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Decision Making Model For Foreign Object Debris/damage (FOD) Elimination In Aeronautics Using Quantitative Modeling Approach

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I would like to dedicate this thesis and all my accomplishments to my parents, Jaime Lafon and Maria de Lourdes Cavazos, I owe everything to them, because of their efforts I am able to be at where I am now. Throughout all this time they have been an example of effort and perseverance.

DECISION MAKING MODEL FOR FOREIGN OBJECT DEBRIS/DAMAGE (FOD) ELIMINATION IN AERONAUTICS USING QUANTITATIVE MODELING APPROACH

by

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ABSTRACT

(FOD) Foreign Object Debris/Damage has been a costly issue for the commercial and military aircraft manufacturers at their production lines every day. FOD can put pilots, passengers and other crews' lives into high-risk. FOD refers to any type of foreign object, particle, debris or agent in the manufacturing environment, which could contaminate/damage the product or otherwise undermine quality standards. Nowadays, FOD is currently addressed with prevention programs, elimination techniques, and designation of FOD areas, controlled access to FOD areas, restrictions of personal items entering designated areas, tool accountability, etc. All of the efforts mentioned before, have not shown a significant reduction in FOD occurrence in the manufacturing processes. This research presents a Decision Making Model approach based on a logistic regression predictive model that was previously made by other researchers. With a general idea of the FOD expected, elimination plans can be put in place and start eradicating the problem minimizing the cost and time spend on the prediction, detection and/or removal of FOD.

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CHAPTER 1. INTRODUCTION

Foreign Object Damage/Debris (FOD) has being one of the most important and expensive issue for military and commercial aircrafts. This concern includes possible damage to the aircraft, such as blade damage; tire damage and reposition, loss of an entire aircraft, and possible loss of human lives. FOD is most commonly found during manufacturing processes and runways. Even though, most efforts of the aeronautical industries have focused on the prevention of FOD; ultimately, these efforts have not been able to solve the problem. Such efforts always work in a reactive manner; and although, they say they are preventing FOD. The truth is that they would clean whatever was created already: in other words, it is a removal of FOD once it was created in the first place. These efforts cannot even imagine the complete elimination of FOD. This research presents a mathematical model that will help on a decision making for the engineers to decide on what technologies or process to focus to eliminate the most FOD expected with the less effort. Foreign Objects are a major cause of aircraft damage and unscheduled maintenance. Damage can result in minor repairs or catastrophic events. The full impact of FOD is difficult to measure, as often times FOD will cause other defects/damage as it migrates within an assembly, creating additional costs that may not be captured. Aircraft safety is a paramount concern in both civilian and military aviation. Compromising safety can cost lives, damage equipment and affect mission accomplishment. According to National Aerospace FOD Prevention Inc. (NAFPI), FOD costs the global (both civil and military) aviation industry $3-4 billion per year in repairs in direct costs and does not include the additional costs associated with incurred delays or cancelations. It is a fact that foreign objects and/or debris and damage have contributed to jammed flight controls, engine damage, electrical shorts, fluid contamination, control valve failures, fires and other major failure incidents that have resulted in costly material damage, loss of vehicle and of life.

1.1 Motivation

The main motivation of this study is the catastrophic consequences that FOD may cause. FOD is one of the main causes for aircrafts incidents, in which not only aircraft damage is caused, but also there is a risk of loss of human lives during commercial flights or combat missions. It is imperative to spell out that aircrafts have become more sophisticated and complex, and as a consequence, the manufacturing process has become more difficult to adapt for the personnel who work with the aircraft, opening the gap for human error to occur, and therefore more incidents of FOD may occur. There exists the need to solve the problem of FOD, to completely eliminate the chances of finding FOD in any aeronautic activity.

1.2 Objective

The objective of this research is to develop a decision making model of FOD. This model should give an exact answer of what technology or process to utilize to eliminate the greater percentage of FOD possible with the fewer amounts of resources (time and money). This model should also provide the percentages of elimination per FOD type. The idea behind this project is that after the decision is made, the personnel on the production line could eliminate the FOD following the instructions the decision making will give. The decision making model is based on a work previously done, a mathematical model that predicts and identifies the type of FOD expected to be generated under specific circumstances. The information of the technologies and processes is based on historical data and surveys made to experts on the area, both provided by an aeronautical company.

1.3 Focus of the study

FOD is caused by a lot of factors, including workflow, manufacturing, assembly, inspection, human factors, etc. This research will focus on the manufacturing processes and human factors of the aeronautics activities. Even though, other factors play a vital role on FOD, this study will not take into account these areas. An aeronautical company says in its FOD Quick-Start Guide [3] that the major role on the creation of FOD is in the process of manufacturing. Moreover, this study will focus on the FOD inside the aircraft. The design of a product is related to its vulnerability to foreign objects.

1.4 Contributions

As a contribution, this research presents a new approach to solve the FOD issue. Even though many aeronautical companies have put efforts into this issue, this is the first complete attempt to predict and eliminate FOD. It is considered complete since the methodology starts with the prediction of FOD and continues until a decision or an action plan to eliminate FOD is done. The decision making on what combination of factors to eliminate FOD is certainly the center part of this study.

CHAPTER 2. PROBLEM STATEMENT

The efforts that have been made for the prevention, detection and removal/elimination of FOD have not been able to solve the problem this causes. These efforts mentioned always work in a reactive manner, even though its attempt is to prevent FOD, the truth is that they would clean the created FOD and removed it once it happened. These efforts are not even close to the complete elimination or prevention of FOD. Furthermore, as the complexity of the manufacturing of an aircraft has increased exponentially, the cost of FOD prevention, detection and removal is rapidly rising.

Recent studies show that only 85% of the employees are aware of their organization's FOD prevention program [5]. However, only 46% of the personnel aware of the FOD engage on the training. This study showed that despite on the efforts of the companies to prevent, detect and remove FOD, not everyone is involved in this problem and additional efforts are needed. FOD is costing to a specific aeronautics company $350 thousand dollars per year just in manufacturing processes and flight line. Internationally, FOD costs the aviation industry $13 billion dollars per year in direct plus indirect costs [6]. The complete cost of FOD is complex to measure; aircraft safety is a primordial concern in both military as commercial aviation. According to (NAFPI) National Aerospace FOD Prevention Inc., FOD cost the aviation industry $3-4 billion per year only taking into consideration direct costs [7]. Data provided by the company for this research demonstrate that in the past three years FOD has cost $1 million dollars, on which the most frequent outcomes are; delays in the manufacturing, product failure, loss of business, injury and/or death.

CHAPTER 3. LITERATURE REVIEW

3.1 FOD Definition

In manufacturing and aviation, the acronym "FOD" is used to describe "foreign object debris." The term includes any type of foreign object, particle, debris or agent in the manufacturing environment, which could contaminate the product or otherwise undermine quality standards [9]. An example of this might be a wire clipping that is unknowingly left inside of an electrical box. In situations where this type of debris has compromised the quality, functionality or economic value of a manufactured item, "FOD" can be used as an acronym for "foreign object damage." Imagine that electrical box fails because that wire clipping caused an electrical short. FOD includes hardware, tools, parts, metal shavings, broken hardware parts, pavement fragments, rocks, badges, hats, paper clips, rags, trash, paperwork and even wildlife. Any foreign object that can find its way into an aircraft or engine can contribute to FOD. Boeing St. Louis has identified nine common foreign object non-conformance codes for classification of foreign objects they find at their manufacturing site/production line which are degradation, manufacturing debris, panstock, consumables, personal items, environmental, tools/shop aids, perishables and expendables and trash [2].

3.2 FOD Prevention

FOD prevention plans have become top one priority of aviation industries. Since most FOD can be attributed to poor housekeeping, facilities deterioration, improper maintenance or careless assembly, lack of accountability on hardware, tools and materials, and inadequate operational practices there are four pillars to FOD prevention: training, inspection, maintenance and coordination. There exists standards that guide prevention plans and from those there are many prevention plans in place which are listed in the next sections describes in the following

paragraphs.

3.2.1 FOD Prevention and Elimination Standards

According to the literature review that was made, on the aeronautical industry, the main two standards that guide FOD prevention and elimination standards are *NAS 412 and* MIL- STD-980.

3.2.1.1 MIL-STD-980

The intent of MIL-STD-980 was to establish FOD prevention guidelines for all government owned aerospace products. The standard is applicable to all Department of Defense contractors for cradle to grave activities [10]. The guideline states that the contracting organization is responsible for establishing and maintaining an effective FOD prevention program. Each program must include basic elements such as training, tool control, FOD collection and procedural reviews. While MIL-STD-980 was initially established for government contractors, it was eventually adapted by the FOD Advisory Board and was instrumental in their formation of National Aerospace Standard 412.

3.2.1.2 National Aerospace Standard (NAS) 412

NAS 412 was developed by the FOD Advisory Board which established standards for U.S. civil and military aviation. The objective of this standard was to promote ground and flight safety and the preservation of private and national assets [11]. It is intended as a baseline FOD prevention policy/procedure. The overall goal of NAS 412 is to provide a well-developed document that industry leaders would accept and implement to overcome the FOD problem.

3.2.2 FOD Prevention Areas (FPAs)

A FOD Prevention Area (FPA) is any area where maintenance, manufacturing, modification and production of aircraft/sub-assembly operations are conducted. Within FPAs exist different levels

of prevention which are described below [8]:

a) FOD Awareness Area: A FPA where manufacturing or modification processes remain open without any potential for FOD entrapment. This includes but is not limited to: components or assemblies undergoing manufacturing or modification without any closeout activities on the product.
b) FOD Control Area: A FPA where assembly or modification processes occur. This includes but is not limited to: components or assemblies undergoing manufacturing or modification in the process of becoming a completed aircraft. One must be FOD-certified to enter area or escorted by someone with a current FOD certification. Dress code strictly enforced.
c) FOD Critical Area: A FPA where assembly, modification and flight and ground operations require the highest level of preventive measures. The elimination of FOD contamination, entrapment, migration or damage is most critical to safeguard the product.

