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STRENGTHS AND WEAKNESSES OF ANTICIPATORY FAILURE DETERMINATION IN IDENTIFYING BLACK SWAN TYPE OF EVENTS

Master Thesis by

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Abstract

Some of the systemic/operational failures that happen in industries like oil and gas, production industry, financial institution are associated with unanticipated/surprise events. These events are known as Black Swan Events; the way in which they occur is so surprising that no one would have predicted the occurrence. When these events happen, the likelihood for extreme consequences cannot be ruled out.

"*Taleb described a Black Swan as a highly improbable event with three principle characteristics: its unpredictable; its massive; and, after it has happened, our desire to make it appear less random and more predictable than it was. The astonishing success of Google was a Black Swan; so was 9/11*"

- Prof Nassim Nicolas Taleb

The consequences of this black swan type of events remain a challenge for many industries because of the failure of traditional risk assessment methods in providing solution to meeting these types of event. Therefore, it has become necessary to improve our hazard/threat identification methods due to the fear of the unforeseen events that could threaten the safety and security of our system or operation.

A new tool for failure and risk analysis called Anticipatory Failure Determination (AFD) has been introduced. It is based on the theory of inventive problem solving and it has two broad applications namely Anticipatory Failure Analysis (AFD-1) and Anticipatory Failure Prediction (AFD-2). The main objective of AFD-1 is to find the causes of a failure that has already occurred while in AFD-2, the goal is to identify all possible failures that have not yet occurred.

This paper will present a new tool for failure and risk analysis called Anticipatory Failure Determination. It will focus on identifying the strengths and weaknesses of this new tool in identifying black swan type of event. General overview and discussion of this tool will be done as well as demonstrating its applicability using a practical example.

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List of Abbreviations

FMEA	Failure Modes and Effects Analysis
HAZOP	Hazards and Operations Analysis
FT	Fault Tree
ET	Event Tree
AFD	Anticipatory Failure Determination
QRA	Quantitative Risk Analysis
QRA	Quantitative Risk Assessment
PRA	Probability Risk Analysis
R	Risk
S_i	Scenario Identification
S_o	Success Scenario
SA	Scenarios Analysis
IE	Initiating Event
MSs	Mid-States
ESs	End-States
HESs	Harmful End-States
TSS	Theory of Scenario Structuring
TRIZ	Theory of Inventive Problem Solving
AFD-1	AFD Failure Analysis
AFD-2	AFD Failure Prediction
ARIZ	Algorithm for Inventing Problem Solving
Sis	Complete Risk Scenarios

1. Introduction

1.1 Background

Most events in the world face uncertainty in different form. United States Secretary of Defence Donald Rumsfeld said “As we know, there are known knowns; there are things we know that we know. There are known unknowns. That is to say, there are things that we now know we don’t know. But there are also unknown unknowns, there are things we do not know we don’t know”(Rumsfeld, 2002). Three categories of event mentioned above are the likelihood of any future event happening. All these categories of events are regarded as the Black Swan.

Black Swan can be interpreted “as surprises in relation to someone’s knowledge and beliefs” (Aven, 2013). Nassim Nicholas Telab also defines black swan using three characteristics: “First it is an outlier, as it lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Second, it carries an extreme impact. Third, in spite of its outlier status, human nature makes us concoct explanations for its occurrence after the fact, making it explainable and predictable (Taleb, 2007).

The consequences of this black swan type of events pose serious questions and challenges for the oil and gas industry due to the fact that the traditional risk analysis method which include and not limited to Failure Modes and Effects Analysis (FMEA), Hazards and Operations Analysis (HAZOP), Fault Trees (FT) and Event Trees (ET) are intended to reveal and identify potential failure modes in our systems and operations so that they may be corrected before they occur (Kaplan et al., 1999). However, these methods of risk assessment do not provide answer for identifying black swan type of events. In this regards, there is urgent need to improve the hazard/threat identification methods in order to solve the problems of the unforeseen.

