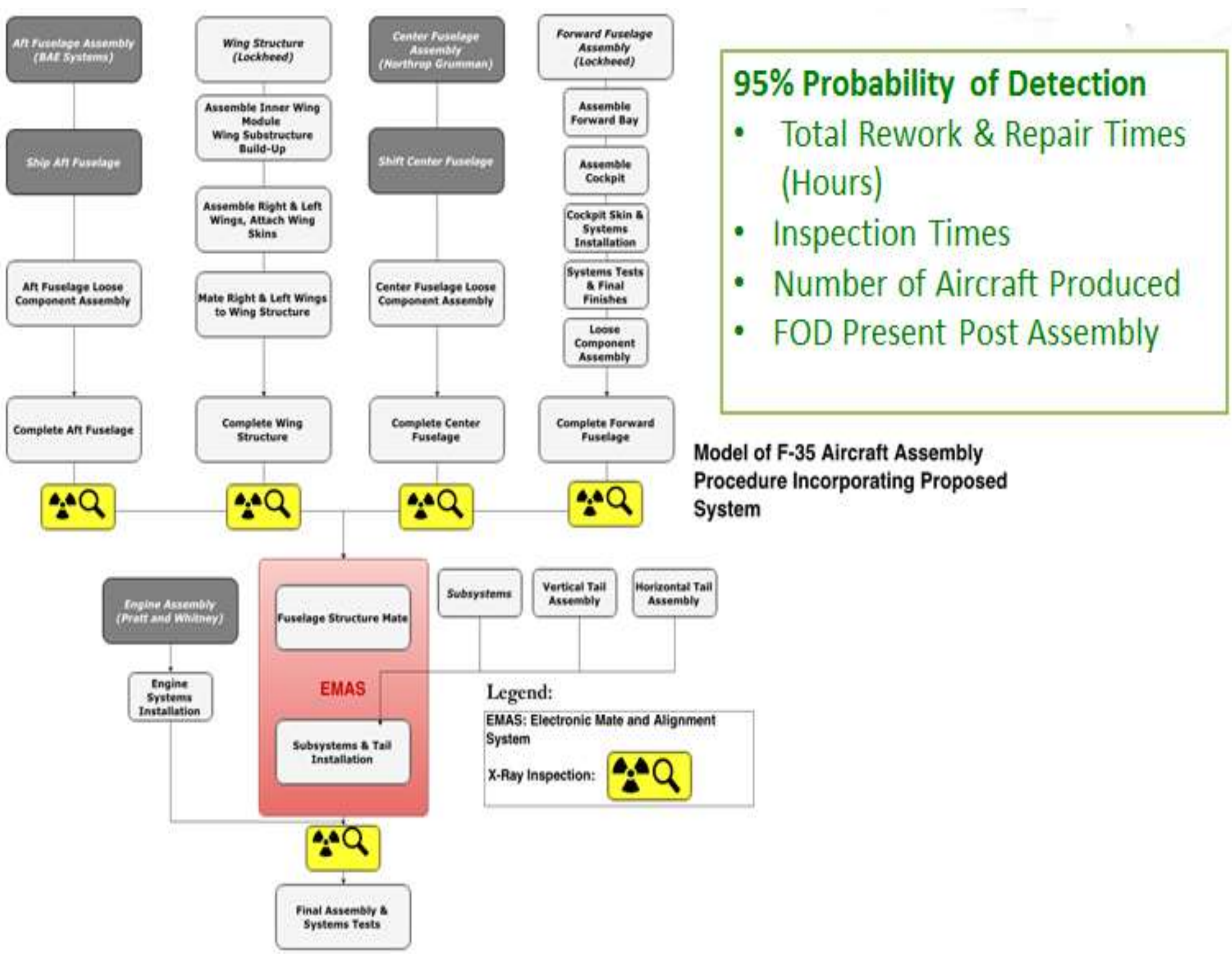


Figure 7: Aircraft assembly flow with Enhanced Inspection

The Enhanced Inspection System will have a 95% probability of detecting the FOD present at each inspection; this was verified using the Penetration Depth and Signal to Noise Ratio (SNR), which will be discussed in section 3.4.1 and 3.4.2. This introduction of this system will have a positive impact on Total rework and repair time, inspection time, number of aircraft produced, and FOD present post assembly. Total rework and repair times are expected to decrease as a result of the rework per aircraft decreasing.

Increasing the probability of detection prior to the Electrical Mate and Alignment System (EMAS) will decrease the likelihood of the decomposition of assembly components to reach the initial component where the FOD was inputted.

The increased probability of detection enables the limited number of inspection locations associated with the Enhanced Inspection System. This system also limits the number of personnel required per inspection station; therefore dramatically decreasing the total hours inspection hours required by limiting the number of inspections and personnel required for each.

Now the 5-10% of shift time previously required for the constant manual inspections can be better utilized to continue working and remain focused throughout the shift on assembly aircraft (Tseng & Guadamuz, 2014). Thus, an increase in number of aircraft produced is expected based on the implementation of this Enhanced Inspection System.

As a measure of quality in Aircraft Assembly, one can assess the number of FOD occurrences post assembly; in other words the number of aircraft containing FOD upon delivery to the customer. This is very dangerous for anyone attempting to fly the plane, and detrimental to the reputation of Aircraft Production Corporations. This Enhanced Inspection Systems limit these occurrences through the increased probability of detection.

3.2 Enhanced Inspection System Stakeholder Analysis

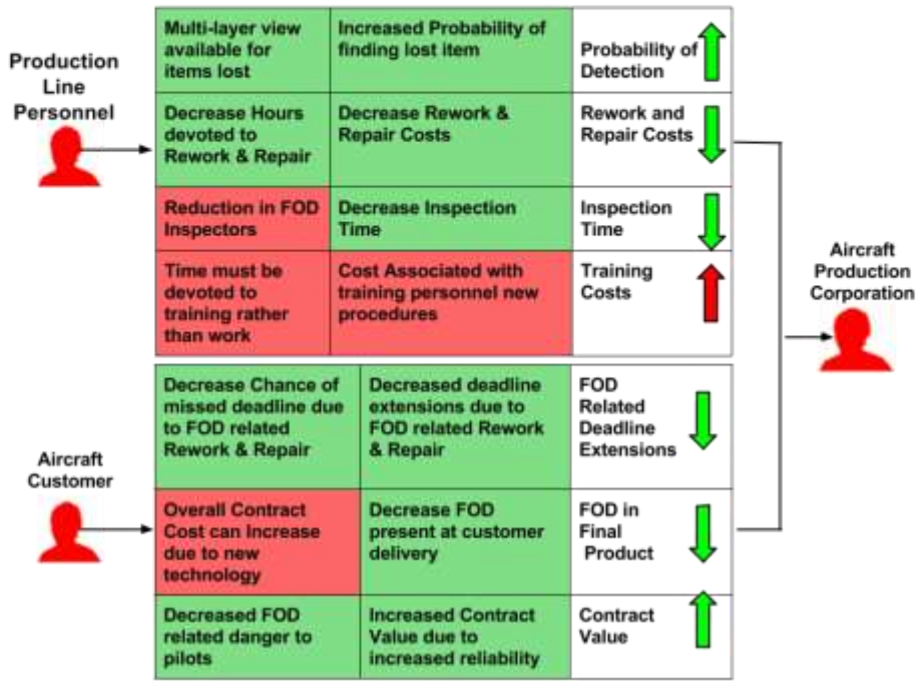


Figure 8: Enhanced stockholder analysis for Enhanced Inspection System

- *Production Line Personnel*
    - Multi-Layer visibility will enable the system to bypass the line of sight therefore providing the system the capability to see any items contained within the assembly component rather than the ones only contained on the top layer.
    - The increased probability of detection will decrease the number of Type II Error occurring, thus limiting the rework and repair hours required per aircraft.
    - The enhanced FOD Inspection System will limit the number of inspectors necessary per inspection, presenting the opportunity to better utilize the labor hours of the production line personnel.
    - Training will be necessary with the introduction of the new system for all personnel interacting with the Enhanced Inspection System.

- *Aircraft Customer*

  - The enhanced system will give the customer a more reliable product delivery time, increasing the demand and contracts the customer will provide to the Aircraft Production Corporation.
  - The enhanced system will create the possibility of increasing the current contract between the Aircraft Customer and Aircraft Production Corporation due to the new technology that would need to be implemented.
  - The enhanced system will decrease the probability of undetected FOD being delivered to the customer.
  - The Enhanced Inspection System will decrease the probability of undetected FOD being delivered to the customer; increasing safety for the users of the product and increasing the contract value.

3.3 Functional Breakdown

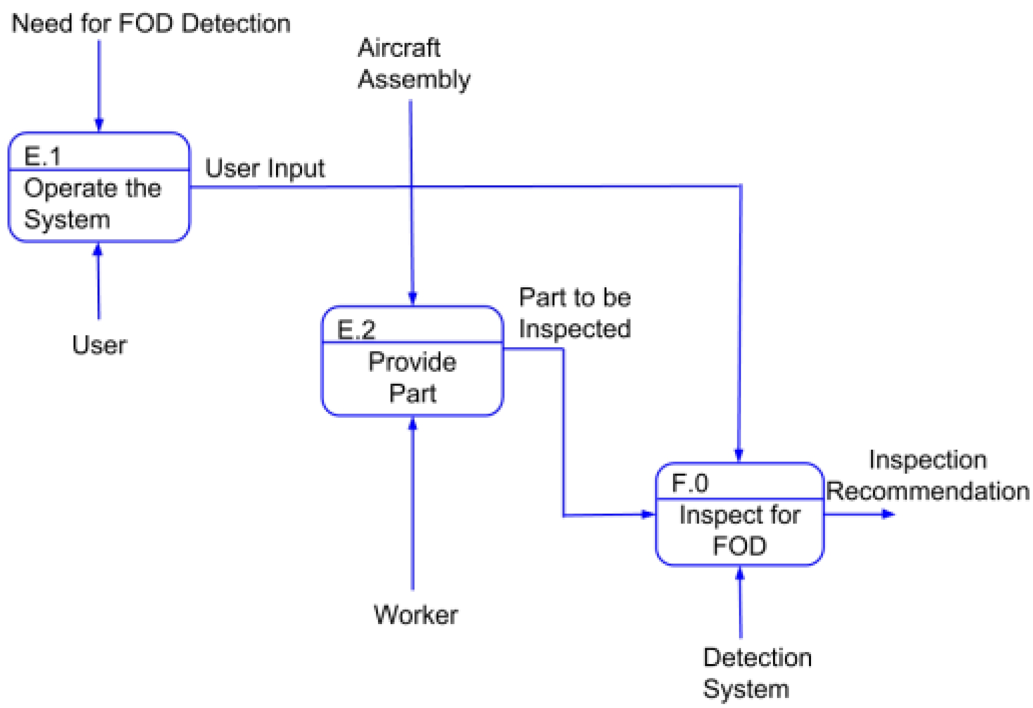


Figure 9: IDEF.0 External Systems Diagram

The External Systems Diagram (IDEF.0) shown above describes how our proposed system shall work with external systems, such as the User who will be providing the system with input, as well as the Worker who will feed the Inspection system the next Aircraft sub-Assembly to be inspected. Ultimately, the system that which we are proposing is performing its primary function F.0, which is to inspect for foreign object debris and output an inspection recommendation.

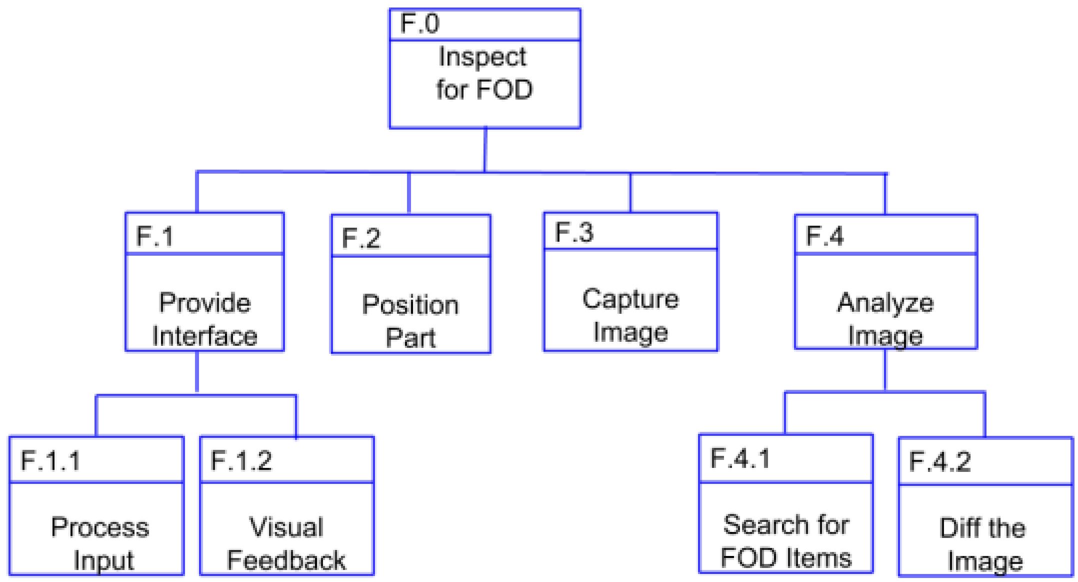


Figure 10: Functional hierarchy diagram

The diagram above is a functional hierarchy diagram describing the functional decomposition of our system's primary function: F.0 inspect for FOD, our system accomplishes its primary function through the symphonic interaction of the system's sub functions. The first sub function facilitates the interface between the user and the system, the second sub function is responsible for positioning the sub-assembly before the X-ray image is to be taken, and finally, the third and fourth sub functions take the X-ray image of the sub-Assembly, as well perform the image analysis required for the FOD inspection.

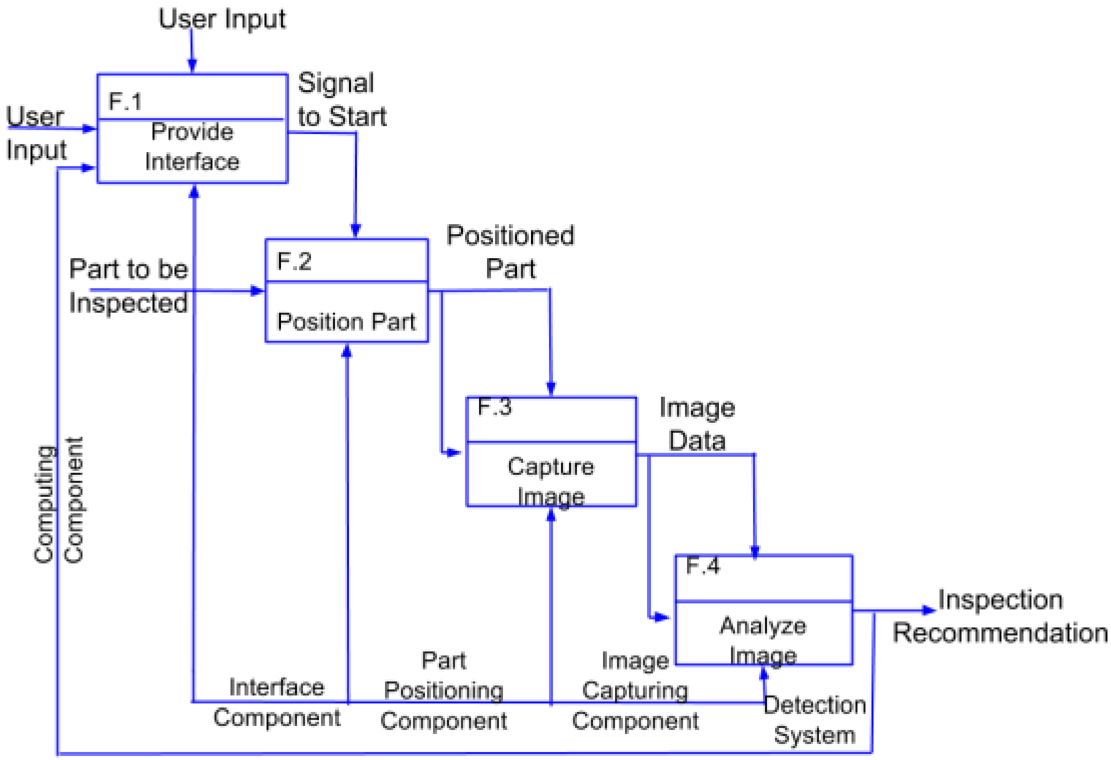


Figure 11: IDEF.0 for Enhanced Inspection System

This IDEF.0 diagram depicts the interaction between the System's sub functions in order to produce the final output; it shows how the signals are sent to trigger the sub functions as well as the dependent inputs that come from the preceding functions. This diagram also shows the physical and allocated architectures for the systems functions, by depicting the component responsible for performing each of the sub functions.

3.4 Allocated Architecture

3.4.1 Imaging Component – X Rays

X-radiation is a type of electromagnetic radiation, which has the very short wavelength range of 0.01-10nm, (frequency range of 3×1016 Hz to 3×1019 Hz). These high-energy, high frequency electromagnetic radiations have the properties of penetrating various thicknesses of all solids and producing secondary radiations by penetrating on materials body. In simple terms it can be referred as a powerful and invisible light ray which can pass through different objects and makes it possible to see inside the things. X-ray has several applications in medical and industrial field.

There are many reason for considering Backscatter X-ray, it can image Foreign Object Debris (FOD), corrosion, defects and flaws. It provides opportunity to image fasteners (entire fuselage and wings) that was not practical before; and it has the ability to image cracks in more than one layer. With Backscatter X-ray, there is no need to remove paint to detect as required utilizing other non-destructive testing (NDT) technologies. As far as low radiation field, very small exclusions zones compared to industrial radiography, and it allows other work to continue in close proximity to imaging field saving money and time. Its modular design allows components to be replaced and customized cost effectively.