3.3 Literature Review for Technologies

Wide ranges of technologies are established in various industries in order to detect FOD in their products that some simple processes cannot detect. For the purpose of this study, apart from the aeronautics industry, the food and medical industry were investigated since these are the areas where FOD has the most acute amount of impact than in the aeronautics industry. Rather than costing the company money, FOD found in these industries can immediately cost the life of a person. The following is a list of the technologies that were found during the beginning of the research, specifically focused in both the food and the medical industry. The following table shows the main characteristics of each of the technologies that were found:

Table 1. Technology Summary

Technologies	Characteristics
Air-Coupled Ultrasonic	• Detects non-metallic objects • Measures length and width
Thermal Image Processing	• Measures difference in emissivity by the use of heat conductivities and infrared radiation • Applies heat and record observations
Hyperspectral Imaging	• Non-destructive • Electromagnetic spectrum that divides into many bands • Measures different spectral wavelengths with LED lights
Ultrasound	• Non-invasive • Estimates food composition • Monitors physiochemical and structural properties • Detects contamination • Sound waves are used for the monitoring
Visible-near infrared (VNIR)	• Applies phytohormone treatments with reflectance VNIR spectra • Observes maturity
Magnetic Resonance Imaging (MRI)	• High quality images that are two-dimensional and three-dimensional • Based on absorption and emission of energy in the radio frequency range of electromagnetic spectrum
Current Transformer/Computed Tomography (CT)	• Non-destructive • Captures images that allows visualizations of the internal features • Evaluates textural characteristics
X-ray Imaging	• Shows reflection, refraction, scattering, interference, diffraction, polarization, and absorption • X-ray reaches a sensor and it converts the energy signal into an image
Nuclear Magnetic Resonance (NMR)	• Product placed in strong magnetic field • Uses uniform field across the sample, and output spectrum can be analyzed to obtain information about the structure of molecules
Fluorescence Imaging	• Ultraviolet lights

	• Detects abnormalities
Infrared Inspection System	• Detects transmitted light through the object from six different infrared LED light • Detects entire concealed damage at a specific inspection rate
Computed tomography (CT) (scan)	• Use of RFID Technology • Most effective tracking small, non-metallic objects
Computer-aided detection (CAD)	• Map-seeking circuit (MSC) algorithm (pattern recognition) and referenced map-seeking circuit
Electrostatic sensor	• Calculates sensitivity distribution and the influence of relevant structural parameters

3.3.1 Food Industry

For research purposes, it has to be made a literature review on other industries, to identify the possible technologies and/or processes that can be used on the aeronautical industry, since is one of the industries that have problem with FOD and can be strongly related to a manufacturing process with the same type of problems.

3.3.1.1 Air-Coupled Ultrasonic

This technology is a capacitive device used to detect non-metallic objects along with detecting the measurements of the FOD (widths and weight). In the food industry this is essential since most of the FOD is not metallic. This specific device is used when dough products, canned goods, and cheeses are being produced. The FOD appears easily because once the known dimensions of the product are known; it is easy to detect unusual measurement or weights that are added to it. [9]

3.3.1.2 Thermal Image Processing

Thermal imaging processing has two ways of detecting FOD in the food being processed. One way is to measure the difference in the emissivity by using different heat conductivities and later distinguishing them by the infrared radiation. The second way is to apply heat pulse into the product and observe how it penetrates into the product. The FOD will immediately be visible due

to the difference in the heat conductivities. This can be seen through images since the FOD will appear in a lighter shade than the food product that is being observed. [10]

3.3.1.3 Hyperspectral Imaging

This method is recognized since it is a non-destructive and a fast quality method of detecting FOD. Hyperspectral imaging collects information by the use of the electromagnetic spectrum that divides the spectrum into many bands by measuring the different spectral wavelength by the use of LED lights and a hyperspectral camera. Currently, there are three main classes in the field of spectral imaging, namely multispectral, hyperspectral, and ultra-spectral imaging. These techniques are especially applied when processing meat, fish, fruit, vegetables, and grain. Moreover, currently some practical implementations for real-time monitoring are already available [11].

3.3.1.4 Ultrasound

Ultrasound provides a non-invasive, cheap and simple technique that can be used for estimating the food composition, monitoring physicochemical and structural properties, and detecting contamination by metals and other foreign materials in the food. The ability of this technology consists of sound waves with frequency beyond the limit of human hearing. It is used for monitoring the composition and physicochemical properties of food components and products during processing and storage. These applications include meat products, vegetables and fruits, cereal products, aerated foods, honey, food gels, food proteins, food enzymes, microbial inactivation, freezing, drying and extraction [12].

3.3.1.5 Visible-near infrared (VNIR)

The food industry is also making the use of visible-near infrared reflectance spectro-photometry in order to improve the quality of the fruit. This technique is being used to differentiate the different characteristics of the fruit in order to predict the level of maturity. Applying phytohormone treatments with reflectance VNIR spectra with a range from 540-1000 mm to the observed fruit induced the variation in the maturity of the fruit [13].

3.3.1.6 Magnetic Resonance Imaging (MRI)

MRI is an imaging technique that is currently being implemented in order to obtain images of high quality from the inside of the product in both two-dimensions and three-dimensions. Research has found that making the use of MRI in the food industry is evaluating the quality attributes of food being produced. This technology is based on the absorption and emission of energy in the radio frequency range of electromagnetic spectrum. This generation of magnetic images can be controlled by the radio frequencies pulse sequences that are being used as a form of excitation of the nuclear spins. Depending on the pulse sequence parameters that are chosen, the quality of the image can result in a good contrast between the area of interest and the surrounding area; detecting any foreign object in the surroundings. Currently, this technique is being used in food products such as fish, fruit, grain, meat, vegetables, and others like cheese and chocolate [14].

3.3.1.7 Current Transformer/Computed Tomography (CT)

This technique is widely used for the reason that it is non-destructive and captures food images that allows visualization of the internal features of any product. This can be achieved by making the use of a movable X-ray source and detector assembly to accumulate the data that is being observed. It is a proven efficient method for evaluating a cross-section of an object and has received extensive applications in the food industry. In addition, it helps to quickly locate any type

of foreign materials in the fruit. CT is being applied to products such as fish, fruit, meat, and vegetables. Specifically in fruit products, the CT scan is used to evaluate textural characteristics and also quickly detecting any internal changes that the product is facing in real-time [14].

3.3.1.8 X-ray Imaging

X-Ray imaging is used to show reflection, refraction, scattering, interference, diffraction, polarization and absorption. Regular X-ray has a photon energy of 10-120 keV and are classified as hard x-rays since they are harmful to products and pollute the food. Specifically for the food industry, soft x-rays must be used with a photon energy of about 10keV for food inspection. The principle of soft XRI inspection is based on the density of the product and the contaminant. As an X- ray penetrates a food product, it loses some of its energy. A dense area, such as contaminant, will reduce the energy even further. As the X-ray exits the product, it reaches a sensor. The sensor then converts the energy signal into an image of the interior of the food product. Foreign matter appears as a darker shade of grey that helps to identify foreign contaminants. Because of the components explained, X-Ray is better used when investigating the internal condition of the food. The downfall of the x-ray machine is that it cannot detect objects whose density is similar to the density of water. Objects such as paper and plastics cannot be detected and consequently another form of technology or process must be implemented for these smaller foreign objects [15].

3.3.1.9 Nuclear Magnetic Resonance (NMR)

In nuclear magnetic resonance (NMR) the food product that will be inspected is placed inside a strong magnetic field of a range from 1±10 Tesla. The magnetic field can usually only be achieved with exclusive helium-cooled superconductors. When the nuclei are subjected to a magnetic field, they may only take up certain orientations with respect to it. The most common nuclei that are applied to NMR are ^{1}H and ^{13}C. The application of a broadband microwave pulse

causes the protons to ascend to their higher energy level. These excited states then decay; giving microwave echoes that can be analyzed. NMR uses a uniform field across the sample, and the output spectrum can be analyzed to give information about the structure of molecules present. Each proton is also subject to a magnetic field caused by electrons in its locality, which slightly modifies the energy levels and causes the frequency of the microwave photon given off during relaxation. The spectrum will then give information about the electrons and consequently the molecular structure [15].

3.3.1.10 Fluorescence Imaging

Ultraviolet and fluorescence imaging are used hand in hand in the food industry. Ultraviolet has been effective in identifying stalks in batches of peas but have also damaged the compound due to the electromagnetic radiation it gives off. Fluorescence imaging can be useful when trying to detect abnormalities such as fat, sinews, surface bones, and aflatoxins [16].

3.3.1.11 Infrared Inspection System

The infrared inspection system is a device that detects transmitted light through the food of choice from six different near infrared LED lights with the use of a sine wave modulation- a demodulation scheme. This system automatically detects the entire concealed damage at a specific inspection rate. In order to know the classification of which food product is damaged or undamaged, multiple linear regression and discriminant analysis are also to be performed and tested. Furthermore, classification error rates need to be evaluated when using this technology. This technology is mostly used in the food industry where small changes in the product need to be identified; such as almonds or nuts [17].

3.3.2 Medical Industry

For research purposes, it has to be made a literature review on other industries, to identify the possible technologies and/or processes that can be used on the aeronautical industry, one of the most use industries that have problem with FOD is the medical industry.

3.3.2.1 Computed Tomography (CT) (scan)

In the medical field, it has been known that many surgical items (RSI) are being left behind when surgery is being conducted. When a RSI is found, it has to be removed; in very limited circumstances, an endoscopic approach can be used (If the foreign body was ingested or placed intraluminal). An operative approach is used when a sponge was left in the peritoneal cavity and subsequently eroded inside the person. Before any of this is done, the RSI must be identified and located in order for the procedure to go any further. Apart from Radiofrequency Identification (RFID), which is composed of RFID tags that contain microchips that act as transponders and send a radio signal that is sent by the RFID scanner, the CT scan is used. The CT scan has emerged as the most reliable method for diagnosing retained items. In the medical field, the CT scan has been the most effective when tracking small, non-metallic objects, including surgical sponges either a laparotomy pad or a 4x4 inch gauze sponge [18].

3.3.2.2 Computer-aided Detection (CAD)

Making use of the computer-aided detection facilitates the detection of RFBs (Retained Foreign Body) on X-rays by utilizing a modified version of map-seeking circuit (MSC) algorithm (pattern recognition) and the referenced map-seeking circuit (RMSC) [19].

3.3.3 Aerospace Industry

On this section, a Literature Review for the technologies that are currently utilized on the aerospace industry was made, it was excluded the technologies founded which were previously stated on other sections.