A new tool for failure and risk analysis called Anticipatory Failure Determination (AFD) has been introduced to the above mentioned traditional methods. It is based on the theory of inventive problem solving which has two broad applications namely AFD-1 and AFD-2. AFD-1 applies to finding the causes of a failure that has already occurred and it is called failure analysis while AFD-2 which is called failure prediction is used to identify possible failures that have not yet occurred (Kaplan et al., 1999).

1.2 Aim of Thesis

The aim of this thesis is to identify the strengths and weaknesses of Anticipatory Failure Determination in identifying black swan type of events. The thesis will present the new tool within the context of the Theory of Scenario Structuring and also demonstrate its applicability using a practical example.

1.3 Content

The first part of this thesis is chapter 1 and it contains the introduction, aim of the thesis and the outline of the contents.

The second part of this thesis, chapter two and three contain some background knowledge. Chapter two contains black swan type of events where we introduce the concept of black swan and categories of black swan. Chapter three contains risk analysis and the theory of scenario structuring. It introduces typical categories of risk analysis methods, scenario analysis as well as the theory of scenario structuring and its eight associated principles.

The second part of this thesis, chapter four contains review of the new analytical method for risk analysis called Anticipatory Failure Determination (AFD). It introduces the concept of this method, the two types of AFD: Anticipatory Failure Analysis (AFD-1) and Anticipatory Failure Prediction (AFD-2). In this chapter, we are going to demonstrate the application of AFD-2 using a practical example of a Plastic Recycling Process in a bid to identify its strengths and weaknesses in identifying black swan type of events.

The last part, chapter 5 contains the recommendation and conclusion part.

2. Black Swan Type of Events

2.1 The Concept of a Black Swan

The term black swan in the risk context has been popularly used to illustrate the idea of surprising events and outcomes (Aven and Krohn 2014). Nassim Telab refers to a black swan as an event with the following three attributes: "firstly, it is an outlier, as it lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Secondly, it carries an extreme impact. Thirdly, in spite of its outlier status, human nature makes us concoct explanations for its occurrence after the fact, making it explainable and predictable" (Taleb, 2007).

Aven's also refers black swan "as a surprising extreme event relative to one's knowledge" (Aven 2013b). This does not necessary mean that all black swan events are attributed to extreme consequences. There are situations in which black swan events do not result in extreme consequences and these situations are known as "near-black swans", meaning surprises relative to ones's knowledge/beliefs (Aven 2013b). In Aven's definition, knowledge means justified beliefs which are typically based on data and information. For example, a risk analyst may assign a probability such that P (A) = 0.8 where A is an event of a system failure. This implies that the risk analyst may compare the uncertainty of event A to occur with drawing a red ball out of an urn containing 10 balls of which 8 are red given his strong knowledge but it doesn't mean that he/she can categorically say the system will not fail. Also Analysts may use data and information, modelling and analysis available to them as basis for their judgement when performing risk assessment. However, this may be wrong as things may occur the other way round.

All these probabilities assigned by someone are to demonstrate or express the strength of our belief about the occurrence of events. In this regards, knowledge is subjective and cannot be objective. A risk analyst (A) belief about the occurrence of an event may be different from another risk analyst (B) belief. For example, risk analyst (A) may have true belief that an event will occur using a contested data and information. According to risk analyst (B) subjective probabilities, risk analyst (A) is unreliable, whereas risk analyst (A) sees it as being reliable.

As a result of this fact, the question of how reliable the knowledge is will always be an issue for debate.

2.2 Categories of Black Swan

The black swan type of events according to (Aven and Krohn 2014) and (Aven 2014a), can be broken down into three main categories shown in Figure 1:

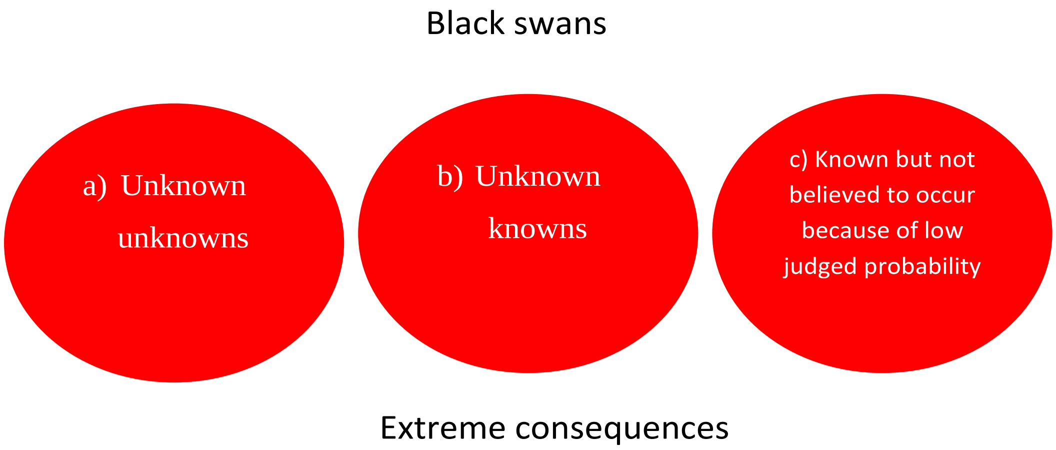

Figure 1: Three different types of black swans in a risk context (Aven and Krohn 2014)

a) **Unknown unknowns**: These are events that were completely unknown to the scientific environment. These events are unthinkable, unpredictable and, carry extreme consequences. An example of this type of event is a new type of virus.

b) **Unknown knowns:** These are events that were not on the list of known events from the perspective of those who carried out a risk analysis (or another stakeholder). This implies that these events were not captured when risk assessment is carried out. The reason for this may be that there was no awareness of such events, or there was limited consideration. An example of this type of event is the September 11 attack on the pentagon.

c) **Known knowns:** These are events that are on the list of known events in the risk assessment but were judged to have negligible probability of occurrence, and therefore not believed to occur. Despite the negligible probability of occurrence, the events still occur with extreme consequences, and this was because of the fact that cautionary measures that should be implemented were not put in place. An example of this type of event is “the tsunami that destroyed the Fukushima Daiichi nuclear plant

> was similarly removed from the relevant risk lists due to the judgement of negligible probability" (Aven and Krohn 2014).

3. Risk Analysis and the Theory of Scenario Structuring

3.1 Risk Analysis

In life, it is absolutely impossible to avoid risk because it is part of our everyday activities. Simple activity such as stepping out of bed could make you slip and fall not to mention more difficult activities in the oil and gas industry. Workers in this industry are subjected to some of the most hazardous industrial conditions. In this regard, company perform risk analysis in order to support decision-making in the face of uncertainties.

"The main objective of risk analysis is to establish a risk picture, compare alternative in terms of risk, identify critical factors with respect to risk and also demonstrates the effect of various measures on risk" (Aven, 2008). It can be performed in most areas, if not all, where risk is perceived. According to (Aven, 2008), the three main categories of risk analysis methods which are well described in **Error! Reference source not found.** are: simplified risk analysis, standard risk analysis and model-based risk analysis.

Main category	Type of Analysis	Description
Simplified risk analysis	Qualitative	Simplified risk analysis is an informal procedure using brainstorming sessions and group discussions. The risk might be presented on a coarse scale e.g. low, moderate or large, making no use of formalised risk analysis method
Standard risk analysis	Qualitative or quantitative	Standard risk analysis is a more formalised procedure in which recognised risk analysis methods are used, such as HAZOP and coarse risk analysis, to name a few. Risk matrices are often used to present the results
Model-based risk analysis	Primarily quantitative	Model-based risk analysis makes use of techniques such as event tree analysis and fault tree analysis to calculate risk

Table 1: Main categories of risk analysis methods (Aven, 2008)

Most of the risk analysis methods fall into the main category of qualitative risk analysis or quantitative risk analysis. The main interest of this thesis is the qualitative method used in the identification of failure scenario in which the AFD makes its contribution. However, there is need to present some vital aspects of quantitative method for the sake of quantifying the likelihood and consequences of identified scenarios.