The Enhanced FOD Detection system being proposed will consider two X-Ray Detection techniques:

- Backscatter
- Transmission

<u>X-RAY Transmission Imaging:</u>

Transmission imaging is a traditional X-ray method, familiar to many through the medical field. Transmission Imaging requires the source and detector to be on opposite sides of the object, enabling X-rays to pass through an object to a detector located on the far side. Detecting the different densities o which objects with greater density block or absorb more X-rays than objects with lesser density will form the image. . This technique is advantageous for the proposed system because transmission images are generally high-resolution emphasizing the densities of the materials contained in the X-Ray image.

Dual-Energy Transmission:

In some of the considered x-ray alternatives, the dual energy transmission, which is a form of transmission technique, has been used. Dual-energy transmission X-rays generate a high-resolution image in which metallic objects are easily. Dual-Energy transmission technology utilizes two X-ray energy levels to determine the atomic number of objects under inspection, and t colorizes the image based on material type inside the object under inspection. Organic materials are orange, mixed materials are green, and metallic are blue.

High-Energy Transmission:

Another form of transmission technique applied in x-ray devices is high-energy transmission. In high-energy transmission X-rays deeply penetrate deeply into object under inspection for greater detection. High-energy transmission X-rays provide very details, even when penetrating up to 400 mm of steel — and offer a precise means of detecting unwanted materials,. The OmniView Gantry offers the option to scan in dual energy modes. By scanning in dual energy mode organic materials are displayed in orange, mixed materials in green, metallic in blue and heavy metals in purple.

X-RAY Backscatter Imaging:

Backscatter imaging is a more recent X-Ray technique that is used frequently for security at borders and airports. Backscatter scanning is based on the Compton backscatter principle. The Compton Effect occurs when x-rays were are directed towards a target and multiple rays are scattered from that object. Due to the low radiation dose emitted by the X-ray systems which incorporate backscatter imaging it is permitted to be used on inspection and screening of sea containers, a wide variety of vehicles, luggage, and even people. Safety is a key consideration when attempting to choose the optimal device for the F-35 case model, thus, the low radiation dose required is advantageous. In contrast to the commonly used transmission x-ray technique, backscatter imaging involves positioning both the source and detection apparatus on only one side of a target object for inspection. This allows the user to inspect in situations that may be extremely difficult for transmission systems that require access by the detector subsystem to the opposing side of the target. Backscatter imaging emphasizes the size and shape of the objects within the image.

Compton Scattering Characteristics:

Compton scattering creates a recoil electron and a new photon from a collision between an atomic electron and incident photon (x-ray). The recoil electron is sometimes absorbed in material; the scattered photon may escape the material and can be detected. Conservation of momentum of the x- ray photons and the atomic electron determines how to calculate the momentum and directions of the scattered electrons. The energy of the scattered x-ray can be calculated using the following:

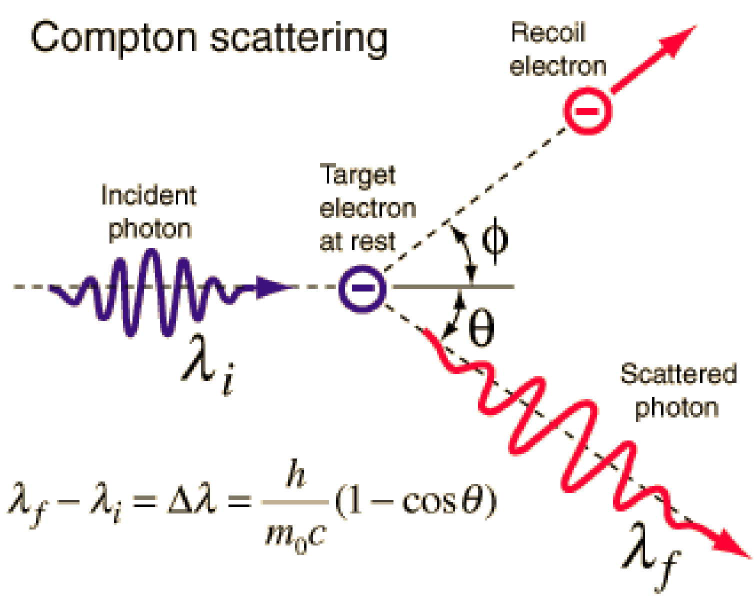


Figure 12: Compton Scatter

λ = Wavelength of incident x-ray photon

λ' = Wavelength of scattered x-ray photon

h = Planck's Constant: The fundamental constant equal to the ratio of the energy E of a quantum of energy to its frequency v: E=hv

m_o = Mass of an electron at rest

c = Speed of light

q = The scattering angle of the scattered photon

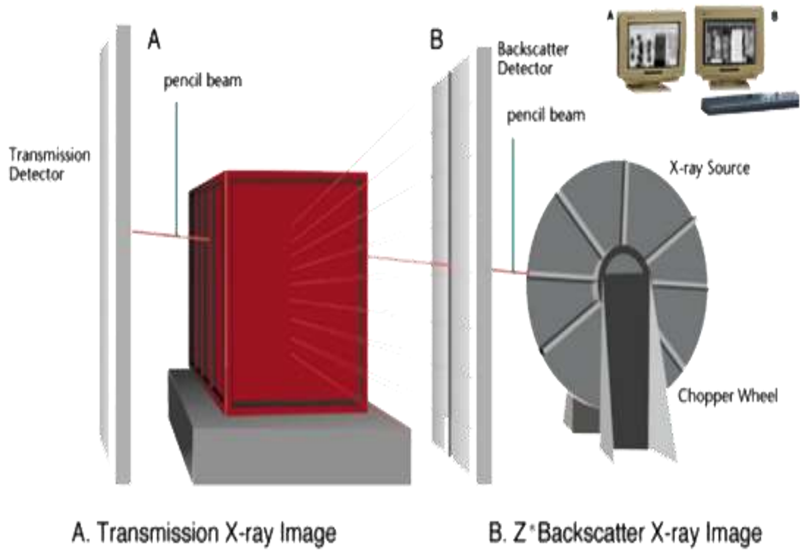


Figure 13: Transmission vs Backscatter

Compton backscatter forms the basis for a unique inspection tool that can be used to view the contents of closed containers without the need for a transmission detector to be placed on the far side of the object under inspection. Therefore scanning with both the X-ray source and detector co-located permits visual images of contents, to be gathered easily and quickly, without concern over access to the opposite side of the target container. In the aircraft production process this is advantageous because it limits the size of the space required to implement the system, and reduces the total wetted area of the aircraft component coming in close-contact with the device.

The image below was the result of an inspection on an identical object with transmission and backscatter imaging. A transmission image produces a shadow-gram of all objects in the beam path, with dark regions indicating low penetration and lighter regions representing higher penetration. Backscatter provides a very different view of the object under inspection by highlighting shapes and textures of the contents contained inside.

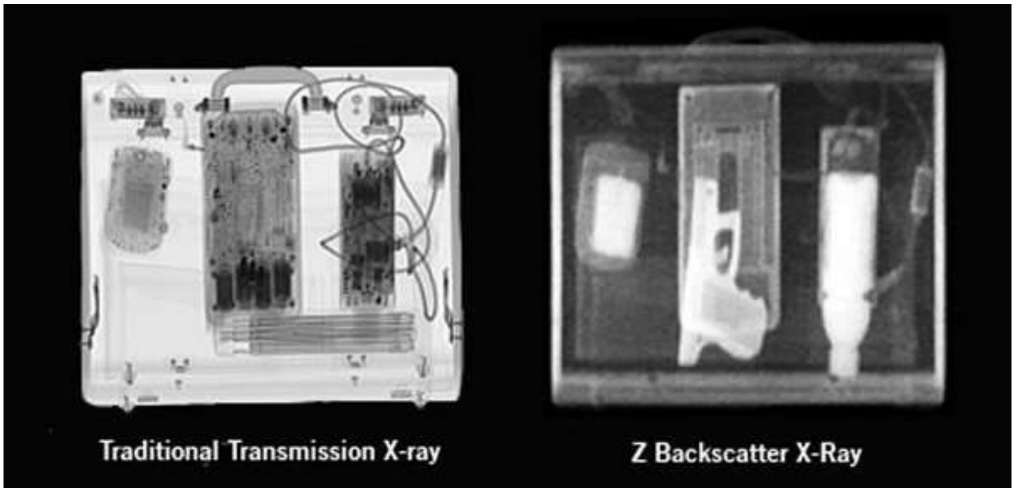


Figure 14: Traditional Transmission X-ray Vs Z Backscatter X-Ray

Combination of Technologies:

Transmission technology can provide fine details with high resolution, and can offer some level of material detection with dual-energy. However, the more clutter in the path of the beam, the fewer objects and material differentiation is obtained. Because of this, many x-ray detection products (AS&E) offer a combination of Backscatter and transmission technology to give inspectors fine detailed information about the contents of objects under inspection. When the backscatter is combined, it complements transmission X-rays by providing clarity to expedite and more precise inspections.

The biological health effects of X-ray are a concern at every inspection station. Any form of X-ray exposure should be carefully monitored and controlled so that the inspectors safety is always insured. Concern over the biological effect of X-ray began shortly after the discovery of X-rays in 1895. Over the years different radiation protection groups have developed numerous recommendations regarding occupational exposure limits. In the Unites States these rule are approved by Occupational Safety and Health Administration (OSHA). In general, the guidelines established for radiation exposure have had two principle objectives:

1) Preventing acute exposure
2) Limiting chronic exposure to "acceptable" levels

Current guidelines are based on the conservative assumption that there is no safe level of x-ray radiation exposure. In other words, even the smallest exposure has small probability of causing a health effect, such as cancer. This assumption has to not only keeping exposures below regulation limits but also keep all exposure "as low as reasonable achievable" (ALARA). With the help of our sponsor the X-ray safety requirements that must be maintained and followed during the inspection have been established and are displayed below.

X-ray System Requirements

- XR.1.0 – System occupational exposure shall be in accordance with OSHA requirements. Supplier shall provide an X-Ray Exposure Protection Plan that addresses the following areas.
- XR.1.1 - The Plan shall be approved by LM 90 days prior to installation.
    - Radiation Exposure Limits
    - Personnel Monitoring
    - Exposure Records
    - Posting Notices
    - Inspections
    - X-Ray Exams of Pregnant or Potentially Pregnant Women
    - Pregnant Authorized Users
- XR.2.0 - Radiation workers shall not receive a dose in 1 calendar quarter over the following limits:
    - Deep Dose Equivalent 1250 millirem (mrem)
    - Lens Dose Equivalent 3,750 mrem
    - Shallow Dose Equivalent (skin) 12,500 mrem
    - Shallow Dose Equivalent (extremities) 12,500 mrem

3.4.2 Analysis Component – Differential Imaging

After scanning sub assembly components of the aircraft with the X-ray imaging component, the image will be analyzed in an attempt to detect FOD using the differential imaging component. Simply put, differential imaging is a process that compares two images and finds the differences between them. There are two techniques for implement differential imaging that are being considered. These include comparison through each individual pixel of each image, called Pixel by Pixel; and comparison through cluster of pixels in each image, called Cluster of Pixels.

The pixel by pixel technique requires two inputs. A basis image, which is the image of a sub assembly component completely clear of FOD. A basis image will be saved for each sub assembly component, which is saved in the database, and an image of the current sub assembly component will be saved from the enhanced inspection system. The individual pixels from these two images will be analyzed and compared. If there is a difference, then they will be made salient to the system operator. The advantage for this technique is that since every single difference between the two images will be picked up, hence the detection rate is higher. Yet, the disadvantage is that since it compares each individual pixel, it has extended time duration for comparison. Furthermore, not every difference between the two images is beneficial to the system operator when attempting to detect FOD. Take shadows for instance. Shadows are differences that will be picked up by the x-ray system, however they have no correlation to FOD.

The second technique relates to the comparison of a cluster of pixels. To do this, the pixel orientation high probability FOD object such as, tools, nuts, bolts, and bags will be inputted into the system. These images will be saved in the database so when the differential imaging system receives the image from the X-ray system, it will search for the previously inputted pixel orientations relating to the FOD objects (which are depicted by clustered of pixels) inside the image from the X-ray system. The advantage for this is that it has less detection time since the system knows what to look for. This technique is also beneficial for incorporating into the FOD detection system when searching for specific high priority items, which present a high probability of danger if over looked in the production process. However, the disadvantage to this technique is that it is not possible to detect any difference if they are not previously inputted into the system.

The proposed solution of use concerning these methods is to evaluate the need and probability of each station where differential imaging could be used. The aircraft sub assembly components which have a high rate of FOD and probability of FOD detection have to be identified. Then a combination of multiple techniques in high probability areas where FOD is detected could be implemented. In the case of an area of high probability of FOD detection, pixel by pixel could produce a high reliability rate in detecting FOD. For areas where FOD is not highly probable to be detected, comparing clustered of pixels technique could be implemented due to its rapid comparison time. Also, differential imaging is a tool for the employees to analyze the image from the X-ray system not a decision making tool by itself. An example of differential imaging software (Developed by classmate Don Brody) interface is shown below.

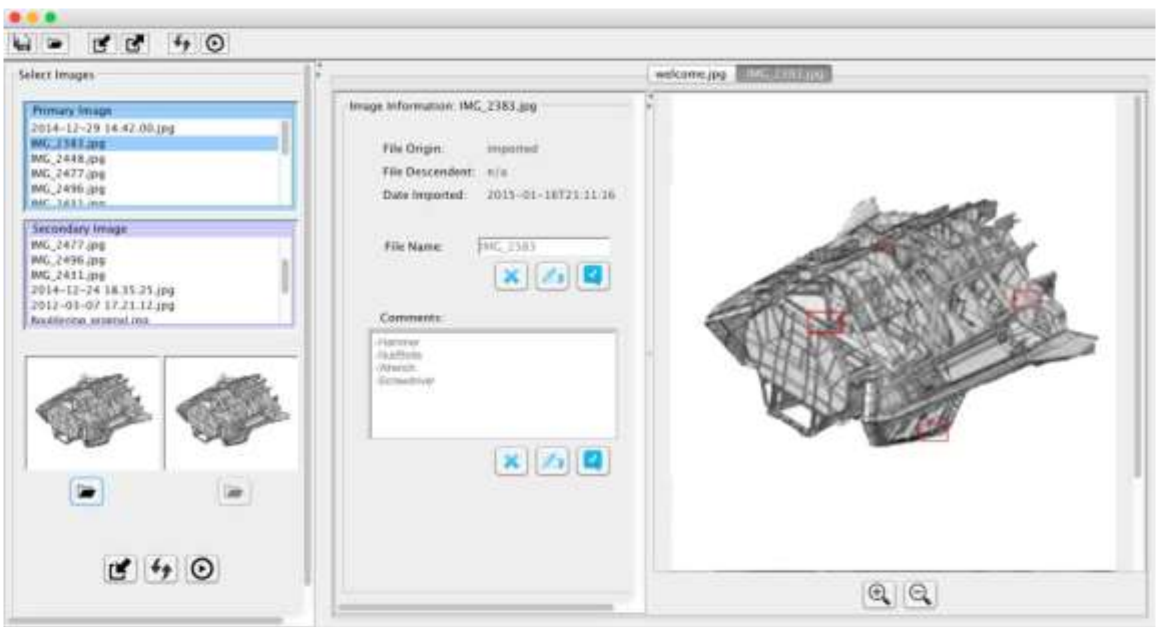


Figure 15: Differential imaging software interface

The interface, which the different methods can be used on, will need to be evaluated and analyzed. Including, meeting the user needs and preferences on software, hardware, trainability, and usability. These methods will be analyzed with respect to the cost to implement the system, the training time to use the system, and the reliably of the method used. The system will be evaluated with respect to the cost of buying the systems from outside vendors or building in-house. These methods will be presented, with the analysis of multiple components and different alternatives to the decision maker.

3.5 System Validation

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 the aircraft subassembly components. X-ray penetration depth was used to verify that with 220 kV of input voltage, the materials and their associated thicknesses could be penetrated at least 95% through. This establishes the plausibility of utilizing X-rays to penetrate the subassemblies at the desired depth, verification that FOD items would be visible and detectable once the assembly component had been penetrated.

3.5.1 X-Ray Penetration Model

X-ray Penetration Depth:

One of the characteristics of X-ray radiation that makes them useful for inspection is the Penetrating ability. When they are targeted to penetrate into an object, a portion of the photons are absorbed and a portion are scattered, while others completely penetrate the object. The penetration can be expressed as the amount of radiation penetrating into the object. The penetration capability depends on the energy of the individual X-ray and the atomic number, density, and thickness of the object that is under inspection.

The probability of photons interacting is related to their energy. Increasing x-ray energy generally decreases the probability of interaction and, therefore, increases penetration. Generally, high-energy x-ray can penetrate deeper than low-energy x-rays.

Half Value Layer (HVL)

Half value layer (HVL) is the perhaps the most significant factor when describing both the penetrating ability of specific radiations and the penetration through specific objects. HVL is the thickness of material of the inspected object penetrated by one half of the transmitted x-ray radiation and is expressed in units of distance (mm or cm). Using the following formulas, the HVL value enables the penetration depth of each X-ray alternative to be calculated.

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

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

Material	HVL (mm)		
	30 keV	60 keV	120 keV
Tissue	20.0	35.0	45.0
Aluminum	2.3	9.3	16.6
Lead	0.02	0.13	0.15

Table 7 – HVL based on Material

Above is a chart that summarizes the relationship between the absorption coefficient (μ), HVL, the inputted energy of the X-ray device and the penetration depth. The absorption coefficient varies based on the density of the material being considered. As the density of the material increases the absorption coefficient increases. The following graph shows the relationship between the absorption coefficients of materials with different densities for a specific input voltage.