3.3.3.1 Electrostatic Sensor (Electrostatic Monitoring Technology)

An electrostatic sensor is a critical component of the electrostatic monitoring system for an aero-engine gas path. The finite element method was adopted to calculate the sensitivity distribution, and the influence of relevant structural parameters on the sensitivity distribution characteristic is analyzed. The data fitting method was employed to acquire the unified spatial sensitivity distribution functions for a given structure sensor, which provides a useful reference for the sensor's installation location. Based on the unified function, the sensitivity distribution function along the particle moving direction and the frequency characteristic of the electrostatic sensor were acquired. Then the corresponding influence factors of the frequency properties were analyzed. Then, simulated experiments were applied to verify the feasibility and validity of the electrostatic sensor, and the experiment results provided a useful reference for the identification of abnormal particles as a characteristic of aero-engine faults [20].

3.4 Literature Review for Processes

Foreign object debris can cause damage that not only costs millions of dollars every year but also lives. FOD can be developed due to poor housekeeping practices, facilities deterioration, improper maintenance, not keeping proper account of tools, and inadequate operational practices. In order to reduce the incurred of lost tools, damaged equipment, and delays in manufacturing many companies including airports have developed FOD prevention processes. The target of these processes is to provide a standardized approach, maintain awareness and prevention, and to ensure

operational processing areas are safe and free of foreign object debris. An effective FOD prevention process will identify potential problems, and correct negative factors that lead to foreign object debris in aeronautics. The table below shows some of the main characteristics of the potential and most recognized FOD prevention processes implemented and provided by an aeronautical company. Such processes will be discussed with more details in the next subsections.

Table 2. Main characteristics of some FOD Prevention Processes

FOD Prevention Processes		Characteristics
Clean as you go		The on-going practice of removing debris during manufacturing operations in the aircraft to ensure product is FOD free [1].
Housekeeping		Keeping work areas organized and clean
Accountability	**Tool Control**	Includes tool marking, tool return time frame, etc.
	Test Equipment Control	Inventory through automatic CribMaster process or manual through Logging or Chit process.
	Consumable Control	Consumables should never be allowed to be loose or un-contained on the aircraft.
	Miscellaneous support equipment control	No un-serviceable equipment is allowed to be used on the aircraft.

	Personal item control	Procedure specifying how personal items will be controlled.
	Chit process	Process used for the Tool, Item, and Equipment control processes.
	Logging process	Process used through electronic in order to account for tools, items, test and support equipment.
	Lost tool item process	Timely notification, identification, and recordkeeping of lost tools and items.
Training		Increase employee awareness to the causes and effects of FOD, promote active involvement through specific techniques, and stress good work habits through disciplines.

3.4.1 Clean As You Go

"Clean as you go" is the on-going/in-progress practice of removing debris during manufacturing, fabrication, modification, operations, or maintenance on/in the aircraft, part, component, assembly, sub-assembly, or engine to ensure product is FOD free [1]. In other words, this specific FOD prevention process consists of cleaning the immediate area when work cannot

continue, when work debris has the potential to migrate to an out of sight or inaccessible area and cause damage or give the appearance of poor workmanship. Also recommends cleaning the area after work is completed, prior to any inspection, and at the end of each shift. For foreign object damage prevention, all aeronautical companies requires that the programs must establish a Progressive Step Clean As You Go method detailing the following actions to occur during the Clean As You Go process [2].

3.4.2 Housekeeping

The housekeeping prevention process, which is the practice of keeping work areas organized and clean, has been adopted for several companies to control FOD. This practice recommends that maintenance, manufacturing and operational areas must remain clean, and that employees should be informed that housekeeping is a part of their job. Some of the requirements to have housekeeping in practice are to [3]:

1. Ensure that production, maintenance and test areas are in compliance with the housekeeping standards that improve foreign object debris elimination. (This includes but is not limited to sweeping and vacuuming production areas)
2. Ensure aisles, taxiways, flight decks and runways are free of any possible foreign object debris that could cause any damage
3. Ensure surfaces where aerospace vehicles and ground support equipment are operated and maintained free of object debris that could cause damage due to ingestion of foreign object debris into propeller exhaust and/or jet exhaust.
4. Maintain safe taxi distances between aircraft to minimize any danger of debris being moved by the propeller exhaust, and/or jet exhaust.
5. In maintenance of existing airfield facilities, assure that all construction debris is removed

at the end of each task and/or shift.

It is everyone's responsibility to keep work areas clean and orderly. Any items found on floors, stands and etc. not properly stored are violation of housekeeping practices and will be identified as such [2].

3.4.3 Accountability

The primary objective of a positive tool control program is to eliminate accidents and loss of life or equipment due to tool FOD. Explains a variety of methods used for tool control and accountability, and finds the most adequate method for every process. A well-established plan for material handling and parts protection can eliminate many potential FOD hazards. Some types of accountability processes will be discussed in the next sections.

3.4.3.1 Tool Control

According to LMC Aero Codes, specific methods such as Tool Control include:

1. General Tool/ Item Control:
    a. Types of kits/containers, Inventory frequency, Corrective action for inventory inaccuracies, Tool marking (Tools that are not too small must be marked/ etched/ serialized to provide traceability), Documentation requirements, and tool return time frame.
2. Manual Tool Control Processes
3. Automatic Dispensing Units SIM-PAC (ADUs)
4. Personal Tool Requirements
5. Company Issued Extended Use Tools

All control methods just mentioned, are required to be applied to all areas that involve manufacturing, modification, maintenance, test and operation of aircraft [2].

3.4.3.2 Test Equipment Control

Test equipment control is required to be applied to areas where Aircraft/Product is to be found. Some of the procedures that are included within the test equipment control are [2]:

1. Test Equipment Inventory and accountability
2. Automated Test Equipment Accountability via Automatic (CribMaster)
3. Manual Process (Logging or Chit Process)

3.4.3.3 Consumable Control

Consumable control procedures are applicable to areas of high level of risk of entrapment or migration into Flight Critical areas. Critical areas are called where assembly, modification and Flight and Ground Operations require the highest level of preventative measures [4]. This specific procedure highly states that consumables should never be allowed to be loose or un-contained on the aircraft. The consumable control process includes the following to be addressed [2]:

1. Prescribed Disposal/ Return process of uses/ unused consumables
2. Consumable control in FOD Control Environments
    a. Types of containment
    b. Method of accountability
    c. Control of rags

3.4.3.4 Miscellaneous Support Equipment Control

This specific preventive process highly states that no un-serviceable equipment is allowed to be used on the aircraft. There are programs that are mandated to be established for Miscellaneous Support Equipment and these should provide the following assurance equipment [2]:

1. Assignment/ Accountability/ Storage
2. Serviceability checks to ensure not FOD or safety hazard to Aircraft/Products/Personnel

3.4.3.5 Personal Item Control

For Personal item control process a procedure is to be established specifying how personal items will be controlled in the FOD Prevention Areas. Depending on the area, the number of processes will be modified and/or added.

3.4.3.6 Chit Process

This specific process is used for the Tool, Item, and Equipment control processes. In order to implement this process it must be ensured that Chits are traceable and accountable to the person using the tools, items and/or equipment. Within this process, the following are addressed [2]:

1. Chit Management
2. Personal Tool Chits
3. Tool Activity Chits

3.4.3.7 Logging Process

Logging process is used through electronic or other methods in order to account for tools, items, test and support equipment, when processes such as traceability do not exist. When these items are removed from distribution areas, a process must ensure what goes to the aircraft in removed or returned. This process must establish the following methods [2]:

1. General Common Logging Procedures
2. Record Keeping, Disposition and Supervisor, and Designee Accuracy Verification Process

3.4.3.8 Lost Tool Item Process

All of Lost tool item processes provide specific methods for all of the following [2]:

1. Timely notification and identification of lost tools and items
2. Shutdown and search expectations
3. Personnel required to participate of the search activities

4. Personnel authorized to release product and aircraft after Lost tool item actions are completed
5. Documentation and record keeping of all the actions taken in the Lost tool item search effort

3.4.4 Training

All employees are required to receive training in the identification and elimination of FOD, including the potential consequences of ignoring it [5]. The main goal for the FOD Prevention 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 disciplines. For employees associated with design, development, manufacturing, assembly, test, operations, repair, modification, refurbishment, and maintenance the FOD prevention training is requires as part of initial job orientation and on a continuing basis. Some of the topics covered by the FOD training program are [6]:

1. Proper storage, shipping and handling of material, components, and equipment.
2. Techniques to control debris.
3. Housekeeping.
4. Cleaning and inspection of components and assemblies.
5. Accountability/control of tools and hardware.
6. Control of personal items, equipment and consumables.
7. Care and protection of end items.
8. Quality Workmanship ("Clean-As-You-Go," inspection).
9. Flight line, taxiway and ramp control methods.
10. How to report FOD incidents or potential incidents.

3.5 Literature Review for Predictive Model Validation

In the next section the method that was used for the validation of the predictive model will be explained, as well as the results of this validation. It has to be mentioned that the predictive model utilized on this research was not validated before, this is the reason of which this had to be made on this research.

3.5.1 Measure of Forecast Precision

Mean Absolute Error is used to measure the approximate error when a prediction has been made by comparing the results of the prediction just made against the actual values of what the prediction was intended for. The Mean Absolute Error calculates the average magnitude of errors in a set of predictions, without considering their direction. The Mean Absolute Error is a linear score; this is that all the individual differences are weighted equally in the average. The Mean Absolute Error is the average of the verification sample of the absolute values of the differences between forecast and the corresponding observation. The equation is as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|f_i - y_i| = \frac{1}{n}\sum_{i=1}^{n}|e_i|$$

The description of variables is as follows: n is the number of predicted results within a specific sample. Since the mean absolute error is an average of the absolute errors $e_i=|f_i - y_i|$, f is the prediction and y the actual value [8]. In statistics, the mean squared error (MSE) of an estimator measures the average of the squares of the "errors", that is, the difference between the estimator and what is estimated. MSE is a risk function, corresponding to the expected value of the squared error loss or quadratic loss. The difference occurs because of randomness or because the estimator doesn't account for information that could produce a more accurate estimate [17].

If $\hat{Y}$ is a vector of n predictions, and Y is the vector of the true values, then the (estimated) MSE of the predictor is:

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n}(\hat{Y_i} - Y_i)^2.$$

CHAPTER 4. METHODOLOGY

The methodology followed to obtain a FOD type decision making model is shown below, and explained in coming subsections. It is also explained the data preparation that had to be done. As well as the technical part of the predictive model used.