3.2 Quantitative Definition of Risk

"In analyzing risk we are attempting to envision how the future will turn out if we undertake a certain course of action (or inaction)" (Kaplan and Garrick, 1981). For the purpose of objective decision making in this regard, it is not enough to only describe risk by identifying possible failure scenarios without quantification of the likelihoods and consequences of these scenarios (Kaplan et al., 1999). Quantitative risk analysis (QRA) also known as quantitative risk assessment (QRA) or Probability risk analysis (PRA) has been introduced with new definition of risk. "A QRA systemizes the present state of knowledge, including a characterization of the uncertainties about the phenomena, processes, activities, and stems being analyzed" (Aven and Renn, 2009).

It uses a set of triplets derived from the following three questions listed below to identify possible hazards/threats, analyzes their causes and consequences for the description of risk.

- What can go wrong?
- How likely is that to happen?
- And what are the consequences if it does happen?

The questions are well described in Table 2

Phase	Question	Output
Identify	1. What can go wrong?	Failure Description Causes → Failure → Modes → Effects
Analyze	2. How likely is that to happen? 3. What are the consequences?	Risk Priority Number (RPN = Occurrence x Severity x Detection)
Act	• What can be done • How can we eliminate the cause • How can we reduce the severity	• Solution for design • Test plans • Manufacturing changes • Error proofing, etc

Table 2: Three Phases of QRA

Answers to these questions require making a list of outcomes or "scenarios" which is presented in Table 3. If all scenarios we can think of are contained in the table below, then we can refer the table as of answer to the three questions; which is simply the risk (R).

Scenario	Likelihood	Consequences
S_1	L_1	X_1
S_2	L_2	X_2
.	.	.
.	.	.
.	.	.
S_i	L_i	X_i

Table 3: List of scenarios

“The first question is answered by a set of scenarios called the “risk scenarios”. The “end states” of the scenarios are the consequences in terms of fatalities, injuries etc., and the “likelihood” refers to the likelihood of the scenarios. We can then present the answers to these questions more formally in the following set f triplets: (Hassanzadeh and Raddum, n. d.)

$$\text{Risk} = [<S_i, L_i, X_i>]c,\ i = 1,2,\dots,\ \text{N}$$

where:

- S_i refers to scenario identification or description,
- L_i refers to likehood of that scenario S_i,
- X_i refers to consequence or evaluation measure of that scenario S_i,
- i refers to the index of the scenario, and
- c means that the set is complete.

The idea of success was introduced and denoted as S_o; then the risk scenarios S_i could be seen as deviation from S_o (Haimes, 2005).

There are five steps of the QRA methodology and these five steps are listed as follow:

1. Using theory of scenario structuring to define the risk scenarios,
2. The consequences of each scenarios are defined,
3. The use of Bayes’ theorem to calculate the likelihood of each identified scenario
4. The likelihood and consequences are aggregated into a probability of exceedance curve, and
5. Using the result to measure risk for decision making.

3.2.1 Quantifying the Likelihood and Consequences

Quantification involves measurement of quantity or amount; literally it means measurement. Lord Kelvin stated that “I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of science, whatever the matter may be” (Lord Kelvin, 1883).

What this meant in general term is a figure or a number that shows the amount of something, therefore quantification in quantitative risk assessment implies a process or measurement that indicates the amount of risk associated with a particular thing in question. The level of risk such as likelihood of different consequences can be visualised using real numbers obtained from quantification.

Quantification of L_i, and X_i are necessary in order to make proper decision. As we know that risk is related to the following concept of: Safety, Danger, Hazard, Loss, Injury, Death, Toxicity, and Peril. All the concept of risk can be captured quantitatively by the parameter frequency. Our interest is to know how often a particular scenarios occurs; since the exact answer is not within our reach, probability of frequency curve can be used to express our state of knowledge about the scenario. (Hassanzadeh and Raddum, n. d.)