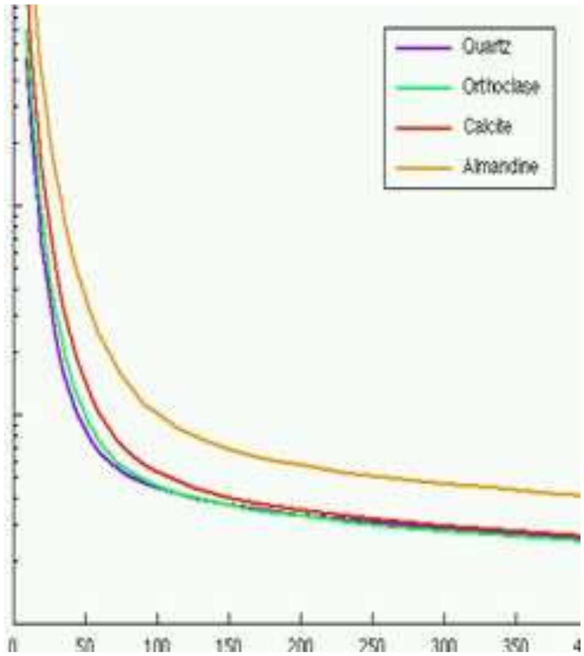


Figure 16: Absorption Coefficient vs Material

HVL is inversely proportional to absorption coefficient. Therefore, by having a smaller absorption coefficient, the value of HVL increases. By increasing the inputted energy, the absorption decreases exponentially and HVL increases exponentially. The following graph shows the relationship between energy and HVL:

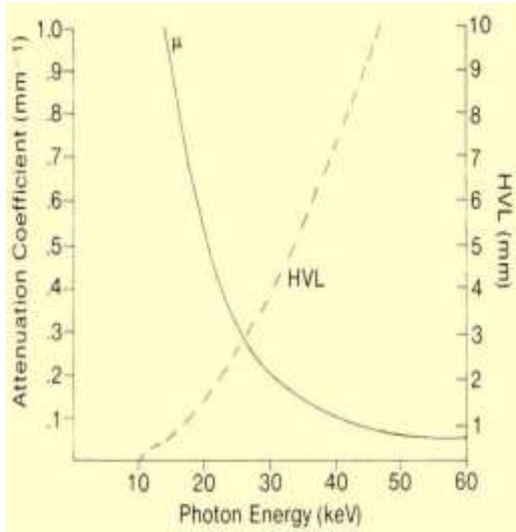


Figure 17: Energy vs HVL

The following chart summarizes the relationship between the penetration depth variables:

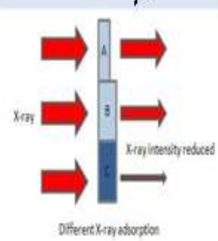
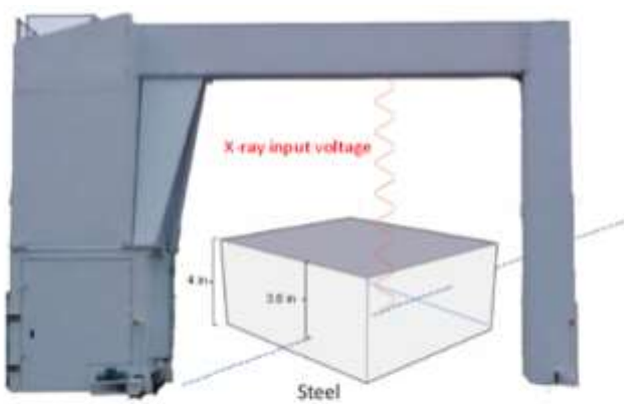
Absorption coefficient (μ)	• Quantity that characterizes how easily a material can be penetrated by a beam of x-ray.	• Density (ρ) Steel>Titanium> Aluminum • X-ray energy • Material	↑Density ↑μ ↑Energy ↓μ
Half Value Layer (HVL)	• 50% of x-ray radiation is absorbed	P = $\left(thickness\right)^{HVL}$ $HVL = \frac{0.632}{\mu}$	↓μ ↑HVL ↑HVL ↑P
Inspected component thickness	• Forward Fuselage • AFT fuselage • Center fuselage • Wing modulus		↑Thickness HVL↓ ↑Thickness Penetration↓

Table 8 – Penetration Depth Variables

Penetration Depth Example:

Below a hypothetical example of the above Penetration Depth model is displayed. Imagine the cube being scanned by the Gantry system as an aircraft sub-assembly component. The absorption coefficient is has been established for the material and X-ray input voltage. With this data the HVL can be calculated, which can then be used as the exponent for the thickness of the component outputting the specific penetration depth. Once the specific penetration depth has been established for the combination of sub-assembly component and X-ray alternative; the penetration depth can be divided by the Sub-Assembly thickness to determine the penetration percentage possible per that combination. Below we have determined a 95% penetration rate, therefore, this X-ray alternative would not be considered at the specific inspection station being tested for

.



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

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

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

X-Ray Machine	Power (Watt)
Gantry	300

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

Figure 18: Penetration Depth Examble

The probability of FOD detection with x-ray inspection alternatives depends on the quality of the formed image by x-ray alternatives. The x-ray images quality parameters are signal-to-noise ratio (SNR) and the contrast-to-noise ratio (CNR) that are evaluated by following equations:

$$\text{Signal} - \text{to} - \text{noise ratio (SNR)} = \frac{(I_S)_{\text{mean}}}{\sigma},$$

$$\text{Contrast} - \text{to} - \text{noise ratio (CNR)} = \frac{(I_S)_{\text{area1}} - (I_S)_{\text{area2}}}{\sigma},$$

Where (I_S) mean is the mean x-ray intensity (gray value) over the inspection region of interest and σ is the standard deviation at the inspection region.

X-ray source energy has an effect on the image. In general, as the x-ray source has higher energy the resulting SNR will be higher and that leads to higher probability of detection. The following image is an image of an identical aluminum object being inspected with the same experimental setup and measured the backscatter images of the test object with different incident X-ray energies. The selected X-ray tube voltages were 100 kV, 200 kV, 400 kV and 600 kV, respectively. Here, the power (1500W) of the X-ray tube and other factors has been kept constant.

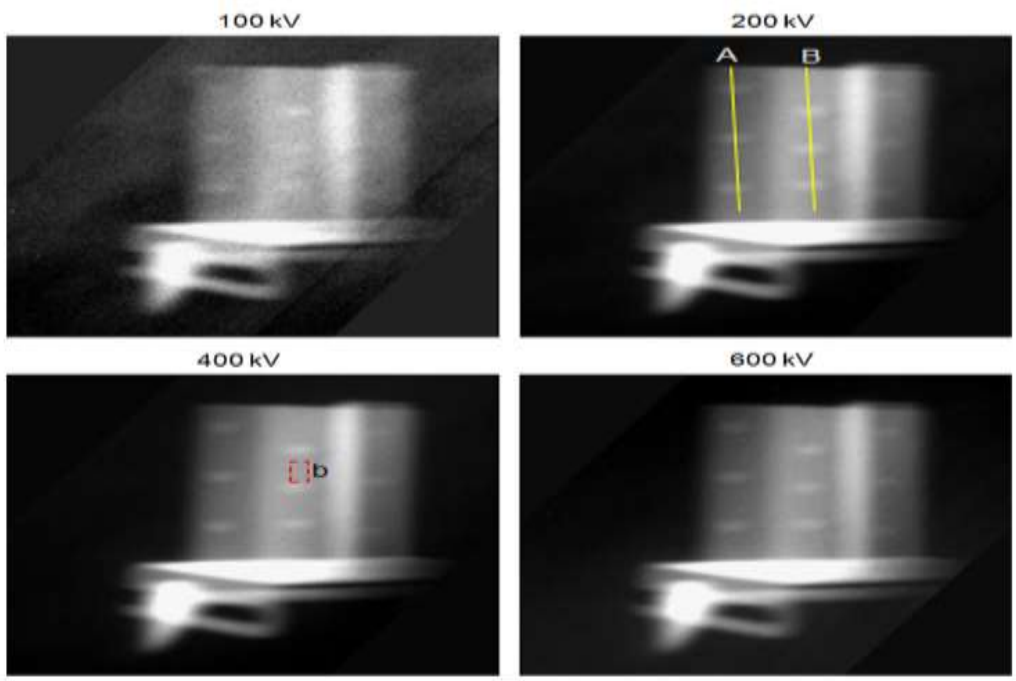


Figure 19: Varied X-ray Intensity

The following graph represents the variation of the achieved intensity level for each of the x-ray tubes with 100KV, 200 KV, 400 KV and 600 KV. The effect of x-ray tube voltage power is reflected on this graph. The blue line which represents the highest x-ray voltage (600KV) has highest corresponding intensity and the black line which represents the 100 KV x-ray tube has least intensity on each segment of the scanned object.

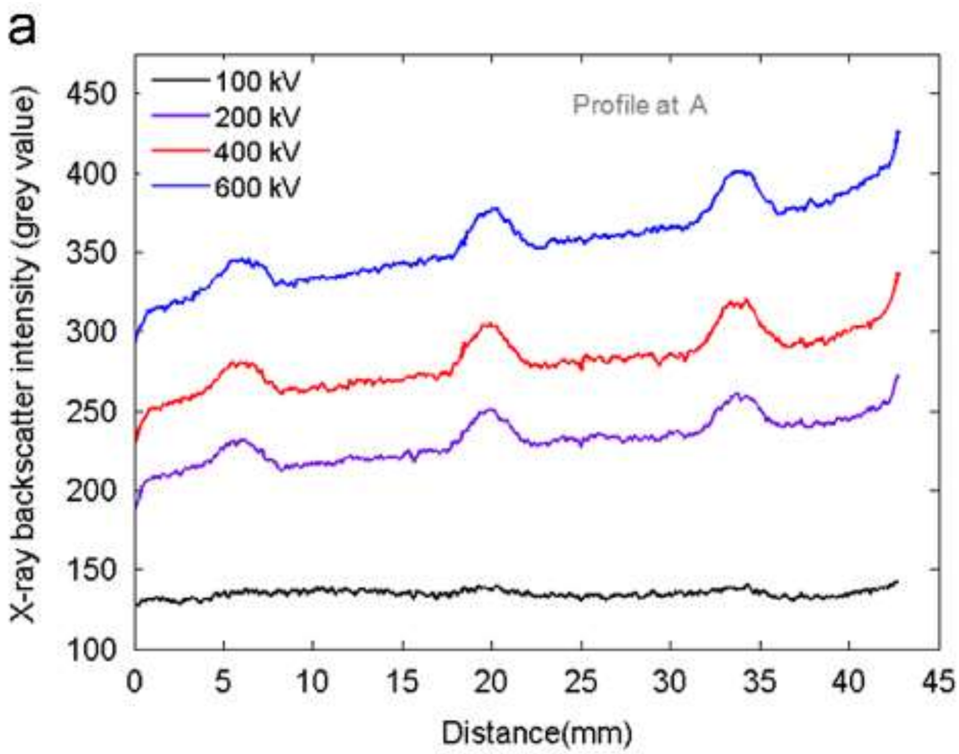


Figure 20: Intensity based on Varied Input Voltage

X-ray tube voltage (kV)	Mean X-ray backscatter intensity (I_{mean}) in gray value	Standard deviation (σ)	SNR = (I_{mean}/σ)
100	153.8	4.501	34.2
200	318.2	7.171	44.4
400	389.1	7.244	53.7
600	461.9	6.206	74.4

Table 9 – SNR of Varied Input Voltages

3.5.2 Signal to Noise Ratio Calculation

The ability to detect a FOD inside an aircraft component during inspection is directly related to the ratio of the x-ray intensity through the specific material of component to the background or object noise level. This ratio is called the absolute contrast to noise ratio, or the image signal to noise ratio. In general, noise is the main limiting factor in the ability to detect the object and being imaged with an x –ray device, especially when viewing objects with small and low-contrast.

$$\text{Signal to Noise Ratio} = (Is)mean/\sigma$$

The mean intensity and SNR equations were utilized to verify the ability of the X-ray alternatives considered to penetrate through the assembly components at each inspection station and output a clear image. Exact dimensions on the F-35 components are proprietary so estimations were calculated based on scaled models. Using a total height of 14.3 ft the fuselage was estimated at 1.64 ft, and wing module at 0.83 feet (Bill). The height of the different component is considered as the distance that the x-ray beam should travel.

The primary materials used in fuselages and wing modulus are carbon and aluminum which have linear attenuation coefficients equal to 0.02 and 0.05 (“Congressional”). The SNR obtained for aluminum and carbon portions of the fuselage and wing module are higher than 1, which represents an accuracy equivalent to 95% probability of detection.

X-Ray Intensity:

X-ray intensity is the amount of energy that passes through a given area that is perpendicular to the direction of x-ray beam in a given unit of time. The intensity of an X-ray source can easily be measured with the right detector. The intensity of an x-ray source is calculated by the following equation:

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

The Linear Attenuation Coefficient (μ):

The Linear attenuation coefficient (μ) is the fraction of a beam of x-rays that is absorbed or scattered per unit thickness of the inspected object. Using the x-ray transmitted intensity equation above and linear attenuation coefficients the following calculations could be performed:

- The intensity of the energy transmitted through a material when the incident x-ray intensity, the material and the material thickness are known.
- The thickness of the material of the inspected object when the incident and transmitted intensity, and the material are known.
- The material can be determined from the value of μ when the incident and transmitted intensity, and the material thickness are known.

The following graph represent the linear attenuation coefficient of different materials for different energy level of x-ray tubes.

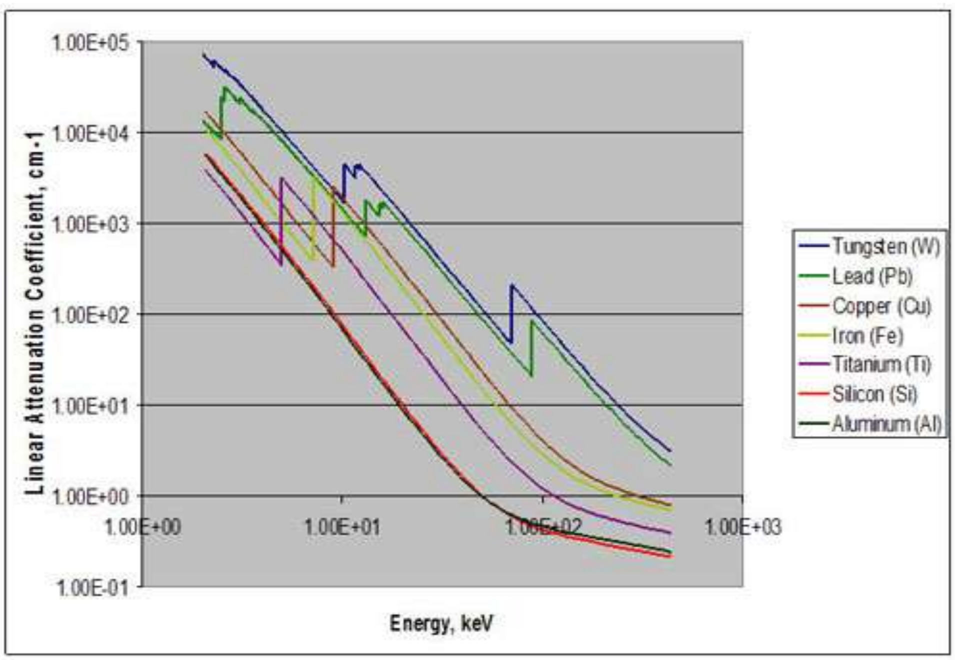


Figure 21: Linear Attenuation Coefficient vs Energy

Signal to Noise Ratio:

The ability to detect a FOD inside an aircraft component during inspection is directly related to the ratio of the x-ray intensity through the specific material of the component to the background or object noise level. This ratio is called the absolute contrast to noise ratio, or the image signal to noise ratio. In general, noise is the main limiting factor in the ability to detect the object and image capture with an x –ray device, especially when viewing objects with small and low-contrast. Therefore, in order to increase the quality of the image the noise level should be high.

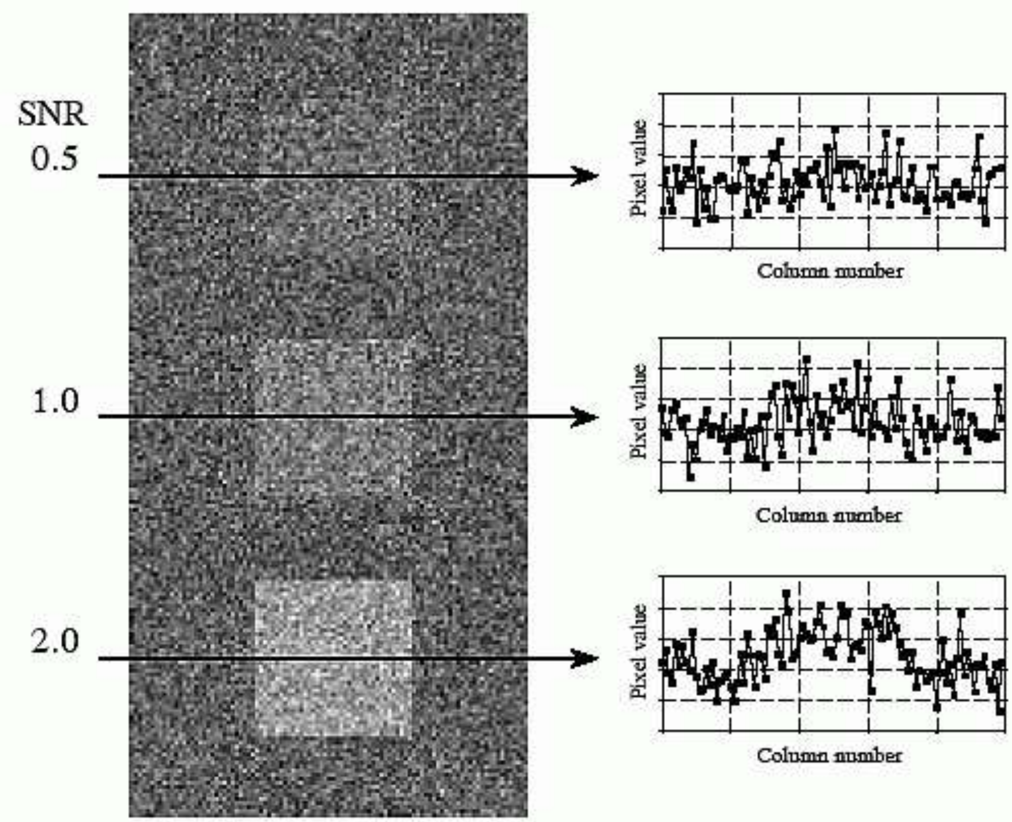


FIGURE 25-8
Minimum detectable SNR. An object is visible in an image only if its contrast is large enough to overcome the random image noise. In this example, the three squares have SNRs of 2.0, 1.0 and 0.5 (where the SNR is defined as the contrast of the object divided by the standard deviation of the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

Figure 22: SNR Levels (0.5, 1, 2)

The exact value of the minimum detectable SNR depends on the size of that specific object inside the container that is being inspected, but in general the larger the size FOD, the higher chance of detectability. In general the trouble of detecting an object with human eyes usually occurs when the resulting SNR falls under 1. Since we have considered differential imaging software which compare the captures image by x-ray and original picture pixel by pixel and has higher ability for detection, we have considered the probability of X% of FOD detection if the SNR of an x-ray alternative be greater than 1 during inspecting an aircraft component.