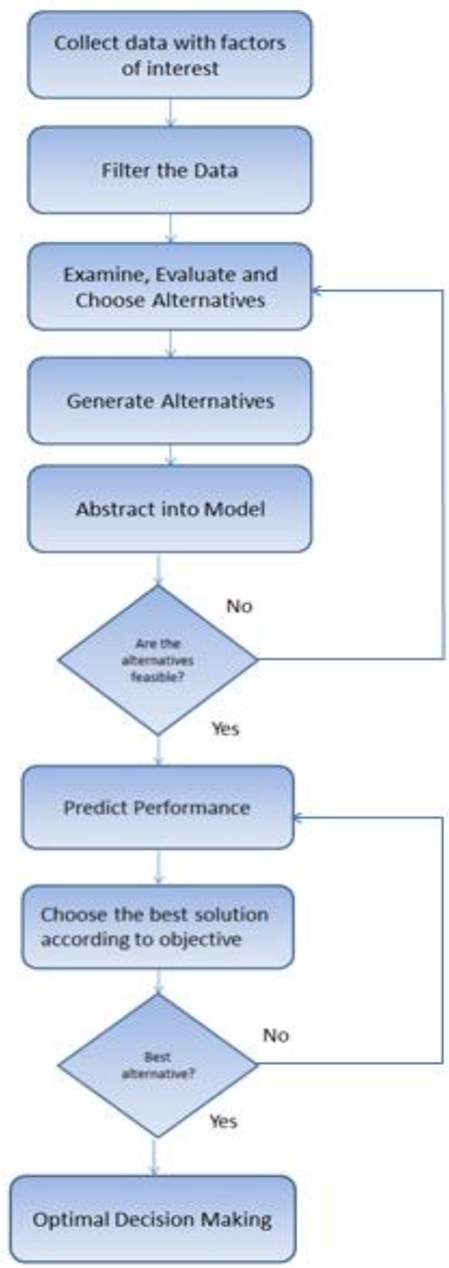

Figure 1: The Flow Chart of Methodology

4.1 Data Preparation

An aeronautical company provided data for this study. Such data included Quality Assurance Reports (QARs) of FOD, which are written by Quality Inspectors during final inspection at their particular SWBS. Data included information of the last three years (2010 through September 2013) of all aircrafts built by such aeronautics company.

QARs detail what the quality FOD problem was. They describe where it was found, at what SWBS, location of the plane, during what month, how much it cost, possible cause of the problem investigated and assigned by a Quality Engineer, actual object (FOD) that was found or defect description, hours invested to solve the problem, system being installed, if it was a supplier problem or not, what specific plane was being built, Julian dates, among other that are not really significant to this analysis.

There were some QARs in the dataset that were not properly written, some with missing information, some others had SWBS written in the cell where date was supposed to be, and as a consequence they were missing the date. For this study only complete QARs and correctly written documents were considered.

Data to be analyzed had to be selected based on different criteria. First criterion was the type of aircraft being built. Data provided contain information of seven different aircrafts. However, out of the seven only two had enough reports from which being able to analyze and make conclusions. These two aircrafts are F-35 and a C-130. All remaining (not of chosen aircrafts) QARs were deleted from the dataset to be analyzed.

After such mentioned preparation, then data were separated into two datasets, one for each type of aircraft. The reason of this separation is that, although same company builds them, they are still two different aircrafts, they are not built at the same facility and not even in the same

manner, through same processes, etc. For instance, dataset of each aircraft contain SWBS. Some SWBSs of the F-35 could be common to the ones of the C-130; but definitely there are some SWBSs of the F-35 that are not similar or not even needed when building the C-130 and vice versa.

The split of the data generates the need of two different predictive models, one for each plane. It is not possible to have a common predictive model due to their differences. It is then more convenient to treat them separately; however, they are treated with the same methodology.

4.1.1.1 Defect Codes with Descriptions

The following tables will depict the relevant Defect Codes pertaining to Design Decision classified under their corresponding FOD Type.

Table 3: F-35 Design Decisions: FOD Type Manufacturing Debris Defect Codes Description

Manufacturing Debris	
Z20	Z21
FOD – Bolt FOD - Fastener Collars FOD - Fastener Stems FOD - Fastener Washers FOD - Fasteners FOD - Test Fittings/Support Equipment Items FOD - Washers	FOD – Chips FOD – Shavings METAL ON MAGNETIC PLUG/FILTER/SCREEN

Table 4: F-35 Design Decisions: FOD Type Tools Defect Codes Description

TOOLS			
Z05	Z20	Z23	
FOD - Hydraulic fluids	FOD - Bolt	FOD - Adapter	FOD - Hot air gun
FOD - Jet fuel	FOD - Fastener Collars	FOD - Allen Wrench	FOD - Knife
FOD - Lubricating oils/grease	FOD - Fastener Stems	FOD - Apex tips	FOD - Magnifier
FOD - Turbine Oils	FOD - Fastener Washers	FOD - Bucking Bar	FOD - Mirror
Z25	FOD - Fasteners	FOD - Calibrated Tools	FOD - Pliers
FOD - Cotter Pins	FOD - Test Fittings/Support Equipment Items	FOD - Chip Chaser	FOD - Power Tools
FOD - Lock Pins	FOD - Washers	FOD - Chisel	FOD - Punch
FOD - Safety Ties	Z29	FOD - Chuck Key	FOD - Ratchet
FOD - Safety Wire	FOD - Nut	FOD - Countersink	FOD - Reamers
FOD - Snap Ring	FOD - Nutplates	FOD - Cutters	FOD - Scale
FOD - String Ties	Z28	FOD - Deburring Tool	FOD - Scotchbrite holder

Z26	FOD - Clamps	FOD - Dies	FOD - Screwdriver
FOD - Stickers	FOD - Clecos	FOD - Dikes	FOD - Scribe
FOD - Tape	FOD - Vise grip	FOD - Drill Bits	FOD - Socket
		FOD - Extension	FOD - Speed Handle
		FOD - File	FOD - Squeeze set
		FOD - Flashlight	FOD - Tools
		FOD - Gages	FOD - Tridair tool
		FOD - Hammer	FOD - Wrench

Table 5: F-35 Design Decisions: FOD Type Consumables Defect Codes Description

Consumables			
Z05	**Z22**	**Z24**	**Z25**
FOD - Hydraulic fluids	FOD - Caps	FOD - Sealant	FOD - Cotter Pins
FOD - Jet fuel	FOD - Covers	FOD - Sealant-Gasket	FOD - Lock Pins
FOD - Lubricating oils/grease	**Z27**	FOD - Seals	FOD - Safety Ties
FOD - Turbine Oils	FOD - Braid	**Z29**	FOD - Safety Wire

Z26	FOD - Elect-Receptacles, Terminals	FOD - Nut	FOD - Snap Ring FOD - String Ties
FOD - Stickers FOD - Tape	FOD - Electrical FOD - Wire	FOD - Nutplates Z30 FOD - Spacers FOD - Spacers-Peel Shim, Insert	

Table 6: F-35 Design Decisions: FOD Type Panstock Defect Codes Description

Panstock		
Z23	Z23	Z05
FOD - Adapter FOD - Allen Wrench FOD - Apex tips FOD - Bucking Bar FOD - Calibrated Tools FOD - Chip Chaser FOD - Chisel	FOD - Pliers FOD - Power Tools FOD - Punch FOD - Ratchet FOD - Reamers FOD - Scale FOD - Scotchbrite holder	FOD - Hydraulic fluids FOD - Jet fuel FOD - Lubricating oils/grease FOD - Turbine Oils **Z20** FOD - Bolt FOD - Fastener Collars

FOD - Chuck Key	FOD - Screwdriver	FOD - Fastener Stems
FOD - Countersink	FOD - Scribe	FOD - Fastener Washers
FOD - Cutters	FOD - Socket	FOD - Fasteners
FOD - Deburring Tool	FOD - Speed Handle	FOD - Test Fittings/Support Equipment Items
FOD - Dies	FOD - Squeeze set	FOD - Washers
FOD - Dikes	FOD - Tools	Z25
FOD - Drill Bits	FOD - Tridair tool	FOD - Cotter Pins
FOD - Extension	FOD - Wrench	FOD - Lock Pins
FOD - File	Z26	FOD - Safety Ties
FOD - Flashlight	FOD - Stickers	FOD - Safety Wire
FOD - Gages	FOD - Tape	FOD - Snap Ring
FOD - Hammer	Z28	FOD - String Ties
FOD - Hot air gun	FOD - Clamps	Z29
FOD - Knife	FOD - Clecos	FOD - Nut
FOD - Magnifier	FOD - Vise grip	FOD - Nutplates
FOD - Mirror		

4.1.1.1 Causes

After the data preparation process, the cause codes remaining were graphed in the following table, this was made to have a better understanding of the causes and the design decision could be made.