3.2.2 Level of Quantification

The levels at which consequences and likelihoods are quantified is one of the most fundamental attributes of any risk measurement. The least quantitative are the easiest measure to calculate but limited amount of information are captured while the most difficult measure to calculate is the most quantitative measures which captures more information. Kaplan listed the various levels of quantification used in risk analysis as follows (Kaplan et al., 1999):

- Verbal Approach
- Ordinal Approach
- Point Estimate Approach
- Bounding Estimate Approach
- Evidence – Based Approach

From the above list, verbal approach and ordinal approach are the easiest measures to calculate, they are both qualitative. The words (i.e. high, medium, and low) are used to describe both consequence and likelihood in verbal approach. In an ordinal approach which can also be called semi-quantitative, numbers are used instead of words; for example, the consequence and likelihood of damage are assigned a number value on a scale of one to tem instead of assigning a verbal description.

The first two that are discussed above are basically qualitative levels of measurement; point estimates and bounding estimates are the next two levels of quantification which are really quantitative. In point estimates, best guess numerical value are given for the actual damage or frequency. This actually represents the underlying magnitude of the system. The pair of point estimates is the bounding estimates.

Among all these levels of quantification, probabilistic approach and evidence-based approach are the last two levels of quantification that represent the highest levels of accuracy. Probability distributions are used to estimate consequence and likelihood of a given scenario instead of using exact value. In evidence-based approach, probability distributions are obtained by compiling a list of all prior evidences which are relevant into the posterior distribution of consequence and likelihood of damage using the Bayes' theorem (Kaplan et al., 1999). This approach is the most disciplined and highest form of quantification because it captures more information.

3.3 Scenario Analysis

An important tool in decision making is scenario analysis (SA). This analysis has been in existence for several decades and has been adopted in various disciplines such as engineering, defence, management, finance and economics etc. SAs are constructed for the purpose of shielding light in the understanding of possible future occurrences of complex systems. It is a tool that, when used at various levels of detail and thoroughness, has the capability of bringing to light many vital aspects of scenarios that would normally be missed (Dutta and Babbel, 2010).

Before the identification of scenarios through SA can be done, the success scenario (S_o) must first be defined. Once it has been defined, the process of identifying risk scenarios involves breaking down the (S_o) into parts or components. These decomposed parts or components need to be critically analysed by asking, “What could go wrong in this part?” By so doing, (S_i) is generated.

The process of identifying and structuring possible failure scenarios in AFD is quite different from the traditional approaches. To be able to understand the AFD’s different viewpoint from the traditional methods, we shall begin by presenting the principles and language of this theory.

3.4 The Principles of Scenario Structuring

This is the first step in Kaplan’s methodology in the identification of all possible risk scenarios. Kaplan stressed that the process of generating failure scenarios is more art than science which often relies on the analyst’s background knowledge. Since it is not possible to present a specific methodology of identifying risk scenarios, Kaplan propose a general theory that could lead to the generation of all possible failure scenarios. The theory is called the theory of scenario structuring (TSS) and it is made up of eight principles which are discussed below:

3.4.1 The Principle of Success (S_o)

This principle states that clear knowledge of the system or activity is required before risk assessment of that system or activity can be performed. It implies that the success (or as-planned) scenario, which is denoted by *So* should initially be defined for proper understanding of failure scenario. Example of *So* described in a diagrammatic form is shown in Figure 2:

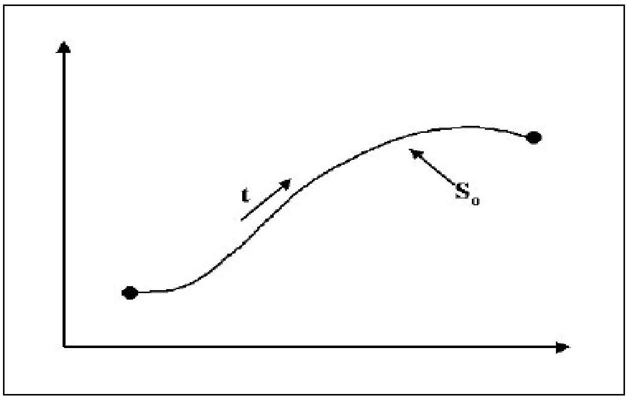

Figure 2: “Scenario as a Trajectory in the State Space of the System” (Kaplan et al., 1999).