SNR validation of X-Ray Alternatives:

In order to determine the signal to noise ratio of x-ray alternatives per assembly component, we have measured this for wing module and fuselage. For this purpose we only have considered the material in the component that has been used as the majority of the structure and has highest density. The following chart is representing the result of this calculations. All the achieved SNR are greater than one hence we assume that the alternatives are passing the minimum detectability requirement.

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

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

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

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

Table 10 – Estimated Assembly Component SNR

3.6 X-Ray Mounting System Alternatives

Four X-ray mounting alternatives were considered for the Enhanced FOD Inspection System proposed for the aircraft assembly process; all incorporating backscatter or transmission imaging and some a combination. AS&E and Nucsafe are the manufacturers of the X-ray devices considered.

- Linear rail (Nucsafe)
- Robotic Arm System (Nucsafe)
- Gantry (AS&E)
- Portal (AS&E)

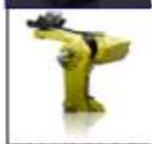
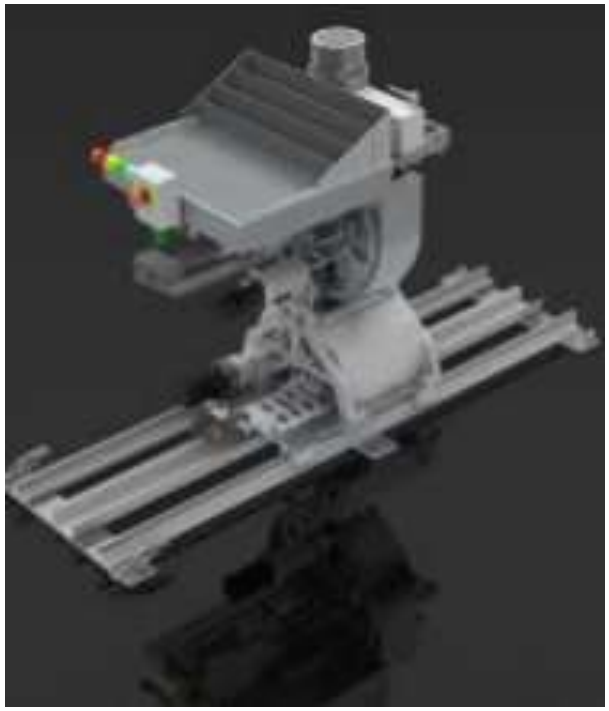
X-ray System	X-ray System	Source	Penetration Power (in steel)	Power Requirement	Scan Speed	Dimensions	Start Up Time	Radiation Dose
	Linear Rail	Backscatter	6.3 mm	250-600 watts	0.185(m^2/s)	DIFFERENT SIZES AVAILABLE	20 min	BASED ON SIZE
	Robotic Arm	Backscatter	6.3 mm	250-600 watts	0.185(m^2/s)	DIFFERENT 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

Table 11 – X-ray Mounting Alternatives

Each of the alternatives considered have different operational features including source of X-ray, penetration power, power requirement, resolution radiation dose and dimensions and cost. There are several factors that are being considered in order to match each of these alternatives as the optimal inspection station in the production process. We have considered the dimension and penetration depth of each X-ray alternative through the thickest and most dense material in the aircraft sub assembly component. The device that has higher penetration ability will have a greater probability to detect the FOD within the subassembly component through the most dense material and furthest distance within.

Linear Rail System



The linear rail is an adjustable system; the length can be adjusted based on the desired object being scanned or can be adjusted to image different lengths/portions of the object. The linear Search system is designed in a way to scan objects either straight up or upside down. The system is set up in a way to move requiring 2 people (MiGFlug).

Mounting Alternative	Source	Penetration	Power Requirement	Scanning speed	Dimension	Startup t	Radiation dose
Linear Rail	Backscatter	6.3 mm	250-600 watt	2 sqr meter/	Different Sizes Available	Less than	Based on Size

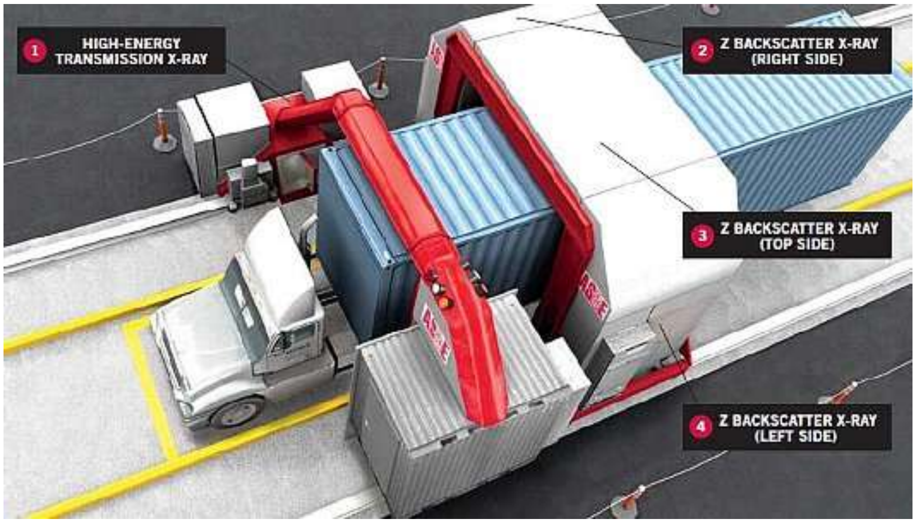
Robotic Arm System

This imaging system technique allows for single sided x-ray imaging, this is a better system in comparison to traditional transmission x-ray that requires the access to both sides of the target. With its unique capability, this system is able to identify sub-millimeter cracks and flaws within multilayer materials in which results in a great image quality and resolution. With the shape of a robotic arm, this is new type of X-ray backscatter imaging that utilizes radiography by selective detection (RSD).

Nucsafe offers scatter X-ray imaging devices that utilize RSD with a pencil beam Compton backscatter imaging (CBI) technique. RSD techniques offer greater subsurface resolution than uncollated techniques, at speeds at least an order of magnitude faster than highly collimated techniques. Moreover, backscatter RSD selectively detects X-rays that boost the signal-to-noise ratio, allowing the detection of features, which may otherwise go, undetected using conventional CBI or transmission radiography.

X ray system	Source	Penetrat	Power requi	Scanning sp	Dimensio	Startup	Radiation
Robotic Arr	Backscatter	6.3 mm	250-600 watt	2 sqr meter/	Different Sizes Available	20 min	Based On Size

Omniview Gantry



OmniView Gantry inspection System combines high penetration transmission X-rays with Z Backscatter technology to deliver the most reliable means of uncovering contraband and threatening materials in densely loaded cargo containers. This combination makes the system the most reliable means of detecting contraband and threatening materials, such as drugs, weapons, and explosives hidden in cargo containers, tankers, and large vehicles.

The technology eliminates the need for costly infrastructure such as an outer building for radiation safety often required with other gantry systems. The system operates by moving on rails past stationary vehicles and cargo. The system is bi-directional that would allow for high throughput of two trucks per scan, 28 trucks per hour.

X ray System	**Source**	**Penetration**	**Power Requirement**	**Scanning speed**	**Dimension**	**Startup**	**Radiation Dose**
Gantry	Transmissic backscatter	400 mm	380-480 VAC	0.2,0.30.4	Length 36.5 m,width 3 ,height 5.0 m	15 min	5 mR

Z **Portal**

Z portal is a high-throughput, drive-through cargo and vehicle screening system with multi-view Z Backscatter imaging in order to detect contraband. It produces images from three sides of the object under examination, and is the most effective drive-through screening system for congested security checkpoints. This screening system is available in two different sizes. Small size is being used for passenger vehicles, and the other one is used for buses, large trucks, and cargo vehicles. Due to its high-throughput screening gateway, the Z portal would allow roughly about 80 trucks or 120 passenger vehicles per hour. The Z Portal is leveraging Z Backscatter technology to produce photo-like images of the contents of a container or vehicle, highlighting organic materials such as explosives, illegal drugs, currency, and other contraband (Bill)

X ray system	**Source**	**Penetration**	**Power requir**	**Scanning speed**	**Dimension**	**Startup t**	**Radiation Dose**
Z Portal	Backscatter	300 mm	480 VAC	TBD	Width 8.9 Height 6.5	15 min	5 mR

3.6.1 Mounting Alternative Decision Analysis

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

Table 12 – X-ray Mounting Alternatives Swing Weights

With the help of our sponsor we were capable of establishing weights for the different attributes associated with each of the alternatives; the swing weights method was utilized to determine the specific weights. After converting each of the individual values to a 0/1 scale, Utility vs Cost analysis could be conducted.

3.6.2 Utility vs. Cost Analysis

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

By multiplying each of the weights with their correlating values and summing them it was possible to determine a score for each of the X-ray mounting alternatives considered. The graph below displays these utility scores and their associated acquisition costs. The robotic arm proved to be the optimal choice, with the highest utility score (.62); and second lowest cost ($301,000).

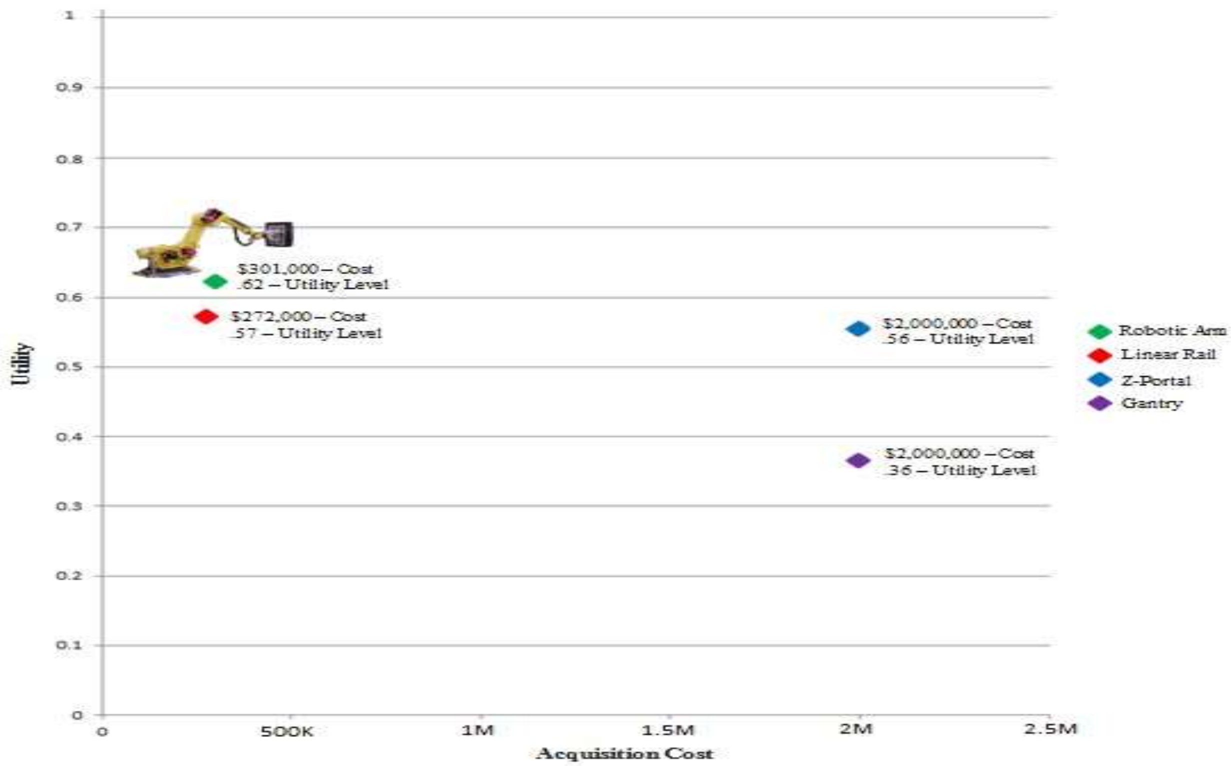


Figure 23: X-ray Mounting Alternatives Utility vs Cost

4.0 Method of Analysis

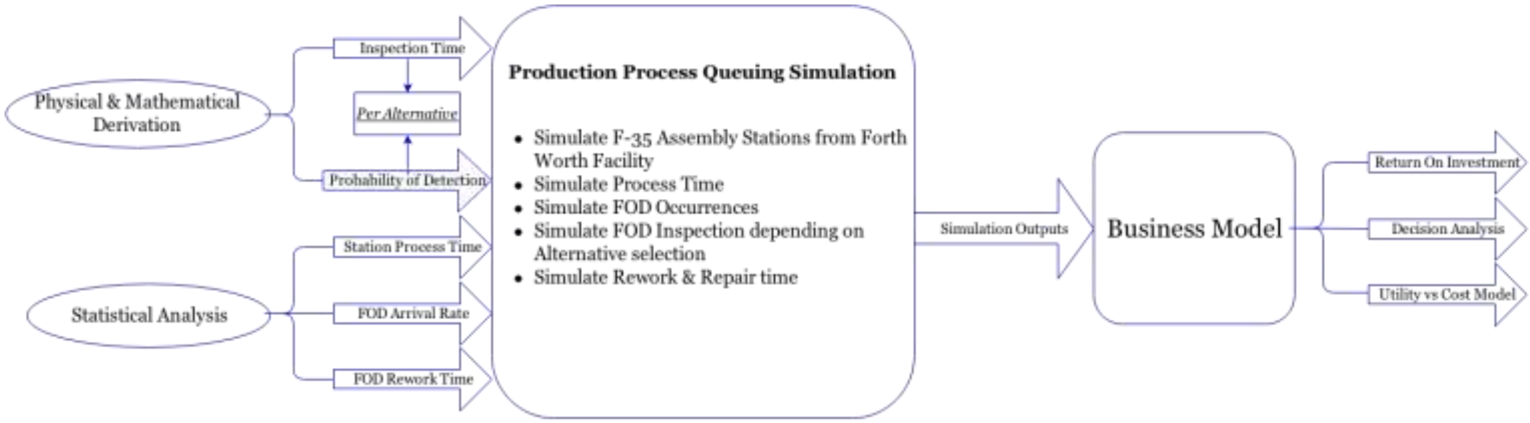


Figure 24: Method of Analysis

The diagram above depicts the order in which we are performing the analysis; the primary idea is to use production line simulation output data in a business model to evaluate the benefit of the X-Ray System.

4.1 Simulation

Our primary method of analysis for our proposed system will be through a simulation of the F-35 Assembly Process at Lockheed Martin's Ft. Worth facility, from part Arrival to final finishes, with emphasis on FOD events, what this will do is, through the use of discrete event simulation; provide insight on the effect of FOD and its time of detection throughout the production of the F-35, we shall be able to simulate different inspection system alternatives from manual inspection to different instantiated architectures of the proposed X-Ray system. What this will primary show is the difference in rework and repair hours and cost with different rates and timings of detection. By doing this we will shed light on the non-linear relationship between time of FOD detection and costs of rework and repair, explaining that even the smallest increase in detection earlier on in the production process, can lead to a substantial difference in costs.

4.1.1 Simulation Overview & Model Boundaries

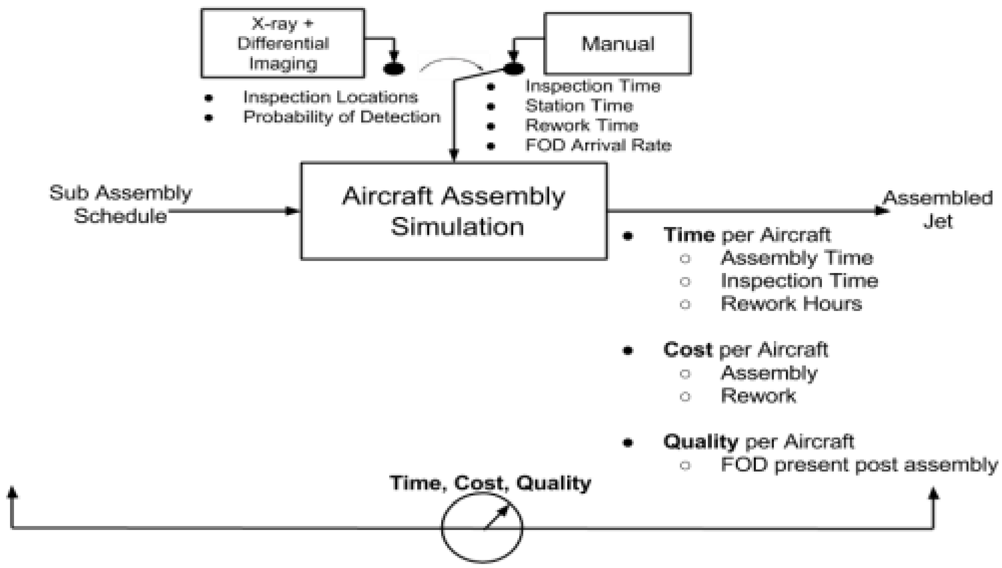


Figure 25: Aircraft Assembly Simulation Diagram

The diagram above depicts the processes being simulated with inputs, outputs as well as parameters. The Simulation Tool, which had been named FODSIM, is capable of simulating the production process incorporating both manual inspection and the proposed FODXSYS inspection. This will primarily show is the difference in rework and repair hours and cost (Time Cost & Quality) with different detection rates, shedding light on the non-linear relationship between the time of FOD detection and costs of rework and repair.