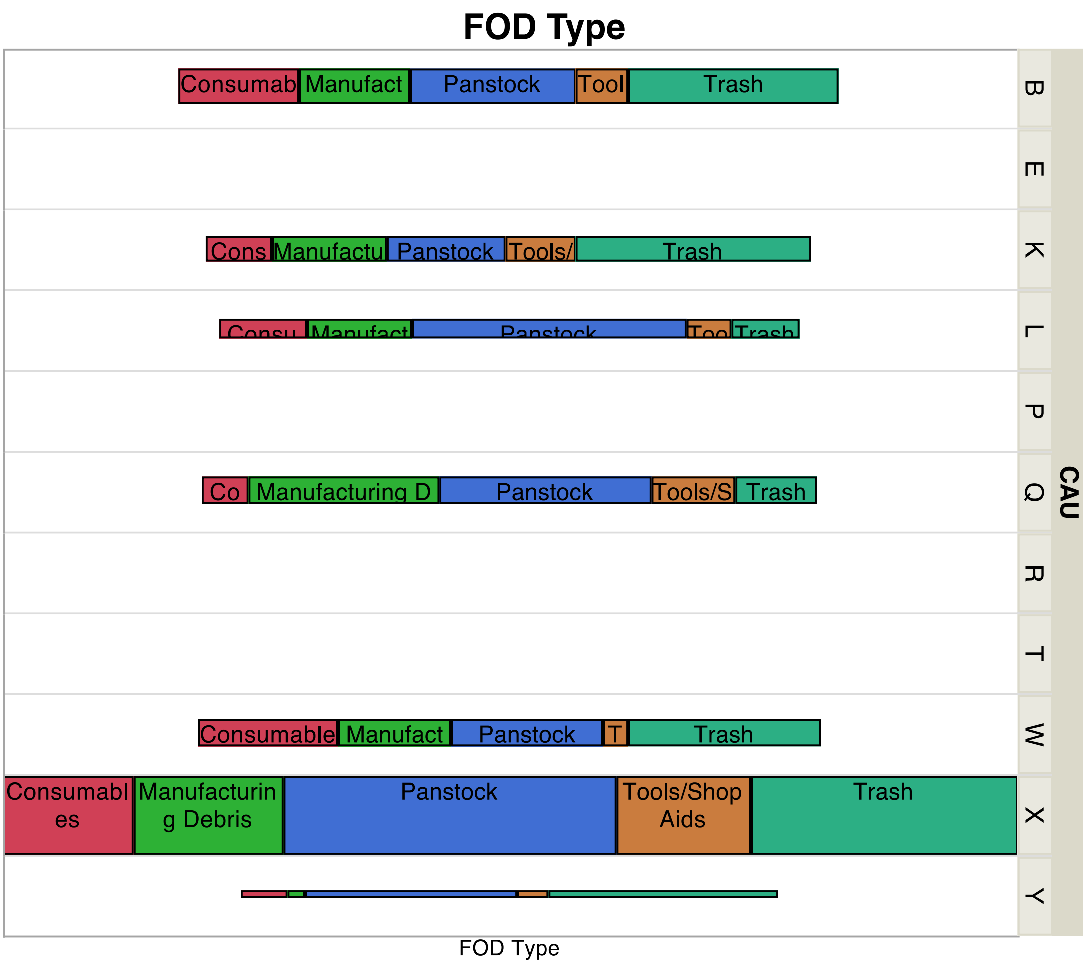

Figure 2: F-35 Design Decisions: Cause Codes

A. **Cause Codes**

"B" Issue identified for corrective action, (temporary code)

"E" Engineering - any engineering related issue

"K" Process Deficiency-Eliminate or Reduce Risk of Recurrence

"L" Cause Indeterminable - Positive responsibility cannot be determined

"P" Planning issue

"Q" Deferred - Low Cost, non-repetitive issue. Cause determination not cost effective at this time

"R" Lower Assembly or Secondary failure (cause and responsibility determined on referenced QAR)

"W" Out-of-Area Workmanship

"X" In-Area Workmanship

"Y" Management Decision

4.1.1.2 Workstations

The SWBSs, or the workstations that the aeronautical company uses on the data received, were described and grouped as follows. This codes have been explained to have an understanding of the data preparation and analysis that has to be made.

Table 7: F-35 Design Decisions: F-35 SWBS Grouping

SWBS Grouping and Descriptions		
J200	Forward Component Completion	
J220	Fwd Sys Instl TS, MFD, PIM, Seat Rail	
J230	Forward, FEB, Cockpit, Skin Instl	J240
J240	Forward, Tube, Harness, Canopy	
J260	Fwd, Floor, Console & NLG Hinge Fitting	
J420	Win Compl, Upr Skin, Fuel Tank Test, Insp	J420
J430	Wing, Subsystems install & Checkout	
J450	Wing, Outer to Inner Splice Autodrill	J430-460

J460	Wing, Outer to Inner Wing Mate	
J461	Wing LH Outer Upr & Lwr Autodrill	J461-2
J462	Wing, RH Outer Upr & Lwr Autodrill	
J470	Wing, Inner Wing Module Prep	J470
J475	Wing, Inner Wing Module 2 Assy	J475
J480	Wing, Inner Wing Module 1 Assembly	J480
J810	Airplane Assy	J810
J825	Airplane Assy Ground Operations	J825
J830	Final Assy - Systems and Testing	J830
J850	Final Assembly	J850
J860	Mate, Fuselage, Major Mate, Structure	J860
J800	Flight Line	J800

4.2 The Predictive Model

The mathematical model of the logistic regression, or log odds, has been adjusted to this specific problem, to the significant independent variables of this problem. The FOD type logistic regression model follows the following adjusted mathematical formula:

$$\log(odds) f(n)_{wm} = \beta_0 + \sum_{w=J2*}^{J860} \sum_{m=Jan}^{Dec} [\alpha_w x_w + \tau_m z_m + (\alpha\tau)_{wm} x_w z_m] \qquad (2)$$

where,

$f(n)$: FOD Type Ratio

$f(1)$: Consumables vs. Trash

$f(2)$: Manufacturing Debris vs. Trash

$f(3)$: Panstock vs. Trash

$f(4)$: Tools/Shop Aids vs. Trash

w: SWBS

m: Month

β_0: Intercept

α_w: SWBS Estimate

x_w: SWBS Value (0 or 1)

τ_m: Month Estimate

z_m: Month Value (0 or 1)

$(\alpha\tau)_{wm}$: Interaction Estimate

Notice that the chosen base for the log odds was FOD type trash; it was chosen by JMP® Software which selects the most popular outcome. Four log odds ratios were generated: consumables vs. trash, manufacturing debris vs. trash, panstock vs. trash, and tools/shop aids vs. trash. Each log odds regression model has a total of 144 estimates/coefficients, which includes all levels of the independent variables, all possible interactions, as well as intercept There are no estimates for the bases of the model, which for this case study are month December and SWBS J461-2; remember that intercept takes care of those bases.

4.2.1 Transforming FOD Type Log Odds to Probabilities

FOD type log odds can be transformed to probabilities using the following mathematical formulas. These formulas have also been adjusted to the significant independent variables of this case study. Formula (3) is the formula used for consumables, manufacturing debris, tools/shop aids and panstock. A different formula (4) is needed for converting the base log odds, which is trash, into probabilities.

$$\pi_{f(n)_{wm}} = \frac{e^{\beta_0 + \sum_{w=J2*}^{J860} \sum_{m=Jan}^{Dec} [\alpha_w x_w + \tau_m z_m + (\alpha\tau)_{wm} x_w z_m]}}{1 + \sum_{f(1)}^{4} e^{\beta_0 + \sum_{w=J2*}^{J860} \sum_{m=Jan}^{Dec} [\alpha_w x_w + \tau_m z_m + (\alpha\tau)_{wm} x_w z_m]}} \quad (3)$$

$$\pi_{f'_{wm}} = \frac{1}{1 + \sum_{f(1)}^{4} e^{\beta_0 + \sum_{w=J2*}^{J860} \sum_{m=Jan}^{Dec} [\alpha_w x_w + \tau_m z_m + (\alpha\tau)_{wm} x_w z_m]}} \quad (4)$$

where,

f': Trash

π: Probability

4.2.2 FOD Type Prediction for Specific Circumstances

Decision situations with incomplete information are characterized by a decision maker without a precisely defined, stable preference structure; by probability distributions not known completely; or by an inexact evaluation of consequences. Within the paper a general framework for decision making with incomplete, information is presented which shows how to solve problems from descriptive as well as prescriptive decision theory. There are many methods in the field of decision analysis that try to help a decision maker to come up with a decision, that is, to find an optimal or satisfying solution.

4.2.3 Computational Results

These models can be applied for several desired circumstances, including all F-35 and C-130 SWBSs and months. Results for both aircrafts, every SWBS throughout the year can be observed in following graphs. The results of these predictive model factors are going to be the base of the decision making model presented.

4.3 Validation of the Predictive Model

Validation of the FOD Logistic Regression Predictive Model was needed to know the approximate accuracy of the model. Accuracy can be defined as how close a measured value is to

the actual (true) value [17]. In the other hand, precision can be defined as how close the measured values are to each other [17]. This is the reason why it was chosen to calculate the accuracy and not the precision of the model. The criterion which was set at the beginning of the validation of the model was that 50% accuracy would be acceptable but some adjustments will have to be applied to the current model in order to try to make it more accurate. A lower than 50% accuracy would not be acceptable and the current model would have to face many changes such as using different factors for its construction, and/or corrections to data in order to have a more accurate predictive model. However, some data adjustments had to be made for the validation part in order to compare the prediction results to the actual values. Such adjustments will be better explained in the next subsections. The method of Mean Absolute Error was utilized to approximate the average error found when comparing predictions made to the actual values.

4.3.1 Raw data separated by year (2011, 2012, and 2013)

As mentioned in earlier sections an aeronautical company provided data from the past three years in order to complete this study. This data was only Quality Assurance Reports of FOD. As explained in earlier sections this data was utilized for the construction of the predictive model using factors such as SWBSs and months of the year. For the construction of the predictive model variables or coefficients all the data from the past three years was used. This meaning that the predictive model was good to predict for the following three years. However, for the validation of this model data was separated by year this meaning there were separate files of data for the years 2011, 2012, and 2013. By separating data new coefficients for the model had to be calculated in the JMP® Software. These adjustments had to be applied in order to predict for one year ahead and then have actual values for that specific year and be able to compare it with the prediction results to see the model's accuracy.

4.3.2 Construction of FOD Logistic Regression Predictive Model for years: 2012, 2013, and 2014

As just mentioned in the past section, data was separated by year (2011, 2012, and 2013). This means that 2011 data was used for the construction of the estimates for the predictive model in order to predict for 2012, then 2012 data was used for the construction of the estimates for the predictive model in order to predict for 2013, and so on. The following is an example of estimates using data from 2011 to predict for 2012. The circumstance that will be evaluated is Airplane Assembly 2 (J825 Airplane Assy Ground operations) and month November (11) both for predictions of year 2012 (using data from 2011 to construct estimates):

Table 8: F-35 Predictive Model Estimates for Airplane Assembly for the month of November 2012

Log Odds	Covariate	Estimate
Consumable vs. Trash	Intercept	12.0645269
	Month: November	-12.06588
	SWBS: Airplane Assembly 2	-1.6611949
	Interaction: November in Airplane Assembly 2	0
Manufacturing Debris vs. Trash	Intercept	7.25938872
	Month: November	14.9879665
	SWBS: Airplane Assembly 2	-21.738255
	Interaction: November in Airplane Assembly 2	0

Panstock vs. Trash	Intercept	10.4663302
	Month: November	14.5393074
	SWBS: Airplane Assembly 2	-24.868879
	Interaction: November in Airplane Assembly 2	0
Tools/Shop Aids vs. Trash	Intercept	-4.1754912
	Month: November	4.17392774
	SWBS: Airplane Assembly 2	-0.0515464
	Interaction: November in Airplane Assembly 2	**0**

All of the estimates for the different years, months and SWBSs can be found in Appendix A. Then, with the above estimates the predictions for 2012 under the circumstance of month November (11) and SWBS Airplane Assembly 2(J825 Airplane Assy Ground operations) can be calculated. The four different log odds are shown below using the predictive model (equation 19). Notice that the remaining estimates for different months and SWBSs are excluded since they are not needed in the formula since they will zero out because they are not part of the desired circumstance for prediction.

log (*odds) f(1)J825, 11* = 12.0645269 -12.06588 (1) − 1.6611949(1) + 0(1)(1) = -1.662548

log (*odds) f(2)J825, 11* = 7.25938872 +14.9879665(1) − 21.738255(1) – 0(1) (1) = 0.50910022

log (*odds) f(3)J825, 11* = 10.4663302+ 14.5393074(1) − 24.868879(1)−0(1) (1) = 0.1367586

log (*odds) f(4)J825, 11* = -4.1754912−4.17392774(1) − 0.0515464(1) – 0 (1)(1) = -0.05310986

As a result the log odds of consumables is -1.662548, for manufacturing debris is 0.50910022, for

panstock is 0.1367586, and for tools/shop aids is -0.5310986. For a better understanding of these log odds; the most positive is the most likely type of FOD to be found under specific circumstance, and the most negative is the least likely type of FOD to be found under specific circumstance. By comparing these log odds just calculated above the most likely type of FOD to find in Airplane Assembly 2 (J825 Airplane Assy Ground operations) during November is manufacturing debris, then would be panstock, tools/shop aids and lastly consumables. For instance, for the FOD type trash value, whose value is zero is right between panstock and tools/shop aids that makes this type of FOD the third one with greatest chances to be found.