3.4.2 The Principle of Initiation

This principle states that for any failure scenarios which is denoted by *Si* to deviate from the initially defined success (as-planned) scenario, there must be a point of deviation. A specific point at which an Initiating Event (IE) occurs which brings about the deviation (Kaplan et al., 1999). Failure within the system itself known as internal failure could cause the IE or failure outside the system known as external failure such as natural disaster could also make the system fail. Example of risk scenario *Si* as a departure from *So* described in a diagrammatic form is shown in Figure 3:

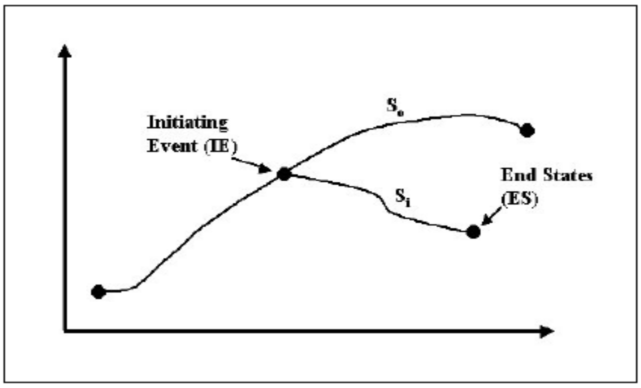

Figure 3: "The Risk Scenario *Si* as a Departure from *So". (Kaplan et al., 1999)

3.4.3 The Principle of Emanation

This principle states that an entire tree of scenarios can originate from each of these IE. The points of deviation within these trees of scenarios are called branch points. The place where all the paths of the scenarios trees terminate are called end states.

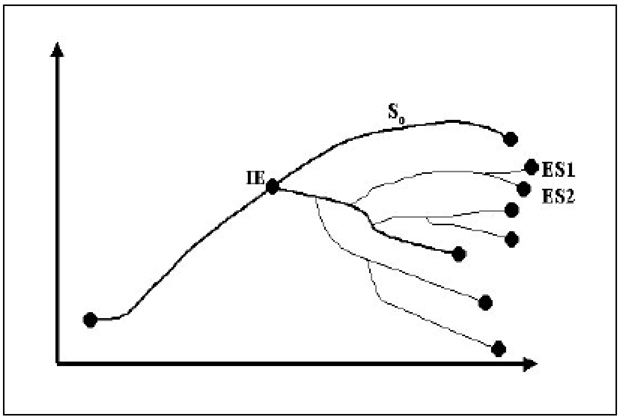

Figure 4: "Scenario Tree Emerging from the Initiating Event" (Kaplan et al., 1999).

3.4.4 The Principle of Unending Cause-Effect

“This principle states that every cause/effect chain extends indefinitely in both directions” (Kaplan et al., 1999). It implies that what is identified as an end state for a particular scenario could also be an initiating state for another therefore it is necessary to impose a finite scope on this chain in order to make the problem traceable.

3.4.5 The Principle of Subdivision

This principle states that “every scenario that we can describe with a finite set of words is itself a set of scenarios i.e., “it can be broken down into sub-scenarios” (Kaplan et al., 1999). Different sets of scenarios can describe the same situation with the use of this principle.

3.4.6 The Principle of Pinch Point

This principle states that a scenario tree may contain pinch points at which the downstream tree is independent of the upstream tree from a pinch point. Kaplan gave an example that “once a shipment of contaminated meat leaves the packing plant, the downstream consequences will be the same, regardless of which cow was diseased” (Kaplan et al., 1999). This implies that the amount and type of contamination is the same.

3.4.7 The Principle of Fault and Event Tree

This principle only signifies that the determination of the risk scenarios can be done with the use of fault tree and event tree. When end states are known, fault trees can be applied while event trees are applicable only when initiating events are known. In addition, both fault trees and event trees can be used when mid-states are known.

3.4.8 The Principle of Resources

The final principle is the principle of resources. Kaplan denotes the term resources to all substances, fields, configurations, time or space intervals, or other factors present in a situation (Kaplan et al., 1999). Given the denotation of the term resources, the principle then states that “if all the resources necessary for an initiating event are present in a situation, then that event will occur; and conversely, if at least one of the necessary resources is not present, then that event will not occur” (Kaplan et al., 1999).