4.1.2 Simulation Requirements

In this section, the requirements for the simulation are explained, providing for a solid idea of what the simulation must exactly accomplish.

Input Requirements

IR.1 Number of Shifts to run Simulation

IR.2 Inspection Design Alternative

IR.3 FOD Arrival Rate

IR.4 Customized Inspection Time and Probability of Detection

IR.5 Customized Station Order and Station Time

Functional Requirements

FR.1 The Simulation Shall simulate FOD events

FR.2 The Simulation Shall simulate FOD inspection

FR.3 The Simulation Shall simulate FOD rework

FR.4 The Simulation Shall standard assembly

FR.5 The Simulation Shall be entirely configurable by the user

Output Requirements:

OR.1 Total production time per Aircraft

OR.2 Total Labor hours & cost per Aircraft

OR.3 Total Rework & Repair hours per Aircraft

OR.4 Queue Statistics for each part (Insight on Wait Time)

4.1.3 Simulation Implementation

Simulation development had primarily been done in Java; the UML class diagram below describes the class breakdown and interaction.

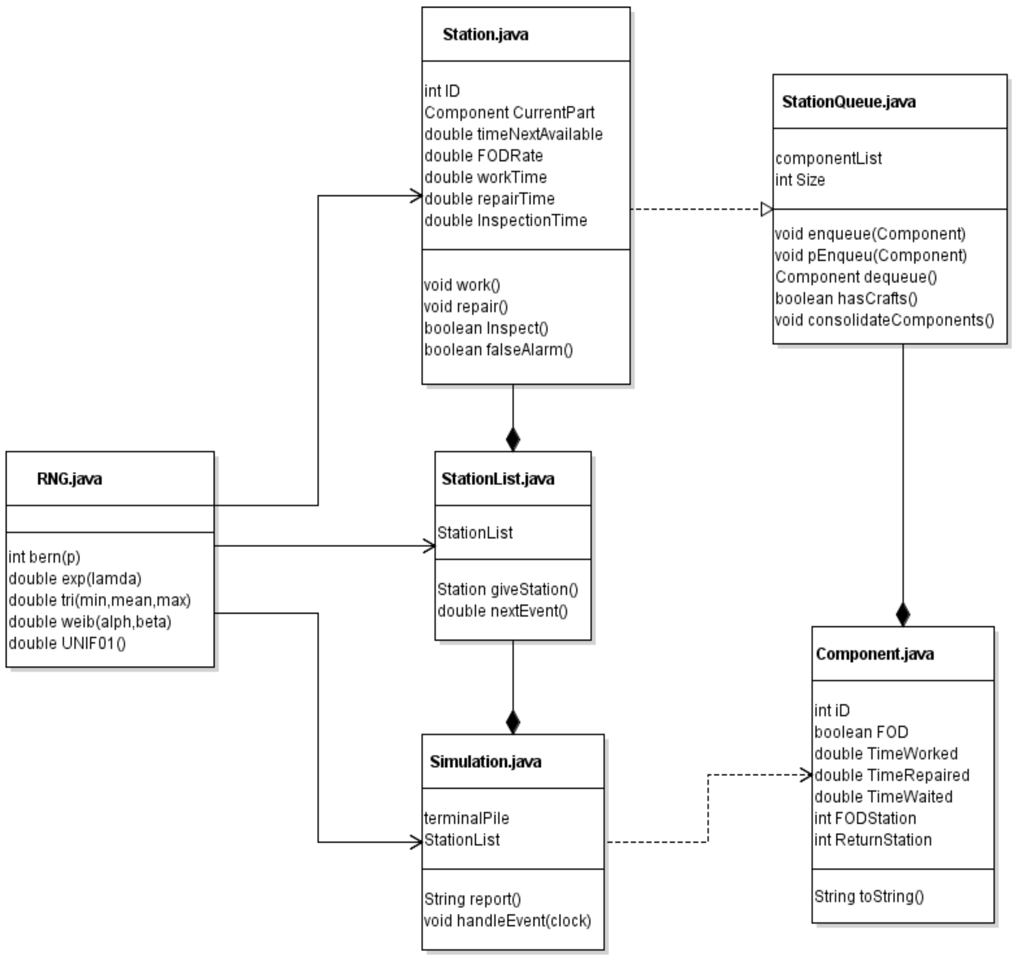


Figure 26: Simulation UML Diagram

The Simulation primary structure is in Simulation.java, where components traverse through Stations that belong to separate StationLists, they are then put together in the Simulation class which performs event handling for each event. Both the components and stations track their statistics, which potentially allow for a deeper analysis and easier troubleshooting and debuggging.

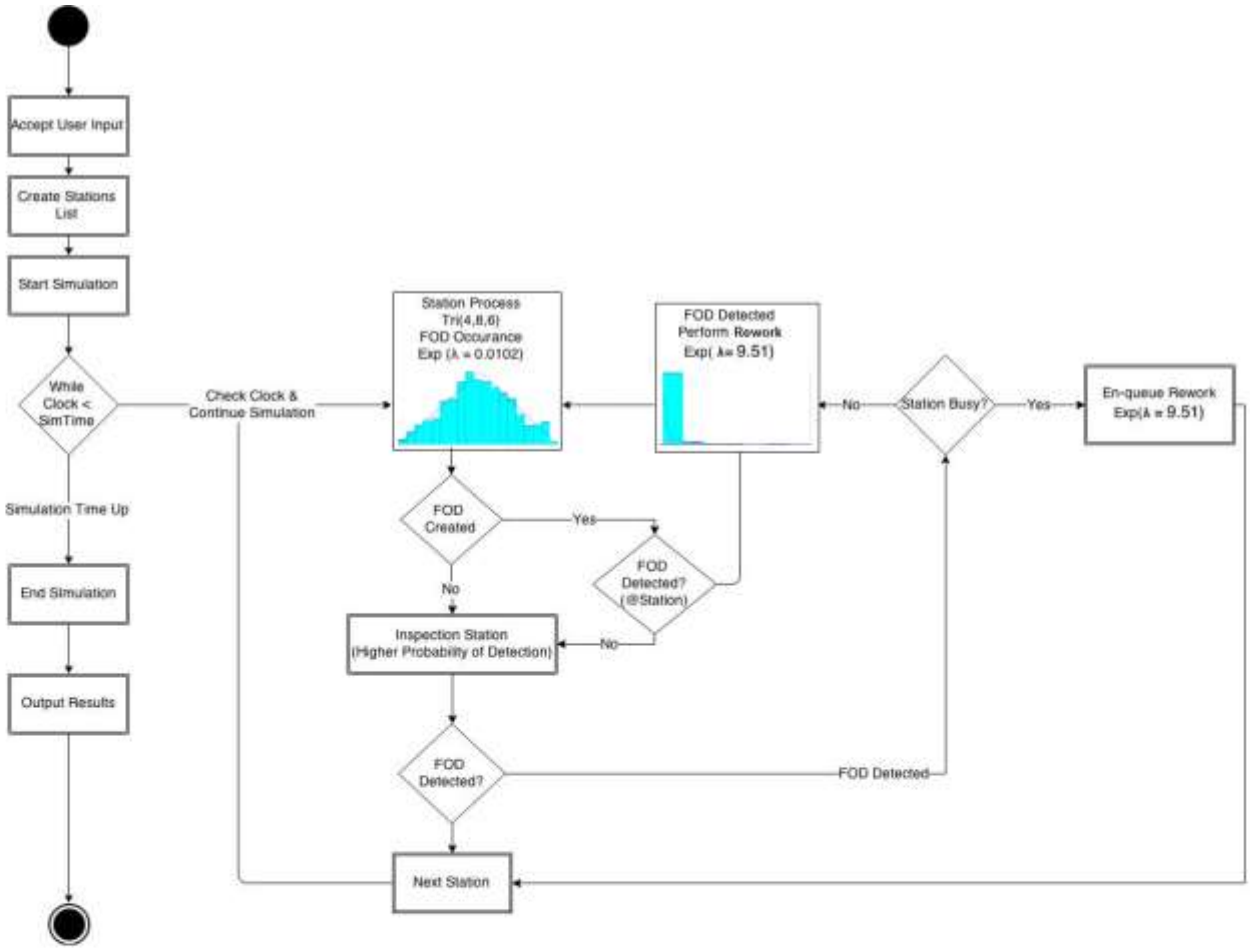


Figure 27: Simulation Flow Diagram

This diagram above depicts the flow of our simulation, logically showing how the subassembly objects will run through each station where they are worked on for a duration determined by the Triangular distribution random number generator, with a chance to create and detect FOD on sight, modelled by exponential distribution and Bernoulli distributions respectively. If FOD is missed, the subassembly will continue forward to the next station, until it reaches an X-Ray inspection station will have a significantly higher probability of detection than the standard assembly stations. If FOD is detected, it will be sent to have the rework and repair necessary for it to be completed, which is modelled

4.1.4 Case Study Parameters & Assumptions

For any Simulation, one must make assumptions in order to be able to represent the real complex system, for our particular case study of the F-35 production at Ft. Worth; we were forced to make some assumptions from secondary data as to what is occurring in the facility due to issues with data provision.

- There are 26 total Stations: 21 Assembly and 5 Inspection Stations with FODXSYS (52 Stations Manual)
  - Process Time modeled by TRI(50,60,70)
  - FOD Events are based on an arrival Rate EXP(λ =0.0102)
  - FODXSYS Inspection time modeled by Norm(0.42, 0.0347)
  - Manual Inspection time modeled by Norm(4.2, 3.35)
  - 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 modeled as Bernoulli Distribution based on Probability of Detection Model
  - 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)

4.1.5 Simulation Validation

Simulation results have been validated by comparing simulation output to historical data. The average output of simulation iterations were then compared to the obtained data set. Parameters for Station Labor Time, FOD Arrival Rate and Rework Time were then minimally adjusted until FODSIM output data was within three standard deviations of the historical data.

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

4.2 Design of Experiments

Our Design of Experiments table below explains that various FOD rates and Detection Accuracies will be compared. Each variation will represent a design alternative for each of the scanning stations, which are explained by the viable alternatives diagram from the alternatives section above. The primary parameters that will be changing for each run of the simulation are the FOD Rate and probability of detection which will vary with each of the X-ray alternatives. This allows for the measuring of the sensitivity of the parameters.

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)					

Table 13 – Design of Experiments

4.3 Business Case Model

It is important to emphasize once again that a key feature of the simulation is the customizable capability, which enables it to adapt to any aircraft production corporation. Due to issues with proprietary data it is very difficult to attain realistic data points from our sponsor Lockheed Martin, yet once the simulation is completed, it can be provided as a tool for Lockheed Martin or any Aircraft Production Corporations to input their own data. This will enable them to evaluate whether or not the investment in the enhanced FOD inspection system is justified.

Initially, the Aircraft Production Corporation will input their current production statistics into the simulation, which will output the data points to later be compared between their current system and the expected output with an Enhanced Inspection System. After converting the FODSIM hours output to monetary data the results for Manual and the Enhanced Inspection System can be graphed over time. The equations below display the way in which the conversion was carried out from hours to dollars.

5.0 Results & Analysis

5.1 Simulation 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. Analysis was then conducted using a t-test to establish the robustness of the data towards drawing conclusions.

Average of 1000 iterations of 1-year long runs		**Manual**	**FODXSYS**	**% DIFFERENCE**
Total Rework & Repair Times (Hours)	↓ Better	1856	1111	40 % ↓ **Decrease from Manual**
Inspection Times Per Station (Hours)	↓ Better	1041	208	80 % ↓ **Decrease from Manual**
Total Number of AC Out per Year (Aircrafts)	↑ Better	23	39	48 % ↑ **Increase from Manual**
FOD Present Post Final Assembly (Aircrafts)	↓ Better	3	0.3	197 % ↓ **Decrease from Manual**
Average Queue Wait (Hours)	↓ Better	7	27	75 % ↑ **Increase from Manual**

Table 14 – Results Summary

I. Total Rework and Repair Hours

Summing the total rework and repair performed by each station and dividing by the total of number stations outputted an average number of rework and repair hours for each iteration. A comparison of total repair hours is shown in the histogram below, the distributions between the manual and FODXSYS over the 1000 runs.

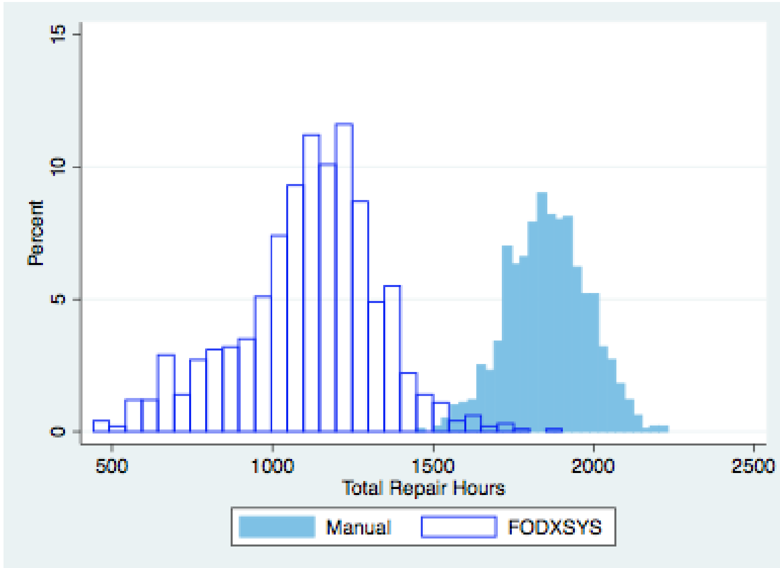


Figure 28: Total Repair Hours Distribution (Manual vs FODXSYS)

```
. 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
```

Table 15 – Total Repair Hours paired t-test(Manual vs FODXSYS)

FODSIM indicates that the implementation of FODXSYS will decrease the average rework and repair being performed each year by 40%. This is due to the fact that FODXSYS guarantees that no FOD occurrence prior to E-MAS reaches EMAS, eliminating the more severe cases of FOD where the Aircraft must be disassembled.

II. Total Inspection Labor Hours

By eliminating the repeated inspections after each station, FODXSYS dramatically reduces the total inspection hours per year in comparison to the manual process, total inspection hours for FODXSYS averaged to 212 hours/year, while total manual inspection hours 2811 hours/year.

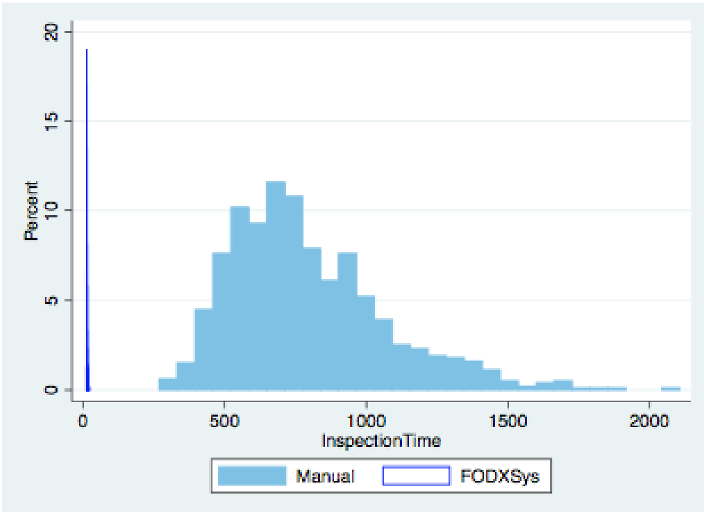


Figure 29: Inspection Time Distribution (Manual vs FODXSYS)

```
. 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
```

Table 16 – Inspection Time paired t-test (Manual vs FODXSYS)

III. . Average Difference of Aircraft Assembled

A t-test provided significant enough results to reject the null hypothesis, which stated the mean number of aircraft produced with Manual and FODXSYS would be equal. With

95% Confidence it can be estimated that between 5 and 6 more aircrafts will be produced per yearlong iteration with FODXSYS.

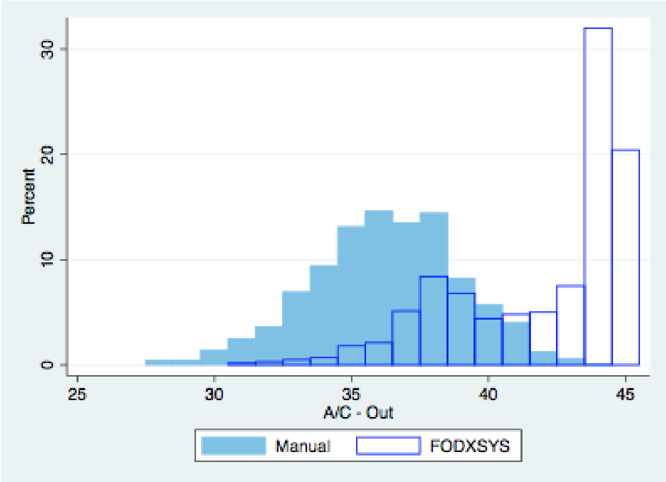


Figure 30: Total Aircraft Assembled Distribution (Manual vs FODXSYS)

. 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

Table 17 – Total Aircraft Assembled paired t-test (Manual vs FODXSYS)

This statistic relates directly to potential profit for an Aircraft Manufacturer. The increase in average number of aircrafts produced per year is a result of the decrease in average hours required per aircraft.