However, there is an easier way to understand the probabilities of finding each type of FOD, this is using equations (20) and (21) to transform log odds into actual percentages. The following are the results of the log odds just calculated transformed into actual percentages:

$$\pi_{f(1)_{J825,11}} = \frac{e^{-1.662548}}{1 + e^{-1.662548} + e^{0.50910022} + e^{0.1367586} + e^{-0.05310986}} = 3.83\%$$

$$\pi_{f(2)_{J825,11}} = \frac{e^{0.50910022}}{1 + e^{-1.662548} + e^{0.50910022} + e^{0.1367586} + e^{-0.05310986}} = 33.62\%$$

$$\pi_{f(3)_{J825,11}} = \frac{e^{0.1367586}}{1 + e^{-1.662548} + e^{0.50910022} + e^{0.1367586} + e^{-0.05310986}} = 23.17\%$$

$$\pi_{f(4)_{J825,11}} = \frac{e^{-0.05310986}}{1 + e^{-1.662548} + e^{0.50910022} + e^{0.1367586} + e^{-0.05310986}} = 19.16\%$$

$$\pi_{f'_{J825,11}} = \frac{1}{1 + e^{-1.662548} + e^{0.50910022} + e^{0.1367586} + e^{-0.05310986}} = 20.21\%$$

Interpreting results are that manufacturing debris has a probability of 33.62%, panstock of 23.17%, trash of 20.21%, tools/shop aids of 19.16% and consumables of 3.83% of being found in Airplane

Assembly 2 (J825 Airplane Assy Ground operations) during November of 2012. It can be confirmed that interpretations and conclusion made with log odds are true. One more advantage is that the value for the base, which is trash, can also be calculated with an actual percentage. Furthermore, this transformation of log odd to probabilities is easier to understand.

4.3.3 Validation

After calculating all of the log odds then transforming them to probabilities of years 2012 and 2013, the validation of the predictive model using the method of Mean Absolute Error can take place. First percentages of actual data provided by the company of years 2012 and 2013 had to be transformed into percentages in order to be able to compare it to the predictions. This is because the results of predictions are interpreted in percentages. Since for the construction of predictive model estimates a weight of the total defect costs (TOTCOST) was used, this was to give more focus into those FOD types costing the most to the company, then in order to transform the actual data into percentages, the total defect costs (TOTCOST) were involved. The following is an example of how the actual data of 2012 (under circumstance of SWBS Airplane Assembly 2) using total defect cost was transformed into percentages:

Table 9. F-35 Total costs (TOTCOST) of FOD Types for SWBS J825 Airplane Assy Ground operations (Airplane Assembly 2) during year 2012

AIRPLANE ASSEMBLY 2	Consumables	Manufacturing Debris	Panstock	Tools/Shop Aids	Trash	Total
Month 1	85	2125	181	173	413	2977
Month 2	161	0		86	59	306
Month 3	46	0	17	158	17	238

Month 4	110	0	857	0	17	984
Month 5	34	0	35	34	0	103
Month 6	0	0	0	0	0	0
Month 7	104	53	103	0	0	260
Month 8	0	226	136	0	17	379
Month 9	34	287	0	17	114	452
Month 10	0	855	157	17	64	1093
Month 11	345	0	149	17	0	511
Month 12	34	2178	447	0	109	2768

Table 10. F-35 percentages according to Total costs (TOTCOST) of FOD Types for SWBS J825 Airplane Assy Ground operations (Airplane Assembly 2) during year 2012

AIRPLANE ASSEMBLY 2	Consumables	Manufacturing Debris	Panstock	Tools/Shop Aids	Trash	Total
Month 1	2.86	71.38	6.08	5.81	13.87	100.00
Month 2	52.61	0.00	0.00	28.10	19.28	100.00
Month 3	19.33	0.00	7.14	66.39	7.14	100.00
Month 4	11.18	0.00	87.09	0.00	1.73	100.00
Month 5	33.01	0.00	33.98	33.01	0.00	100.00
Month 6	0.00	0.00	0.00	0.00	0.00	100.00
Month 7	40.00	20.38	39.62	0.00	0.00	100.00

Month 8	0.00	59.63	35.88	0.00	4.49	100.00
Month 9	7.52	63.50	0.00	3.76	25.22	100.00
Month 10	0.00	78.23	14.36	1.56	5.86	100.00
Month 11	67.51	0.00	29.16	3.33	0.00	100.00
Month 12	1.23	78.68	16.15	0.00	3.94	100.00

The second table shows the actual percentages of FOD Types that were found in 2012 in Airplane Assembly 2. Then these percentages will be compared against the prediction percentages using the methods mentioned earlier. The following subsection will explain how the validation was made using the different methods mentioned.

4.3.4 Mean Absolute Error

Mean Absolute Error was the method used to calculate the error of the predictive model. The results of the validation (error of the predictive model) will be interpreted in percentages since what is being compared are only percentages from both the predictions and actual data. An example for each comparison of predictions and actual data for year 2012 and 2013 will be presented in the next subsections.

4.3.4.1 Prediction for year 2012 (using Actual data from 2011) vs. Actual data from 2012

In this section an example of how the validation of the predictive model was made will be presented. The circumstance will be of Airplane Assembly 2 in the entire year of 2012.

Table 11. F-35 percentages according to Total costs (TOTCOST) of FOD Types for SWBS J825 Airplane Assy during year 2012 (actual data provided)

AIRPLANE ASSEMBLY 2	Consumables	Manufacturing Debris	Panstock	Tools/Shop Aids	Trash

Month 1	2.90	71.40	6.10	5.80	13.90
Month 2	52.60	0.00	0.00	28.10	19.30
Month 3	19.30	0.00	7.10	66.40	7.10
Month 4	11.20	0.00	87.10	0.00	1.70
Month 5	33.00	0.00	34.00	33.00	0.00
Month 6	0.00	0.00	0.00	0.00	0.00
Month 7	40.00	20.40	39.60	0.00	0.00
Month 8	0.00	59.60	35.90	0.00	4.50
Month 9	7.50	63.50	0.00	3.80	25.20
Month 10	0.00	78.20	14.40	1.60	5.90
Month 11	67.50	0.00	29.20	3.30	0.00
Month 12	1.20	78.70	16.10	0.00	3.90

Table 12. F-35 prediction percentages of FOD Types for SWBS J825 Airplane Assy Ground operations (Airplane Assembly 2) for year 2012

AIRPLANE ASSEMBLY 2	Consumables	Manufacturing Debris	Panstock	Tools/Shop Aids	Trash
Month 1	0.00	100.00	0.00	0.00	0.00
Month 2	100.00	0.00	0.00	0.00	0.00
Month 3	0.00	0.00	0.00	0.00	100.00
Month 4	0.00	100.00	0.00	0.00	0.00
Month 5	100.00	0.00	0.00	0.00	0.00
Month 6	0.00	0.00	0.00	0.00	100.00

Month 7	0.98	88.98	0.00	4.89	5.16
Month 8	0.00	0.00	0.00	0.00	0.00
Month 9	0.00	0.00	0.00	0.00	0.00
Month 10	18.85	0.00	2.04	2.69	76.42
Month 11	3.83	33.62	23.17	19.16	20.21
Month 12	100.00	0.00	0.00	0.00	0.00

Notice that the values in both tables are percentages. All of the predictions for years 2012 and 2013, and percentages for actual data of years 2012 and 2013 can be found in Appendix B. The values that are in these two tables were used to calculate the Mean Absolute Error. Those values were inputted in equation (1) as follows. The circumstance used in the following example is for Airplane Assembly 2 during month November (11):

$$\boldsymbol{MAE} = \frac{1}{5}\sum_{i=1}^{5}(|3.83 - 67.50| + |33.62 - 0| + |23.17 - 29.20| + |19.16 - 3.30| + |20.21 - 0|) = 27.87\%$$

Notice that the 5 values are from the 5 different FOD types. As a result, there is a 27.87% error when comparing the prediction for 2012 and actual data from 2012 under the circumstance of only month November (11) in Airplane Assembly 2. The following table shows the percentage errors of the comparison between predictions for 2012 and actual data of 2012 for Airplane Assembly 2 (J825 Airplane Assy Ground operations). Equation 1 was applied in order to have these percentage errors.

Table 13. MAE calculations for F-35 comparing actual data from 2012 and predictions for 2012 for FOD Types for SWBS J825 Airplane Assy Ground operations (Airplane Assembly 2)

AIRPLANE ASSEMBLY 2	**Consumables**	**Manufacturing Debris**	**Panstock**	**Tools/Shop Aids**	**Trash**	**MAE**
Month 1	2.90	28.60	6.10	5.80	13.90	**11.46**
Month 2	47.40	0.00	0.00	28.10	19.30	**18.96**
Month 3	19.30	0.00	7.10	66.40	92.90	**37.14**
Month 4	11.20	100.00	87.10	0.00	1.70	**40**
Month 5	67.00	0.00	34.00	33.00	0.00	**26.8**
Month 6	0.00	0.00	0.00	0.00	100.00	**20**
Month 7	39.02	68.58	39.60	4.89	5.16	**31.45**
Month 8	0.00	59.60	35.90	0.00	4.50	**20**
Month 9	7.50	63.50	0.00	3.80	25.20	**20**
Month 10	18.85	78.20	12.36	1.09	70.52	**36.204**
Month 11	63.67	33.62	6.03	15.86	20.21	**27.878**
Month 12	98.80	78.70	16.10	0.00	3.90	**39.5**
					MAE (Average %Error) =	**27.45%**

By interpreting the results the average percent error when comparing predictions for 2012 and actual data for 2012 in Airplane Assembly 2 (J825 Airplane Assy Ground operations) is 27.45%, meaning that the accuracy of the model for this year and this specific SWBS is of 72.55%. The table below shows the average %errors of all SWBSs in the comparison of predictions for 2012 and actual data of 2012.