4. Review of New Analytical Method for Risk Analysis

4.1 Anticipatory Failure Determination

Anticipatory Failure Determination (AFD) which was developed by Boris Zlotin and other colleagues in Kishnev TRIZ School in Russia is a systematic analysis method for identifying either potential future failures or root causes for already failed system. (Engel, 2010). It is a relatively new tool that has just been added to the list of RA methods. "The new method, AFD, is the application to RA of I-TRIZ, and advanced form of the Russian-developed Theory of Inventive Problem Solving known as TRIZ" (Kaplan et al., 1999).

As we have already known that traditional risk analysis and prevention methods such as Failure Mode Effect Analysis (FMEA), Hazards and Operations Analysis (HAZOP), Fault Tree Analysis (FTA), Event Tree Analysis (ETA) lack the systematic procedure for predicting the dangerous or harmful events that might be associated with a system (Engel, 2010). AFD methodology is different from these traditional risk assessment methods because it focuses on the aspect of generating failure scenarios by transforming the failure problems into inventive problems through the process of reverse thinking. That means the main objective of AFD is to "identify, and bring to awareness, potential scenarios that could lead to the failure of our systems and operations, so that they may be fixed before they actually occur" (Kaplan et al., 1999).

AFD methodology brings in different idea of how to identify failure scenarios. One of these patterns that is actually off interest to us is the concept of finding possible failure initiating events and drawing the resulting failure trees from each initiating events (Engel, 2010). "This process works because identification of initiating events or failure scenarios trees can be carried out at various levels of detail and thoroughness and every failure scenario can be broken down into sub-scenarios" (Engel, 2010).

4.2 The Concept of Inversion in AFD

Ordinary risk analysis "begins with decomposition of success scenario (S_o) into a complete, finite, and distinct set of parts, components, segments and/or phases" (Kaplan et al., 2001) and focuses on the question "What can go wrong" with this decomposed parts in the process of identifying failure scenarios. What is unique about AFD is how it reverses the question around and asks "If I wanted to, how could I make something go wrong with this decomposed parts?" (Kaplan et al., 1999).

The advantage of this process that Kaplan called an "inventive problem" is that it defeats the problem of psychological phenomenon called *denial* that we humans are subjected to. Kaplan explained this denial phenomenon as the tendency of humans to "resist thinking about unpleasant things" (Kaplan et al., 1999). In a more simplified term, when we have the mindset that things will not fail or things will turn out all right, our altitude to critically investigate bad news or the possibility of our system going wrong will surely be negative and we begin to show a defensive altitude and deny or minimize the possibility of adverse consequences. This is due to the presence of denial phenomenon; however, if the inverted question is asked "How can I make something go wrong" we simply channel our attention on the offensive, proactive side of the decision making. Given this altitude and approach, it is very likely to uncover many set of risk scenarios or even a complete set of risk scenarios. It also makes us to take and exaggerate the ineffective or harmful aspect of the system to the most catastrophic form of failure (inverted problem) which will then becomes the desired performance. Kaplan splits AFD into two broad applications:

1. **AFD Failure Analysis (AFD-1):** The purpose of AFD-1 is to capture the causes of a failure that has already occurred and this application is also called failure analysis.

2. **AFD Failure Prediction (AFD-2):** In AFD-2, identification of possible failures that have not yet occurred is its main goal and it is called failure prediction. The prediction of failures that have not happened before is exactly what makes this application of AFD a step ahead of the traditional failure and risk analysis methods.

Kaplan also states that AFD applies the following benefits to both of these important applications:

- What AFD-2 adds to risk analysis is an aggressive pro-active approach of predicting failures in advance before their occurrence i.e. "to predict the failure you should invent it" This completely changes our altitude toward failure due to the fact that people's altitude towards risk analysis has always been focused on learning about and explaining the failures that have happened before in order to prevent their future occurrence (Kaplan et al., 1999).