IV. Quality

The reputation of the Aircraft manufacturer and the safety of the Aircraft operators are dependent on the delivery of FOD-free Aircraft. FODXSYS successfully manages to reduce the yearly number of aircrafts delivered with FOD.

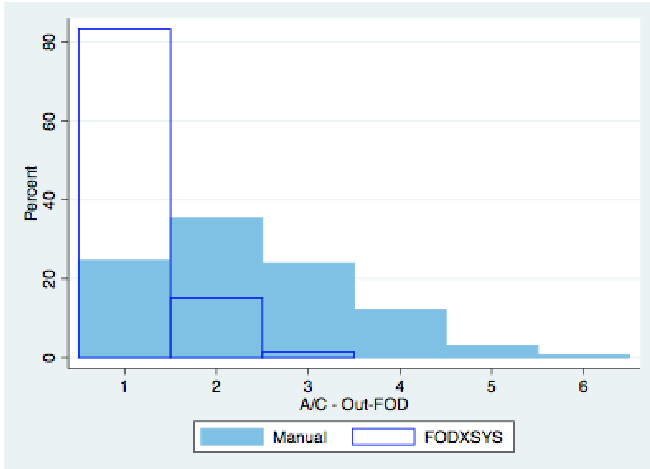


Figure 31: Aircraft Assembled containing FOD Distribution (Manual vs FODXSYS)

```
. 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
```

Table 18 – Aircraft Assembled with FOD paired t-test (Manual vs FODXSYS)

V. *Total Labor Hours per Aircraft*

By adding the standard labor, inspection labor and rework labor, the Total hours of labor are calculated, the figure below depicts the total labor hours divided by the number of Aircraft assembled for FODXSYS and manual.

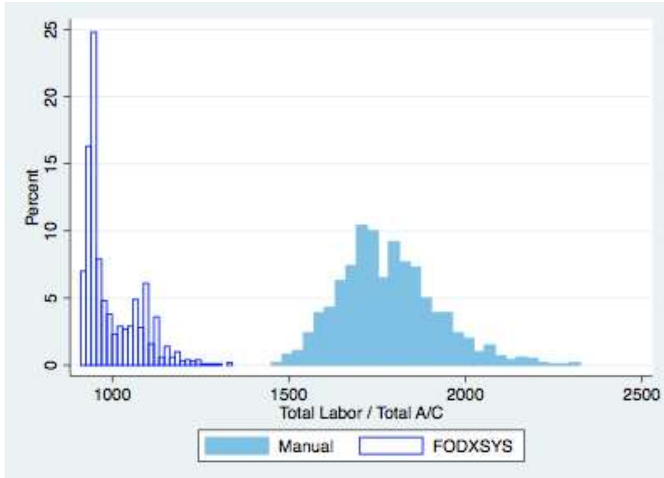


Figure 32: Total Labor Hours/Total Aircraft Distribution (Manual vs FODXSYS)

```
. 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
```

Table 19 – Total Labor Hours/Total Aircraft paired t-test (Manual vs FODXSYS)

5.2 Business Case Analysis Results

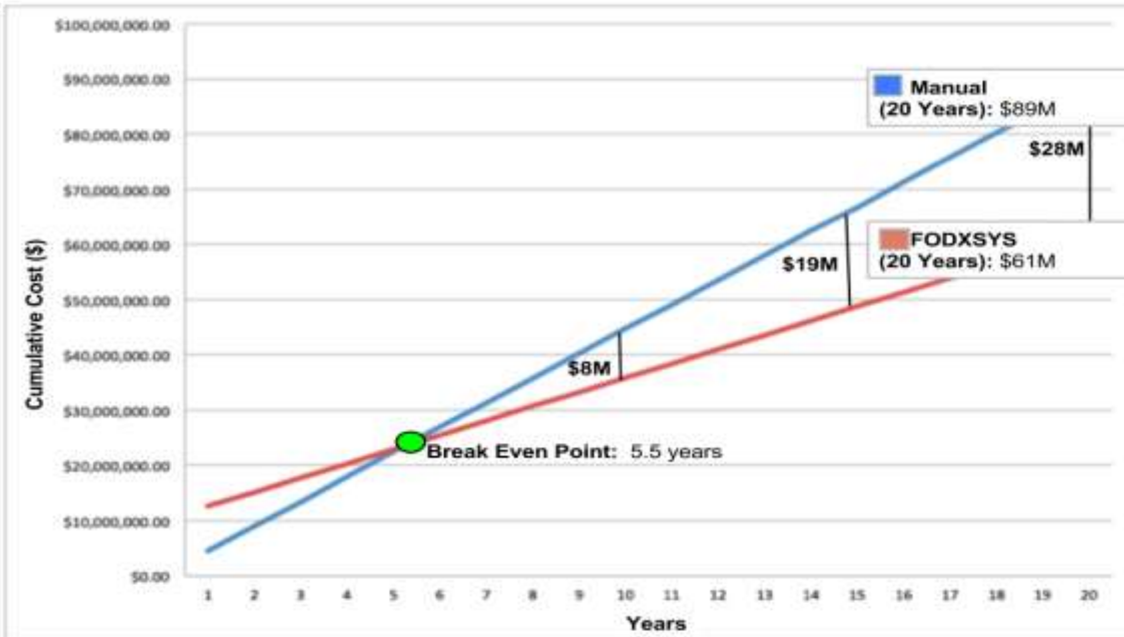


Figure 33: Business Case Graph: 20 years (Manual vs FODXSYS)

- $Cumulative\ Cost\ (Manual) = (Hours\ for\ Manual\ Inspections) * (3\ Inspectors) * \left(\frac{\$45}{hour}\right) + (Hours\ for\ Assembly) * (5\ Mechanics) * \left(\frac{\$45}{hour}\right) + (Hours\ for\ Rework) * (3\ Rework\ Personnel) * \left(\frac{\$45}{hour}\right)$

- $Cumulative\ Cost\ (Enhanced\ Inspenction\ System) = (Hours\ for\ Enhanced\ Inspections) * (1\ Inspector) * \left(\frac{\$45}{hour}\right) + (Hours\ for\ Assembly) * (5\ Mechanics) * \left(\frac{\$45}{hour}\right) + (Hours\ for\ Rework) * (3\ Rework\ Personnel) * \left(\frac{\$45}{hour}\right)$

An initial investment of $10M was established in the business case. This investment was representative of the cost for 5 X-ray machines; $2M was the average unit cost of the most expensive of alternatives considered. This was chosen to account for any unexpected costs that may arise during the system's lifecycle.

By using the equations displayed above it was possible to convert the simulation output to monetary data for the manual inspection technique and compare it to the monetary data for the Enhanced Inspection System (FODXSYS).

The graph above, highlights the expected breakeven point for the project, 5.5 years post implementation. Based on the output, 10 years after introducing the Enhanced Inspection System $8M is expected in cumulative savings, $19M after 15 years, and $28M after 20 years.

5.3 Sensitivity Analysis

Sensitivity analysis was performed to gauge the impact of changing the model parameters. Using the Aircraft Assembly Simulation, it was possible to vary the two primary input parameters – FOD Rate, and Detection Accuracy. The FOD Rate was varied between three λ levels distributed – low (.0042), medium (.0102), and high (.0260); while the Detection Accuracy varied from 50%-95%, incrementing by 15%. The Figures below depict the sensitivity analysis results.

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

Table 20 – Sensitivity Analysis

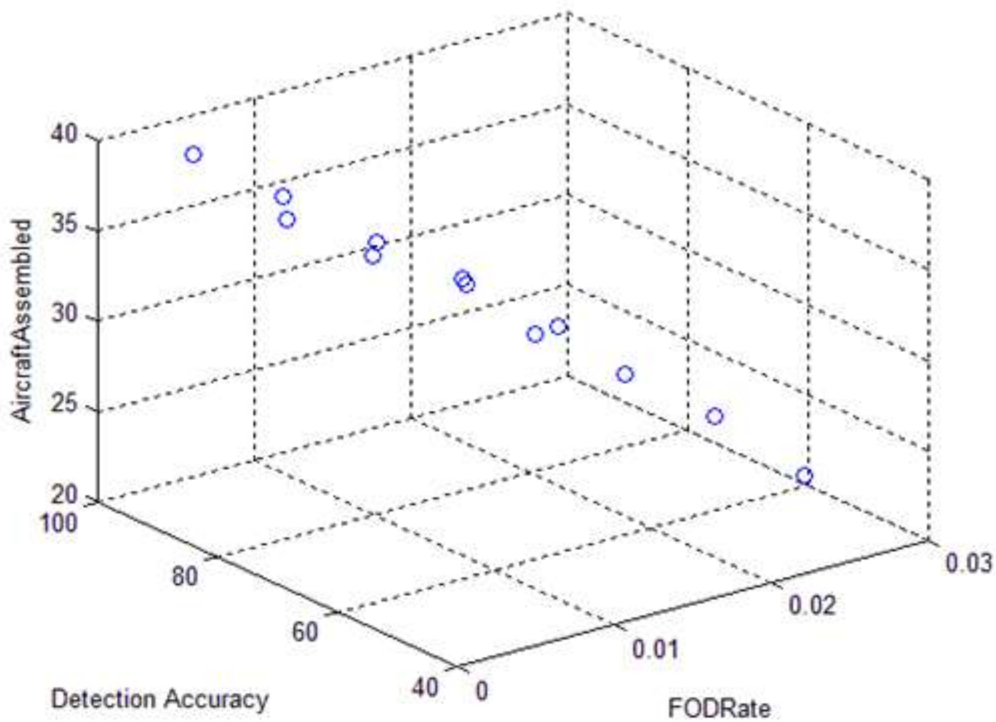


Figure 33: Detection Accuracy vs FOD Rate vs Aircraft Assembled

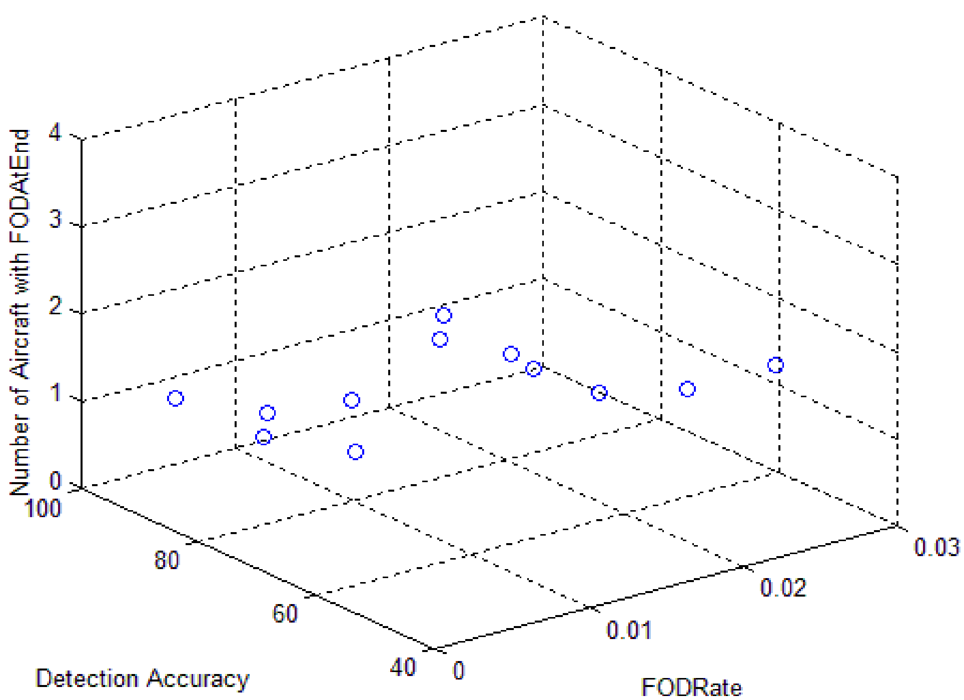


Figure 34: Detection Accuracy vs FOD Rate vs FOD present post Assembly

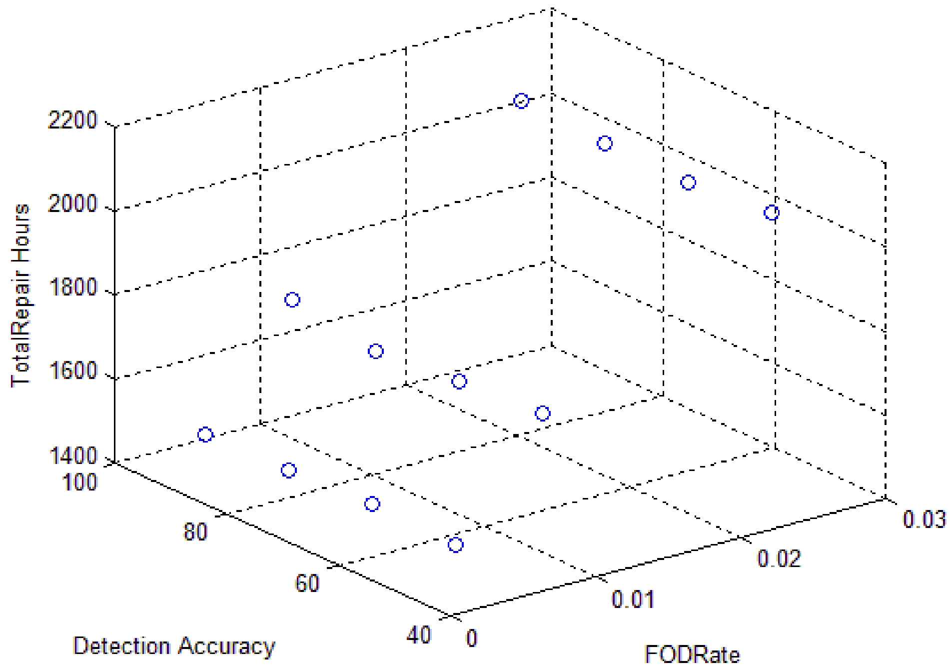


Figure 35: Detection Accuracy vs FOD Rate vs Total Repair Hours

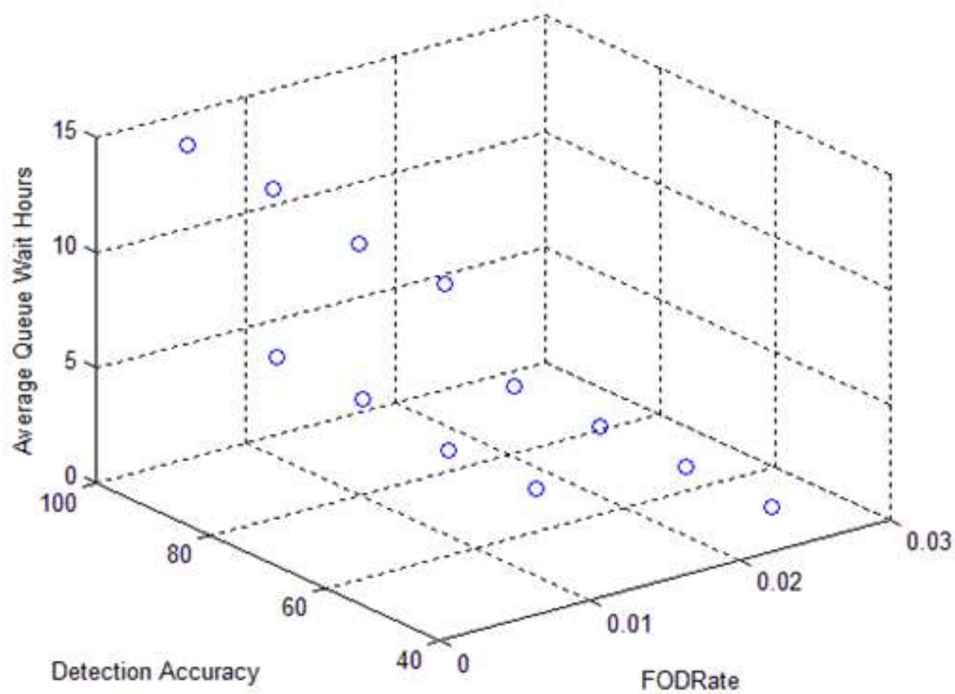


Figure 36: Detection Accuracy vs FOD Rate vs Average Queue Wait Hours

The primary finding from the analysis is that the most sensitive parameter in the system is the FOD rate, the rate at which FOD arrives into the system. This suggests that the best method to improve assembly and lower costs is to attempt to remedy the problem at the source by preventing FOD occurrences.

The detection accuracy does however, play a significant role in the total repair hours required and the quality of the delivered aircraft by reducing the number of delivered aircraft containing FOD as the detection accuracy increases. Yet, Sensitivity Analysis made the diminishing returns experienced very clear. Once 80% Detection Accuracy is reached, the system outputs begin to react as somewhat constant functions.

5.4 Conclusions & Recommendations

Ultimately, the installation of the enhanced X-Ray inspection system, FODXSYS, is recommended. The system successfully addresses the majority of the issues that are associated with the manual-visual inspection method through by-passing line-of-sight visibility restrictions and proving that a probability of FOD detection of 95% is possible. Simulation results of the production line have indicated that FODXSYS will improve aircraft production by considerably reducing total inspection hours as well as FOD-related rework hours through eliminating the majority of the severe rework cases. The study positively concludes that, by increasing the probability of detecting FOD at earlier stages of manufacturing, considerable costs may be averted from rework later in the production line

Sensitivity analysis indicates that, if there were a possible method to increase the probability of FOD detection for manual inspection up to approximately 80%, manual inspection would be a comparable, and potentially more efficient, method than FODXSYS. Figure 16 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. Yet if improvement up to 80% is possible through manual inspection it is recommended. As displayed in the graph the phenomenon known as diminishing returns occurs after passing 80% probability of detection.

6.0 Project Management

6.1 Work Breakdown Structure

The image displayed below depicts the top-level of the work breakdown structure for the Enhanced FOD Inspection System proposed. These are the major divisions of tasks imperative to the completion of this project. Below it we have decomposed each of the task categories into their respective tasks.