Table 14. MAE average percent errors of the comparison between actual data from 2012 and predictions for 2012 for F-35 FOD Types for SWBS

SWBS (Workstation)	Average %Error
(Airplane Assembly 2)	27.45%
(Final Assembly 1)	23.48%
(Final Assembly 2)	31.53%
(Forward)	23.37%
(Mate)	29.22%
(Wing 1)	29.56%
(Wing 3)	19.91%
(Wing 4)	31.97%
(Wing 5)	21.64%
(Wing 6)	21.71%
Average %Error (of all SWBSs)	25.98%

As a result of the comparison of predictions for 2012 and actual data from 2012, the average percent error from all SWBSs is 25.98%, this meaning the accuracy of the predictive model when

predicting for 2012 using data from one previous year to construct model and its estimates is of 74.02%.

4.3.4.2 Prediction (using Actual data from 2012) vs. Actual data from 2013

In this section an example of how the validation of the predictive model was made will be presented. The circumstance will be of Airplane Assembly 2 (J825 Airplane Assy Ground operations) in the entire year of 2013.

Table15. F-35 percentages according to Total costs (TOTCOST) of FOD Types for SWBS J825 Airplane Assy Ground operations (Airplane Assembly 2) during year 2013 (actual data provided)

AIRPLANE ASSEMBLY 2	Consumables	Manufacturing Debris	Panstock	Tools/Shop Aids	Trash
Month 1	14.29	0.00	28.57	14.29	42.86
Month 2	0.00	0.25	9.57	0.00	90.18
Month 3	60.81	0.00	28.83	2.70	7.66
Month 4	6.28	0.00	5.80	0.00	87.92
Month 5	0.00	0.00	0.00	0.00	100.00
Month 6	8.74	0.00	34.95	56.31	0.00
Month 7	71.56	0.00	19.41	0.00	9.03
Month 8	0.50	92.10	5.39	0.50	1.50
Month 9	0.00	0.00	4.51	13.53	81.95
Month 10	20.00	20.00	40.00	0.00	20.00
Month 11	0.00	0.00	0.00	0.00	0.00
Month 12	0.00	0.00	0.00	0.00	0.00

Table16. F-35 Program prediction percentages of FOD Types for SWBS J825 Airplane Assy Ground operations (Airplane Assembly 2) for year 2013

AIRPLANE ASSEMBLY 2	Consumables	Manufacturing Debris	Panstock	Tools/Shop Aids	Trash
Month 1	2.81	71.41	6.08	5.81	13.88
Month 2	46.38	0.00	0.00	31.80	21.82
Month 3	19.62	0.00	7.12	66.15	7.12
Month 4	11.35	0.00	86.93	0.00	1.72
Month 5	32.51	0.00	34.23	33.25	0.00
Month 6	0.00	0.00	100.00	0.00	0.00
Month 7	38.81	20.79	40.40	0.00	0.00
Month 8	0.00	59.63	35.88	0.00	4.49
Month 9	7.41	63.57	0.00	3.77	25.25
Month 10	0.00	78.23	14.36	1.56	5.86
Month 11	66.86	0.00	29.75	3.39	0.00
Month 12	0.12	0.00	99.88	0.00	0.00

Notice that the values in both tables are percentages. The values that are in these two tables were used to calculate the Mean Absolute Error. Those values were inputted in equation (1) as follows. The circumstance used in the following example is for Airplane Assembly 2 during month January (1):

$$MAE = \frac{1}{5}\sum_{i=1}^{5}(|2.81 - 14.29| + |71.41 - 0| + |6.08 - 28.57| + |5.81 - 14.29| + |13.88 - 42.86|) = 28.56\%$$

Notice that the 5 values are from the 5 different FOD types. As a result, there is a 28.56% error when comparing the prediction for 2013 and actual data from 2013 under the circumstance of only month January (1) in Airplane Assembly 2. The following table shows the percentage errors of the comparison between predictions for 2013 and actual data of 2013 for Airplane Assembly 2. Equation 1 was applied in order to have these percentage errors.

Table 17. MAE calculations for F-35 Program comparing actual data from 2013 and predictions for 2013 for FOD Types for SWBS J825 Airplane Assy Ground operations (Airplane Assembly 2)

AIRPLANE SSEMBLY 2	Consumables	Manufacturing Debris	Panstock	Tools/Shop Aids	Trash	MAE
Month 1	11.48	71.41	22.49	8.48	28.98	**28.568**
Month 2	46.38	0.25	9.57	31.80	68.36	**31.272**
Month 3	41.19	0.00	21.71	63.45	0.54	**25.378**
Month 4	5.07	0.00	81.13	0.00	86.20	**34.48**

Month 5	32.51	0.00	34.23	33.25	100.00	**39.998**
Month 6	8.74	0.00	65.05	56.31	0.00	**26.02**
Month 7	32.75	20.79	20.99	0.00	9.03	**16.712**
Month 8	0.50	32.47	30.49	0.50	2.99	**13.39**
Month 9	7.41	63.57	4.51	9.76	56.70	**28.39**
Month 10	20.00	58.23	25.64	1.56	14.14	**23.914**
					MAE (Average %Error =	**26.8122 %**

By interpreting the results the average percent error when comparing predictions for 2013 and actual data for 2013 in Airplane Assembly 2 is 26.81%, meaning that the accuracy of the model for this year and this specific SWBS is of 73.19%. Notice that there are no values for month 11 and month 12, this is because actual data provided by the aeronautical company for 2013, did not include these two months. Since there is no actual data for these two months the Mean Absolute Error cannot be calculated. The average percent errors for years 2012 and 2013 from all SWBSs

can be found in Appendix C. The table below shows the average %errors of all SWBSs in the comparison of predictions for 2013 and actual data of 2013.

Table 18. MAE average percent errors of the comparison between actual data from 2013 and predictions for 2013 for F-35 FOD Types for SWBS

SWBS (Workstation)	Average %Error
(Airplane Assembly 1)	29.22%
(Airplane Assembly 2)	26.81%
(Final Assembly 1)	21.31%
(Final Assembly 2)	22.79%
(Flight line)	26.92%
(Forward)	19.11%
(Mate)	23.12%
(Wing 1)	28.28%
(Wing 2)	27.23%
(Wing 3)	37.42%
(Wing 4)	23.72%
(Wing 5)	26.35%
(Wing 6)	36.00%
Average %Error (of all SWBSs)	26.79%

As a result of the comparison of predictions for 2013 and actual data from 2013, the average percent error from all SWBSs is 26.79%, this meaning the accuracy of the predictive model when

predicting for 2013 using data from one previous year to construct model and its estimates is of 73.21%.

In conclusion, after validating the predictive model using the method of Mean Absolute Error for years 2012 and 2013, we found out that the accuracy for the model when predicting for only one year ahead is approximately of 73.61%. The target is to have a more accurate predictive model, of at least 85% of accuracy. Efforts will be implemented to find a means of making the predictive model more accurate.

Another Measure of error that was calculated in order to create a baseline for the next improvements on the predictive model was the Mean Squared Error, which was explained on previous sections. The results were divided into workstations and then generated a total MSE, it was divided to have more specific results on all the workstations for further investigation. For the MSE of the predictive model compared with the actual data of 2014 is 1281.01. This measure of error will have to be enriched as well as the MAE when trying to improve the accuracy of the predictive model.

4.4 Decision Making Model

Decision making with incomplete information on probability distributions lies somewhat between decision making under uncertainty set of all possible probability distributions, no information) and decision making under risk, complete information. Within this section we want to briefly present methods for decision making based on sets of probability distributions. References for more detailed descriptions are given throughout this section. A problem exists if we want to know whether there are any probability distributions consistent with this information, that is, whether these judgments elicited are compatible with the laws of probability theory. Instead of repeating parts of our arguments we want to conclude by giving suggestions for future research.

Obviously the application of incomplete information on utility functions needs further investigation. The extension of traditional methods as well as empirical research would be necessary. Questions like ‘how can we really measure incompleteness?’ and ‘what does the observed incompleteness mean for practical purposes?’ still have to be answered. A theory of measuring incomplete information has to be developed. In a prescriptive setting it would be helpful to do further research on a structured information gathering process. We see group decision making as an important area of possible applications for the concept of incomplete information.

The objective of the decision making model with linear programming is to minimize the total FOD expected for a set of FOD type on each workstation per month. The purpose of this research is to establish a system or methodology by setting an objective function that will calculate the summation of the FOD type expected, and to minimize this objective function as much as possible. There are five different types of FOD, (i) Manufacturing Debris, (ii) Panstock (PLS), (iii) Consumables, (iv) Tools/shop aids and (v) Trash. In this particular linear programming decision making model the subsequent assumptions are considered: (a) there isn’t any cost related with the technology implementations, (b) there isn’t any cost related with the processes implementations, (c) there isn’t any time constraint related with the technology applications, (d) there isn’t any time constraint related with the processes utilized, € it will be assumed the exact effectiveness of the process or technology is known (f) there is no limit on the technologies or processes used by the decision maker and (g) the interactions, this means the percentage that overlaps between one technology/process and the other technology/process, are known.

The mathematical model of the Decision Making model has been adjusted to the specific problem, to the exact outcome of the Predictive Model previously discussed. The FOD type Decision Making Model follows the mathematical formula:

$$Total\ Effectiveness = \sum_1^n (Tj) - \sum_1^n Tj * Tj + \prod_j^n Tj \quad (1)$$

The main goal of the first mathematical formula will be to calculate the total effectiveness the usage of the specified technologies /processes used, this will be one of the main factors to consider on the decision making model. Effectiveness represents the percentage of prevention, detection and/or elimination of FOD the process will acquire if done properly. On the formula *n* represents the total number of technologies and processes utilized, *j* = the individual technology and process and $\prod$ represents the interactions for all possible Tj. The other two factors the decision making model will consider will be the cost and the time. The cost refers specifically to how much it will be the workforce of applying the specified combination of technologies and/or technologies. The mathematical formula for this calculation will be the following: Cost = (labor rate/hr.) * (hours using technology/process). For this research, it will be assumed the labor rate and the hours of use all the technologies or process will be known. Finally, the last factor to consider on the decision making model will be the time, this time is given by the company, this time was calculated through time studies and the time will be the addition of the different time that is needed to apply all the technologies and processes on the combination specified. The model could be adapted to give certain weights to give a specific result, however since the company did not give any specific weights yet, the decision making model will only show the results to let the people at the company have a better decision, but with more background information of the real consequences of applying that specific combination of technologies and/or processes. This methodology can become more mature if the company will give a specific weight and therefore know the exact importance of the three different factors considered on the model. All the technologies/processes used on this model

have two data sets, the first is on what workstations the specific technology/process could be used, and on which workstations the specified technology or process is restricted. The other data set would be the exact effectiveness the process or technology has on every specific type of FOD, with this two data set given as inputs, plus the results from the predictive model that was previously discussed, the model will be able to work properly and give the desired outputs. The model will calculate the effectiveness of the combination of the technology and process with the specific percentage of FOD type given by the predictive model, later it will add up the five different percentages to create a total effectiveness of the combination specified. Finally, for all the combinations it will also calculate the time and the cost to be compared and have a better decision of what combination will be the optimal to the workstation. An example of this will be provided later on this research to explain in a graphical manner the methodology as well as the output it will result of this mathematical formulations. This decision making tool is planned to be used by the company to eliminate FOD in a more practical and effective approach, on which the engineer will decide what combination would better fit on the desired workstation on a specific time frame, giving the company a complete framework that will focus all the desired categories by the company.

CHAPTER 5. VALIDATION/CASE STUDY

To test the performance of this research a mock problem was created. Six different technologies/processes were assigned randomly and the effectiveness between the technologies/processes were assigned with random numbers that represent the percentage of elimination of the specific technology/process with certain FOD type, this effectiveness are indicated by Table 19. Table 20 indicates the workstations constraint each technology/process has, which were also assigned randomly. Moreover, the time the workforce spends on each technology/process was assigned randomly and it is indicated on Table 21, the cost is directly related to the time, assuming a cost of $20/hr., it will be a multiplicative factor times the time spend on the technology/process, this value is expressed on Table 22. The interactions, or the overlaps that the technologies/processes have with each other is also known, and described on Table 23. Furthermore, Table 24 also gives the overlaps between more than two technologies and or processes. On Table 25, it is the real information of FOD expected on a specific workstation, Final Assembly for the entire year, for the purpose of this mock problem, it was used the information of this workstation on the month of January, and the information was used as an input for the problem. Given all the information needed, and using the methodology expressed on last chapter, an analysis was created and programmed using the MATLAB software. The solution from the methodology, as well as the information specified on tables is shown below. The results of all the combinations are stated on Table 26, and on Table 27 it is compared the current solution used by the aeronautic company and compared with the optimal solution the new methodology will give us.

Table 19. Effectiveness of elimination of FOD per FOD type

F. O. E. Technology / Countermeasure (on the product)	FOD TYPE				
	Manufacturing Debris	PLS	Consumables	Tools/Shop Aids	Trash
A	80%	0%	10%	50%	44%
B	20%	0%	43%	95%	0%
C	75%	90%	44%	50%	75%
D	60%	25%	15%	0%	25%
E	25%	62%	15%	25%	0%
F	18%	15%	40%	0%	65%

Table 20. Workstations Constraints

F. O.E. Technology / Countermeasure (on the product)	Workstations							
	Forward Fuse	Wing Build	Wing Mate	Wing Systems	EMAS (Mate)	Moving Line	Final Assembly	Flight Line
A	X	X	X	X	X	X	X	X
B	X	X	X				X	X
C	X	X		X	X	X	X	
D	X	X	X	X	X	X		X
E		X	X	X	X			
F			X	X	X	X	X	X

Table 21. Time to apply each technology

Tech/process	Hrs.
A	1
B	3.5
C	1.25
D	0.25
E	0.75
F	3

Table 22. Cost of applying technology.

Rate ($/hr.)	$20.00
Tech/process	**Cost**
A	$20.00
B	$70.00
C	$25.00
D	$5.00
E	$15.00
F	$60.00

Table 23. Interactions/overlap between two technologies

	Manufacturing Debris						PLS						Consumables					
	A	B	C	D	E	F	A	B	C	D	E	F	A	B	C	D	E	F
A	-	30.00%	60.00%	60.00%	25.00%	18.00%	-	0.00%	0.00%	0.00%	0.00%	0.00%	-	10.00%	10.00%	10.00%	10.00%	10.00%
B	30.00%	-	30.00%	40.00%	20.00%	18.00%	0.00%	-	0.00%	0.00%	0.00%	0.00%	10.00%	-	43.00%	15.00%	15.00%	40.00%
C	60.00%	30.00%	-	60.00%	25.00%	18.00%	0.00%	0.00%	-	25.00%	62.00%	10.00%	10.00%	43.00%	-	15.00%	15.00%	40.00%
D	60.00%	40.00%	60.00%	-	25.00%	18.00%	0.00%	0.00%	25.00%	-	25.00%	15.00%	10.00%	15.00%	15.00%	-	7.00%	15.00%
E	25.00%	20.00%	25.00%	25.00%	-	18.00%	0.00%	0.00%	62.00%	25.00%	-	15.00%	10.00%	15.00%	15.00%	7.00%	-	10.00%
F	18.00%	18.00%	18.00%	18.00%	18.00%	-	0.00%	0.00%	10.00%	15.00%	15.00%	-	10.00%	40.00%	40.00%	15.00%	10.00%	-

	Tools/Shop Aids						Trash					
	A	B	C	D	E	F	A	B	C	D	E	F
A	-	48.00%	30.00%	0.00%	18.00%	0.00%	-	0.00%	34.00%	14.00%	0.00%	28.00%
B	48.00%	-	49.00%	0.00%	23.00%	0.00%	0.00%	-	0.00%	0.00%	0.00%	0.00%
C	30.00%	49.00%	-	0.00%	14.00%	0.00%	34.00%	0.00%	-	8.00%	0.00%	60.00%
D	0.00%	0.00%	0.00%	-	0.00%	0.00%	14.00%	0.00%	8.00%	-	0.00%	20.00%
E	18.00%	23.00%	14.00%	0.00%	-	0.00%	0.00%	0.00%	0.00%	0.00%	-	0.00%
F	0.00%	0.00%	0.00%	0.00%	0.00%	-	28.00%	0.00%	60.00%	20.00%	0.00%	-

Table 24. Interactions/overlap between more than 2 technologies

	Manufacturing Debris	PLS	Consumables	Tools/Shop Aids	Trash
ABC	18%	1%	10%	20%	0%
ABF	10%	0%	5%	0%	0%
ACF	8%	0%	4%	0%	24%
BCF	12%	0%	2%	0%	0%
ABCF	11%	8%	20%	0%	28%

Table 25. Results of Predictive Model used on the problem

January Final Assembly	
Type of FOD	**FOD expected**
Manufacturing Debris	10.64%
PLS	71.26%
Consumables	0.27%

Tools/Shop Aids	0.00%
Trash	17.83%

Table 26. Combination of all possible results

Combinations	Hrs.	Cost	Effectiveness
A	1	$20.00	16.38%
AB	4.5	$90.00	15.41%
AC	2.25	$45.00	89.15%
AF	4	$80.00	33.75%
ABC	5.75	$115.00	87.52%
ABF	7.5	$150.00	31.83%
ACF	5.25	$105.00	91.81%
ABCF	8.75	$175.00	92.28%
B	3.5	$70.00	2.24%
BC	4.75	$95.00	84.26%
BF	6.5	$130.00	24.52%
BCF	7.75	$155.00	87.98%
C	1.25	$25.00	85.33%
CF	4.25	$63.75	89.78%
F	3	$45.00	24.30%

Table 27. Optimal Result

Current combination used	Hrs.	Cost	Effectiveness
A,B, C, F	**8.75**	**$175.00**	**92.28%**
Optimal Combination	**Hrs.**	**Cost**	**Effectiveness**
A,C,F	**5.25**	**$105.00**	**91.81%**

Concluding, it was found that in order to reduce cost, time and at the same time take into consideration the efficiency of the elimination of FOD the optimal combinations of the parameters would be to use the countermeasures A, C and F to eliminate FOD on Final Assembly on the month of January. In the other hand to reduce the time and cost only the following parameters were the optimal; only use the technology/process A, however this will give us an efficiency of only 16.38%. Moreover, in order to maximize only the effectiveness of the combination of technologies/processes it will have to be used all the possible technologies that are suitable for the specific workstation. Finally, to have a final optimal solution it is needed some weights into the factors that are being analyzed to have a real number of how much money or time it is worth it for a percentage of effectiveness. For this case study, the difference between the current solution and the optimal solution that it has been proposed is only .5% of effectiveness, but with a savings of $70 and 3.5 hours on the implementation of the technologies and processes.

CHAPTER 6: CONCLUSION AND FUTURE WORK

Most efforts of the aeronautical industries have focused on the prevention of FOD; ultimately, these efforts have not been able to solve the problem. Such efforts always work in a reactive manner; and although, they say they are preventing FOD, the truth is that they would clean whatever was created already; in other words it is a removal of FOD once it was created in the first place. On this research a decision making model with several complexities, including the aim to be a preventive tool, concerning the selection of what combinations to use for prevention/detection and /or elimination was solved using a quantitative modeling approach. The goal was to minimize the total operation cost and time, while at the same time maximizing the effectiveness of FOD elimination. The experimental study was evaluated using the MATLAB software. An informal sensitivity analysis was elaborated using a mock problem in order to test the performance of the decision making model. For future work it might be considered a certain weight to give a final optimal solution. Also, the consideration of less assumptions could be possible. Finally, it might be appropriate to test the model with a real life problem.

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GLOSSARY

FOD: Foreign Object Debris or Foreign Object Damage

FPA: FOD Prevention Area

MIL-STD-980: Military Standard 980

NAS-412: National Aerospace Standard 412

NAPFI: National Aerospace FOD Prevention Incorporated

QAR: Quality Assurance Report

SWBS: Scheduled Work Breakdown Station

MAE: Mean Absolute Error

VITA

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