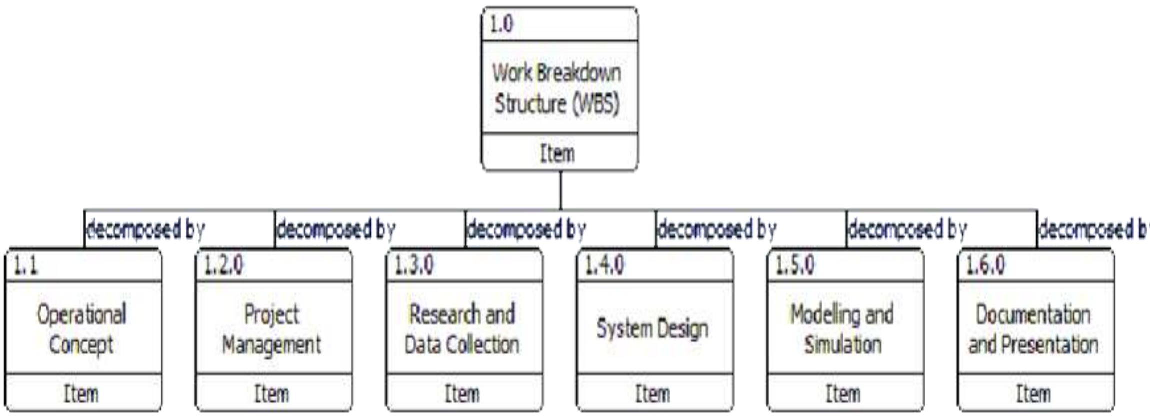


Figure 37: WBS (Top Layer)

6.1.1 Operational Concept

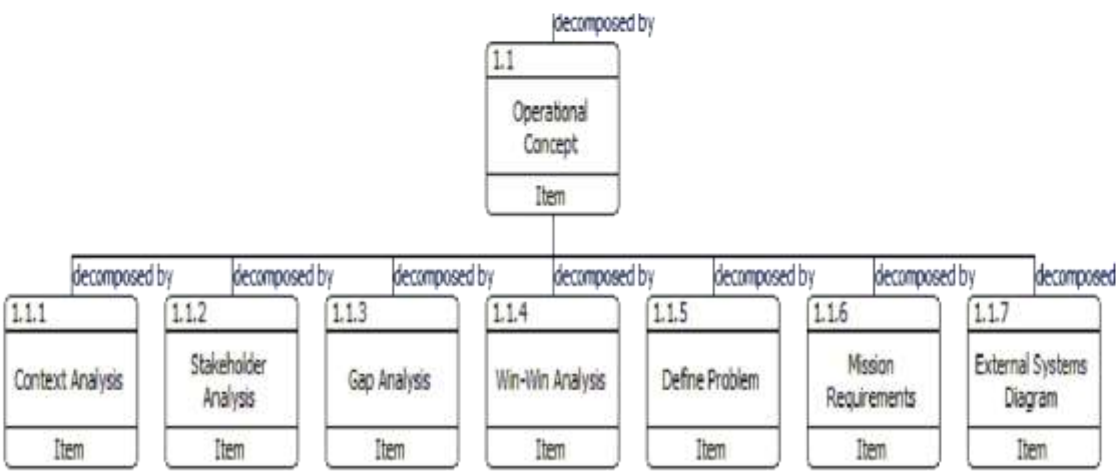


Figure 38: WBS 1.1

6.1.2 Project Management

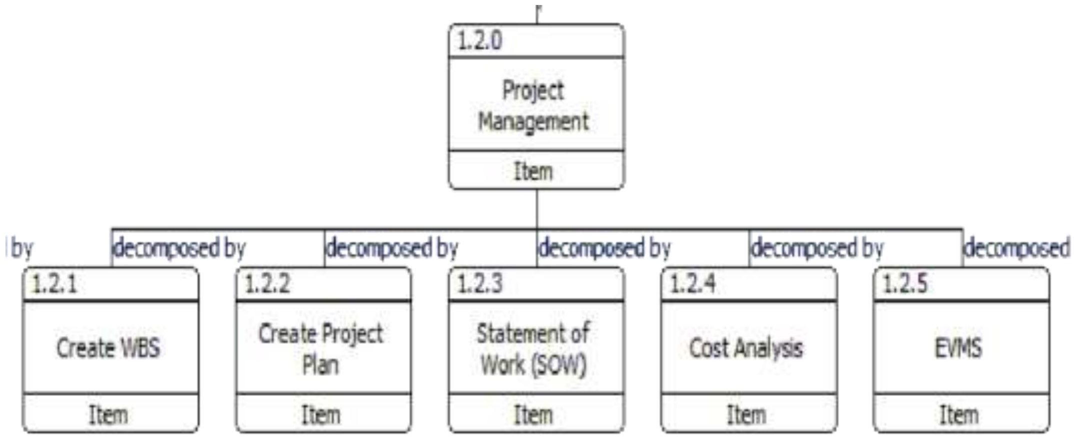


Figure 39: WBS 1.2

6.1.3 Research and Data Collection

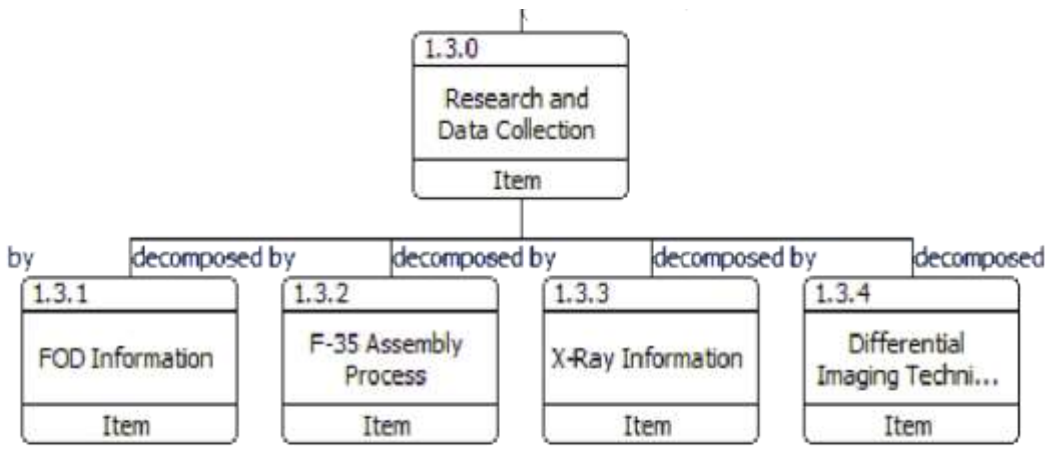


Figure 40: WBS 1.3

6.1.4 System Design

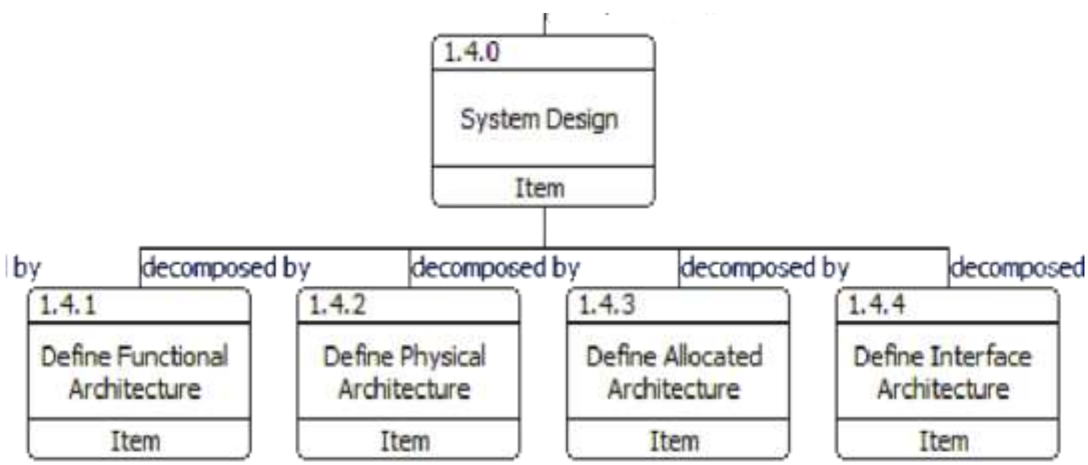


Figure 41: WBS 1.4

6.1.5 Modeling and Simulation

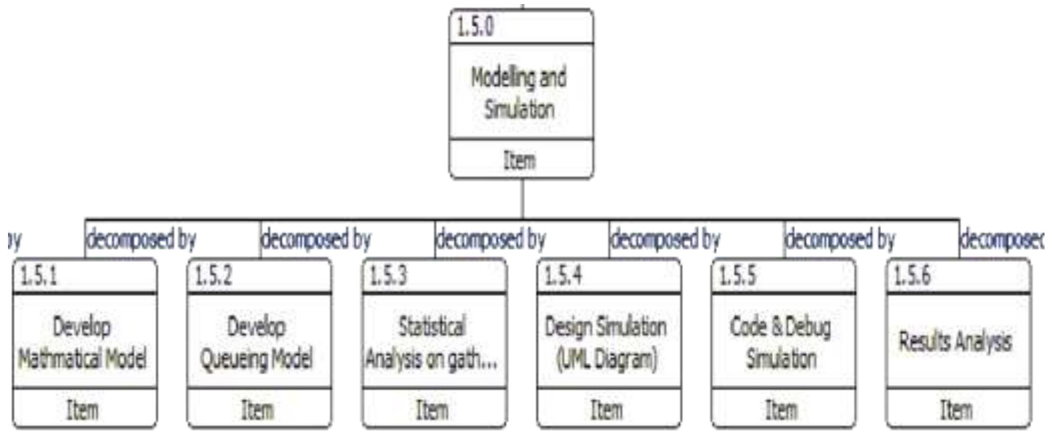


Figure 42: WBS 1.5

6.1.6 Documentation and Presentation

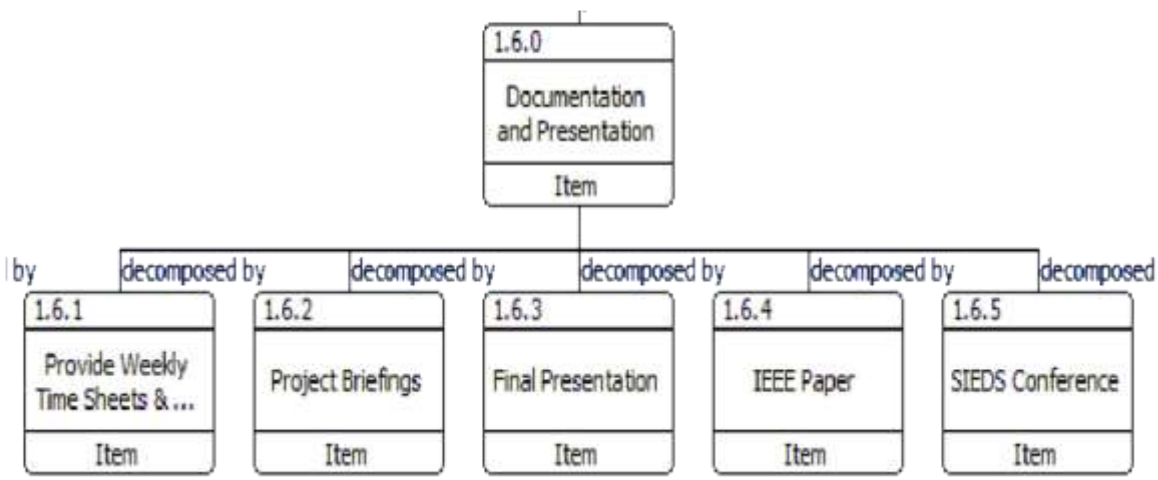
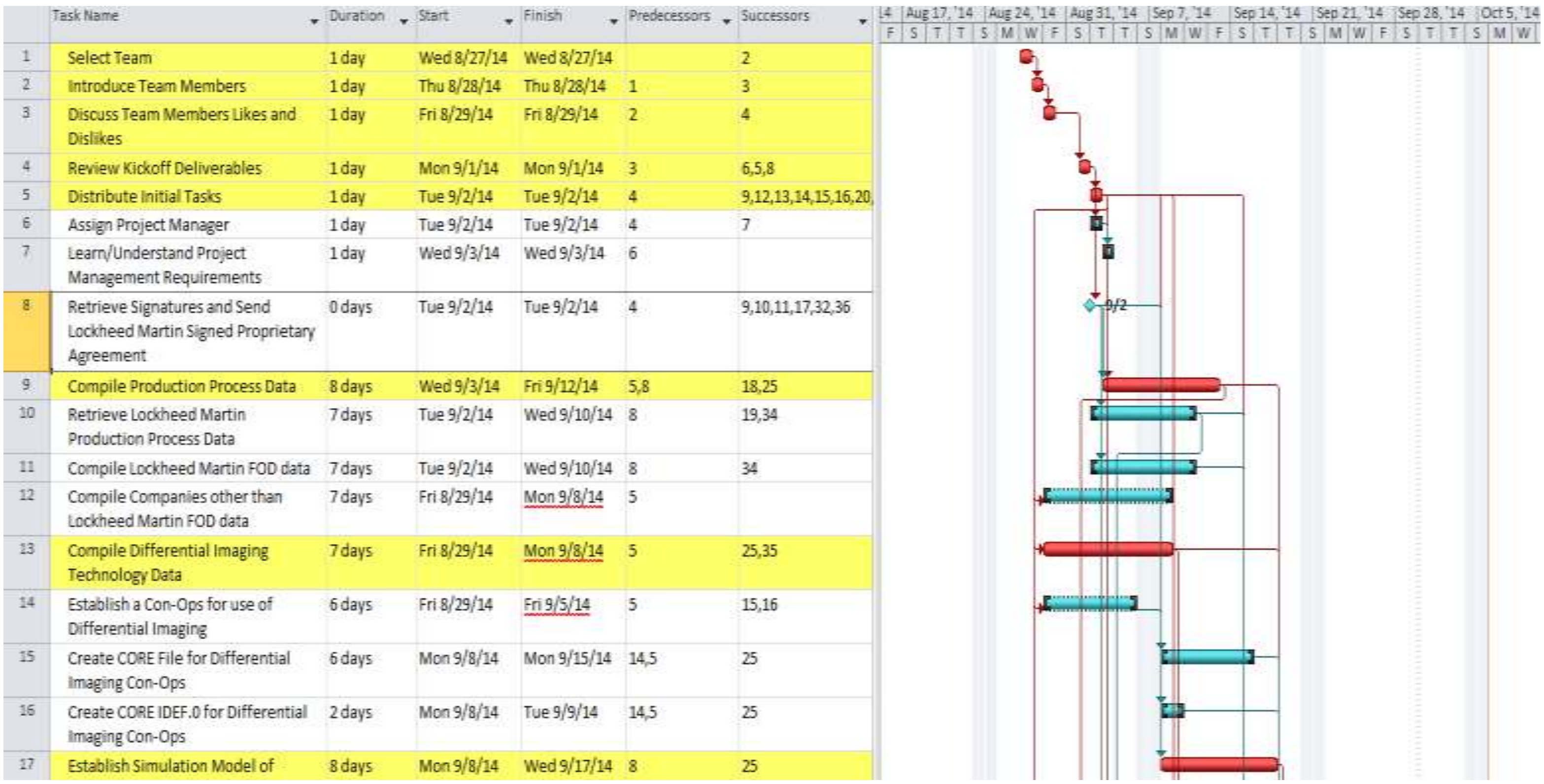


Figure 43: WBS 1.6

6.2 Project Timeline & Critical Path

Microsoft Project was used to develop a project plan that organized all of the foreseeable tasks over the course of the project lifecycle. The Microsoft Project tool assisted in creating a Gantt chart that identified the tasks that lye on the critical path. The critical path is made visible by the red highlighted bars in the Gantt chart, and the highlighted tasks on the left.



	Task Name	Duration	Start	Finish	Predecessors	Successors
1	Select Team	1 day	Wed 8/27/14	Wed 8/27/14		2
2	Introduce Team Members	1 day	Thu 8/28/14	Thu 8/28/14	1	3
3	Discuss Team Members Likes and Dislikes	1 day	Fri 8/29/14	Fri 8/29/14	2	4
4	Review Kickoff Deliverables	1 day	Mon 9/1/14	Mon 9/1/14	3	6,5,8
5	Distribute Initial Tasks	1 day	Tue 9/2/14	Tue 9/2/14	4	9,12,13,14,15,16,20,
6	Assign Project Manager	1 day	Tue 9/2/14	Tue 9/2/14	4	7
7	Learn/Understand Project Management Requirements	1 day	Wed 9/3/14	Wed 9/3/14	6	
8	Retrieve Signatures and Send Lockheed Martin Signed Proprietary Agreement	0 days	Tue 9/2/14	Tue 9/2/14	4	9,10,11,17,32,36
9	Compile Production Process Data	8 days	Wed 9/3/14	Fri 9/12/14	5,8	18,25
10	Retrieve Lockheed Martin Production Process Data	7 days	Tue 9/2/14	Wed 9/10/14	8	19,34
11	Compile Lockheed Martin FOD data	7 days	Tue 9/2/14	Wed 9/10/14	8	34
12	Compile Companies other than Lockheed Martin FOD data	7 days	Fri 8/29/14	Mon 9/8/14	5	
13	Compile Differential Imaging Technology Data	7 days	Fri 8/29/14	Mon 9/8/14	5	25,35
14	Establish a Con-Ops for use of Differential Imaging	6 days	Fri 8/29/14	Fri 9/5/14	5	15,16
15	Create CORE File for Differential Imaging Con-Ops	6 days	Mon 9/8/14	Mon 9/15/14	14,5	25
16	Create CORE IDEF.0 for Differential Imaging Con-Ops	2 days	Mon 9/8/14	Tue 9/9/14	14,5	25
17	Establish Simulation Model of	8 days	Mon 9/8/14	Wed 9/17/14	8	25

Figure 44: Gantt Chart (Tasks 1 – 17)

	Task Name	Duration	Start	Finish	Predecessors	Successors
18	Establish Simulation Model of Production with X-RAY	7 days	Tue 9/2/14	Wed 9/10/14	9	25
19	Establish Planned Variations of Simulation Model with X-RAY	7 days	Fri 9/5/14	Mon 9/15/14	10,22,23	
20	Contact AS&E Regarding Various X-RAY Systems & Retrieve Data	6 days	Fri 8/29/14	Fri 9/5/14	5	
21	Compile Back-Scatter Data	8 days	Wed 9/3/14	Fri 9/12/14	5	25,34
22	Contact AS&E Regarding Back-Scatter Technology	1 day	Fri 8/29/14	Fri 8/29/14	5	19
23	Contact Nucsafe Regaurding Back-Scatter Technology & Retrieve Data	2 days	Fri 8/29/14	Mon 9/1/14	5	19
24	Establish Operational Concept	10 days	Fri 8/29/14	Thu 9/11/14	5	
25	Create Presentation	4 days	Thu 9/18/14	Tue 9/23/14	9,13,15,16,17,18	26,28,29,38
26	Finalize Presentation	1 day	Wed 9/24/14	Wed 9/24/14	25	28,29
27	Graphic Design For Presentation	4 days	Mon 9/15/14	Thu 9/18/14	5	
28	Deliverable 1 Presentation Practice	4 days	Mon 9/15/14	Thu 9/18/14	25,26	
29	Deliverable 1 - Context/Stakeholder Analysis, Problem Statement	0 days	Mon 9/22/14	Mon 9/22/14	25,26	38,31,46,56,
30	Preliminary Project Plan	13 days	Wed 9/3/14	Fri 9/19/14	5	
31	Re-Organize Slides	5 days	Thu 9/25/14	Wed 10/1/14	29	38
32	Reach out to Lockheed Martin Sponsor Regarding Requirements	1 day	Tue 9/2/14	Tue 9/2/14	8	33
33	Receive Requirements Confirmation from sponsor	5 days	Tue 9/30/14	Mon 10/6/14	32	
34	Establish Mission/Functional/Design Requirements	7 days	Mon 9/15/14	Tue 9/23/14	10,11,21	38

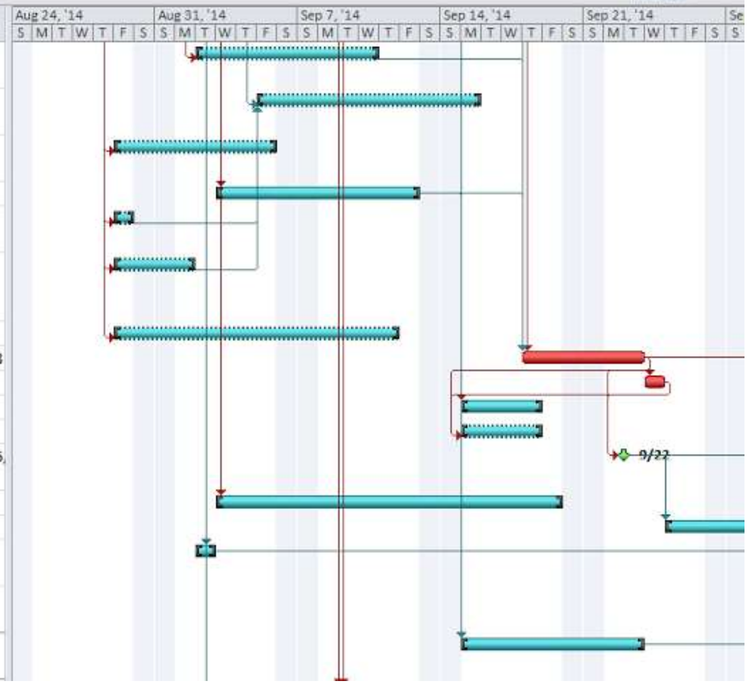


Figure 45: Gantt Chart (Tasks 17 – 34)

	Task Name	Duration	Start	Finish	Predecessors	Successors
35	Differential Imaging Animation Development	20 days	Tue 9/9/14	Mon 10/6/14	13,5	38
36	Reach out to Lockheed Martin Sponsor Regarding Average Times per Production Stage	1 day	Tue 9/2/14	Tue 9/2/14	8	37
37	Receive Data for Average Times per Production Stage	5 days	Wed 9/3/14	Tue 9/9/14	36	38
38	Deliverable 2 Preparation	8 days	Tue 10/7/14	Thu 10/16/14	29,31,34,35,37,2	39
39	Deliverable 2 - Context/Stakeholder Analysis, Problem Statement, Need Statement, Mission/Functional/Design Reqs, SOW/Budget/Pr	3 days	Fri 10/17/14	Tue 10/21/14	38,29	40,46,56,41
40	Deliverable 3 Preparation	11 days	Mon 10/13/14	Sat 10/25/14	39	
41	Deliverable 3 - Context/Stakeholder Analysis, Problem Statement, Need Statement, Mission/Functional/Design Reqs, Sim Reqs/Design, DoE, Prelim Results, SOW/Budget/Project Risk	0 days	Mon 10/27/14	Mon 10/27/14	39	42
42	Deliverable 4 - Dry Run Final Presentation - Context/Stakeholder Analysis, Problem Statement, Need Statement, Mission/Function	0 days	Mon 11/10/14	Mon 11/10/14	41	43,46,56
43	Final Report Draft	8 days	Mon 11/10/14	Wed 11/19/14	42	44
44	Finalize Final Report	9 days	Thu 11/20/14	Tue 12/2/14	43	45
45	Proposal Final Reports Due	0 days	Wed 12/3/14	Wed 12/3/14	44	46,49
46	Final Presentation Draft	25 days	Wed 12/3/14	Tue 1/6/15	29,39,42,45	47,49

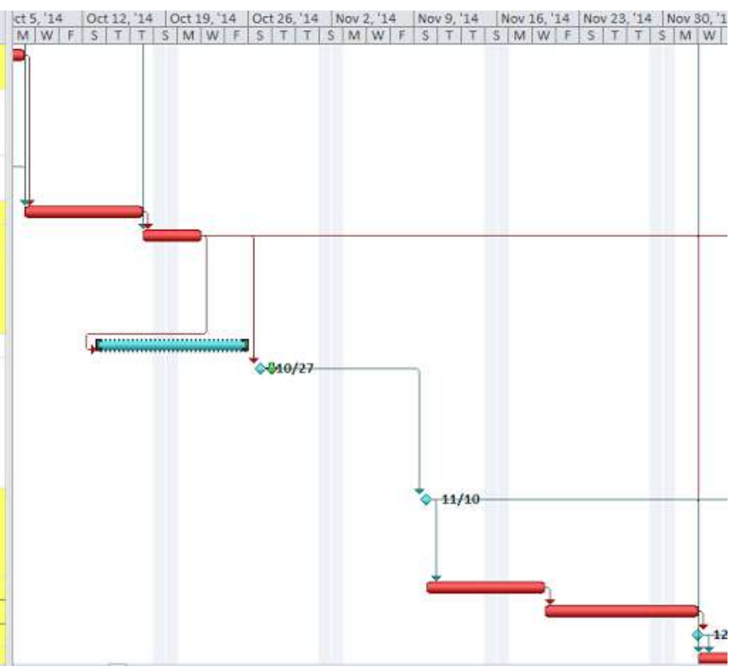


Figure 46: Gantt Chart (Tasks 34 – 46)

	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	

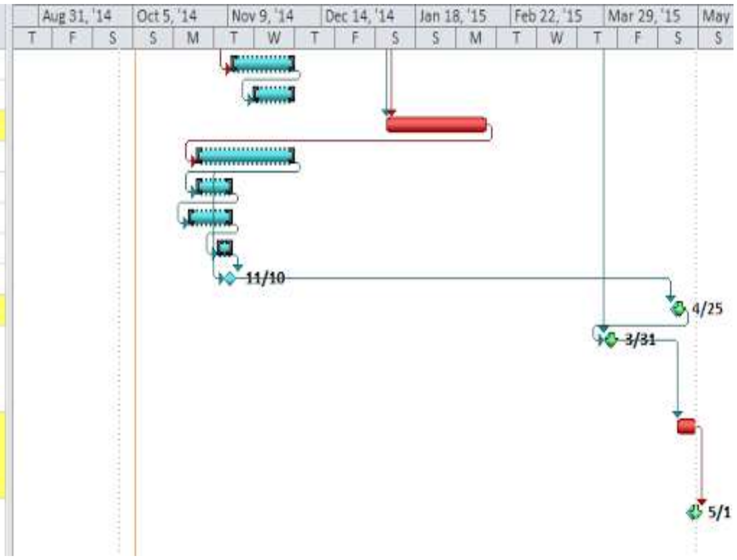


Figure 46: Gantt Chart (Tasks 34 – 58)

6.3 Risk Management

In an attempt to prepare ourselves for possible risks later in the project life cycle we have developed a risk/mitigation table for some of the tasks visible on our critical path. On the left we have displayed the specific tasks that relate to the risks, which are listed in the next column, followed by the mitigation route we intend on using if necessary.

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 and applying a random number generator as a multiplier will create multiple data points which can then be run through the simulation and graphed to find the various distributions.

Table 21 – Risk Management

6.4 Project Budget & Performance Indices

After reviewing average salaries for recent engineering graduates, $40/hour was established as the wage for all 5 of our team members. A George Mason University overhead rate of 2.13 was applied to the $40 wage which outputted a total hourly rate of $85.20. This wage was used for our overall budget for the project - $127,118. This was created by multiplying the total hourly rate ($85.20) by expected hours per week, and then summing these values for the overall budget.

Wage	**$40**
GMU Overhead	**2.13**
Total Hourly Rate	**$85.2**

Table 22 – Team Wages

By using current hours and forecasting hours we expect to work during weeks later in the semester, it was possible to create multiple graphs that display data relating to the Earned Value of the FOD Inspection system. These data sets include Earned Value, Cost Performance Index (CPI)/ Schedule Performance Index (SPI), Planned Value, Actual Cost, along with a best and a worse case projection.

The Earned Value graph below displays the data sets listed above up to this point in the project life cycle (week 6). The cumulative planned value (PV) is simply the cumulative value planned for each week throughout the project. The best and worst case sets of data directly relate to a multiple applied to the PV, which was 10% or .1. Multiplying the PV by 1.1 outputted a worst case, showing it would take 10% more time than expected; while multiplying the PV by .9 would display a data set reaching completion 10% earlier. Cumulative Actual Cost (AC) represents the cumulative costs for the weeks that our team has worked thus far. Earned Value (EV) relates to the estimated progress and the estimated costs per week.

The Earned Value graph displayed below highlights the underestimates made in the beginning stages of the project when attempting to forecast the hours necessary to compete this project. The Cumulative Actual Cost displayed in red makes the increased workload experienced towards the final stages of the project very evident. This is where some fluctuations from the expected cost of the project began to occur, which starts to become visible around week 25 in the graph below. This is when the simulation was nearing its completion, and constant analysis was required to ensure the simulation was working properly.

The unexpected increase in hours around this time can partially be attributed to an issue encountered during results analysis. In 2014, 36 F-35 (12 of each variant) were actually produced by Lockheed Martin, thus, this stood as somewhat of a threshold, or means of comparison to the number of aircraft outputted from our simulation; specifically when analyzing the output associated with the manual inspection technique (Lockheed). During the initial stages of analysis for the simulation output it became evident that there were specific simulation iterations that were outputting unrealistic statistics for the total number of aircraft produced. As deeper analysis was conducted it became clear that these occurrences were not as random as previously assumed; 4-6 aircrafts per year turned out to be a somewhat frequent occurrence. After discovering the issue causing this invalid output, it was made clear that it was inherent within the way the simulation was developed and therefore had to be rebuilt to eliminate it. Therefore, unexpected hours were necessary to rebuild the simulation, and re-conduct all of the analysis required.

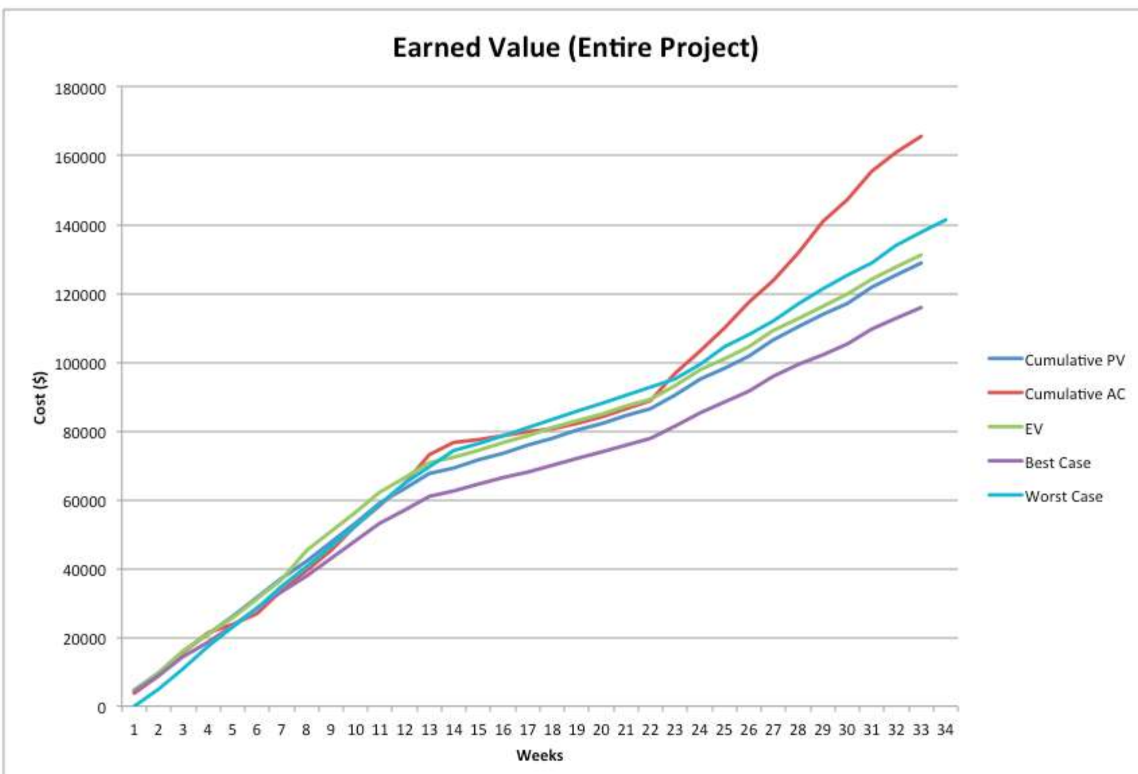


Figure 47: Earned Value Graph

The final graph displayed below shows the Cost Performance Index (CPI) vs Schedule Performance Index (SPI) for our project. The final CPI for the project is .79; thus, the project was completed over the expected budget. This result can be attributed to the unexpected hours associated with rebuilding of the simulation and repetitions of the analysis of the data. The final SPI for the project was 1.01; thus, the project was completed on time. Multiple additions were also made to the project throughout the year, such as the differential imaging proof of concept application, and the GUI developed to link with our simulation.

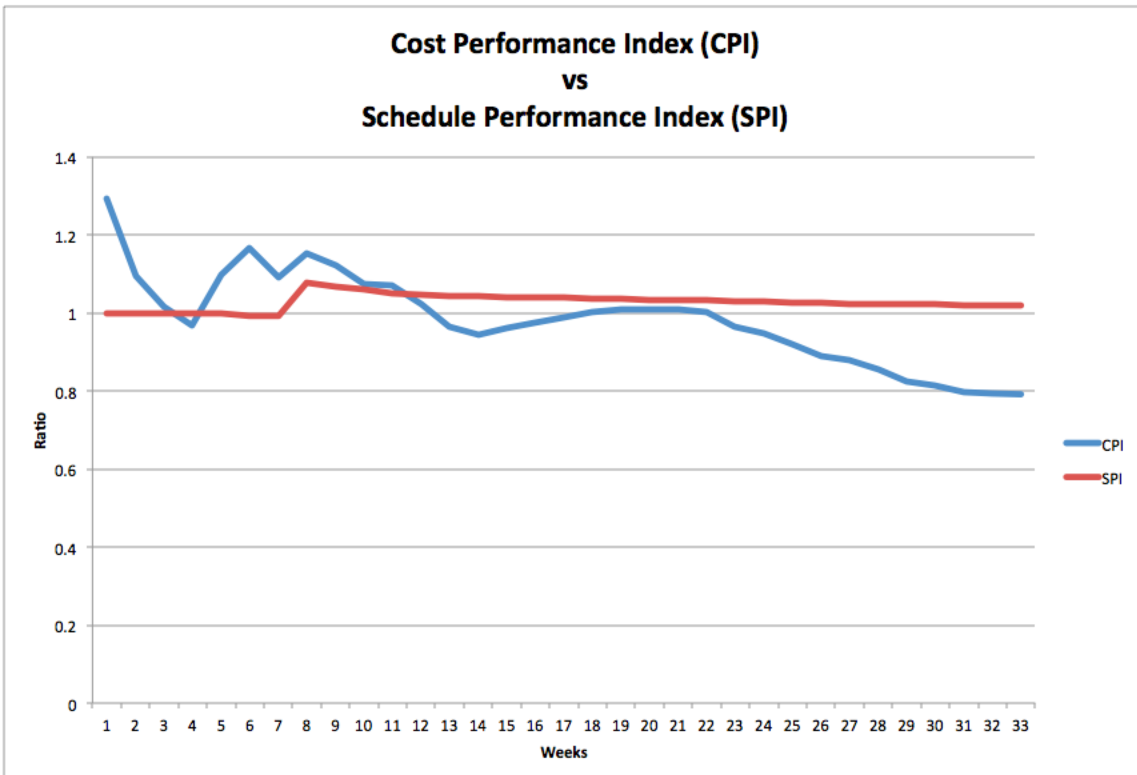


Figure 48: Cost Performance Index vs Schedule Performance Index

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