- AFD-2 reverses the usually asked question of QRA “What can go wrong?” with my system, plan, or operation, with the question of “If I wanted to make something go wrong, how could I do it in the most effective way?” (Kaplan et al., 1999)
- AFD-1 also reverses the question of “How did this failure happen?”asked when performing traditional failure analysis with “if I wanted to create this particular failure, how could I do it?” (Kaplan et al., 1999)
- “The concept of resources: For any failure or drawback to occur, all the necessary components must be present within the system or its nearby environment” (Kaplan et al., 1999).
- Using I-TRIZ tools, revealed failure or drawback can be prevented, eliminated or at least reduced to a minimum level (Kaplan et al., 1999).

“In the language of the theory of scenario structuring, AFD-1 starts with a given end state or mid-state and seeks to determine the actual scenario that led to that end or mid-state. AFD-2 seeks to envision all of the possible end states, mid-states and IEs, and all the possible scenarios leading to and from these states.” (Kaplan et al., 1999). The idea of AFD-2 is to “Find those failures in our system that escapes our scrutiny which often causes extreme impact before the failures find us”. Achieving this requires thorough risk assessment that seeks to uncover all the complete set of scenarios (S_i) we mentioned earlier. This is exactly what AFD-2 is intended for; therefore we can say “AFD-2 is the process for finding the complete set of scenarios (S_i)” (Kaplan et al., 1999).

4.3 AFD Process

According to AFD fact sheet, there are three core steps involved in the process of performing an AFD prediction and risk analysis. The three major steps are:

1. Formulation and Inversion of the Problem

The formulation or inversion of the problem is the main strength of AFD compared to the traditional methods of failure analysis. Instead of the traditional approaches and questions of “Why did the failure happen?.” Analysts should ask the question of “How can I make failure happen?” or “How can I make all possible dangerous or harmful failures happen?”

2. **Identification of Failure Hypotheses**

This process involves searching for a mechanisms or methods to intentionally produce the known or potential failures by using problem solving tools such as I-TRIZ and ARIZ tools.

3. **Testing the System by Utilization of Resources**

This involves verifying if all the resources necessary to realize each hypothesis are available from the seven potential categories of resources which are stated as follows: substances, field effects, space available, time, object structure, system functions, and other data on the system (Inc., 1999).

4.3.1 AFD Procedure for Failure Analysis

Kaplan further divides the three core steps mentioned above into seven steps template for the application of the AFD failure analysis and these steps are stated as follows:

1. Formulation of the Original Problem
2. Identification of Success Scenarios (So)
3. Failure Localization
4. Inversion and Amplification of the Original Problem
5. Search for Solution
    5.1. Search for Apparent or Obvious Solutions
    5.2. Identify Resources
    5.3. Utilization of Resources and Searching for Needed Effects
    5.4. Search for New Solution (Algorithm for Inventing Problem Solving for AFD)
6. Formulation of Hypotheses and Tests for their Verification
7. Prevention of Failures

The reader can refer to Appendix 1 for the template of AFD-1 which is structured in such a way that allows easy application by the user.

As we have mentioned above that AFD has two broad applications. The first has to do with finding the cause of failures that have already occurred (AFD-1) while the other has to do with identification of possible failure scenarios that have not yet occurred (AFD-2). What is off interest to us in this thesis is the AFD-2 since the purpose of this thesis is to identify the strengths and weaknesses of AFD in identifying black swan type of events. AFD-2 will be the appropriate tool to analyze for this purpose; therefore, we are going to limit this thesis to failure prediction only.

4.3.2 Anticipatory Failure Prediction

The Anticipatory Failure Prediction (AFD-2) methodology seeks to find all or at least all of the important scenarios that could lead to failure mode. This also includes all the complete set of failure scenarios that had happened before as well as complete set of predicted failure scenarios that have never been experienced before.

Before presenting various steps of the template, we should introduce the TSS with an example. The example that we are going to present is the use of ladder for maintenance activities and this will serve as an introductory to the procedure of prediction analysis that would be presented in the section. The Planned "Use of Ladder for Maintenance Activities" Operational Scenarios (S_o) is shown in Figure 5:

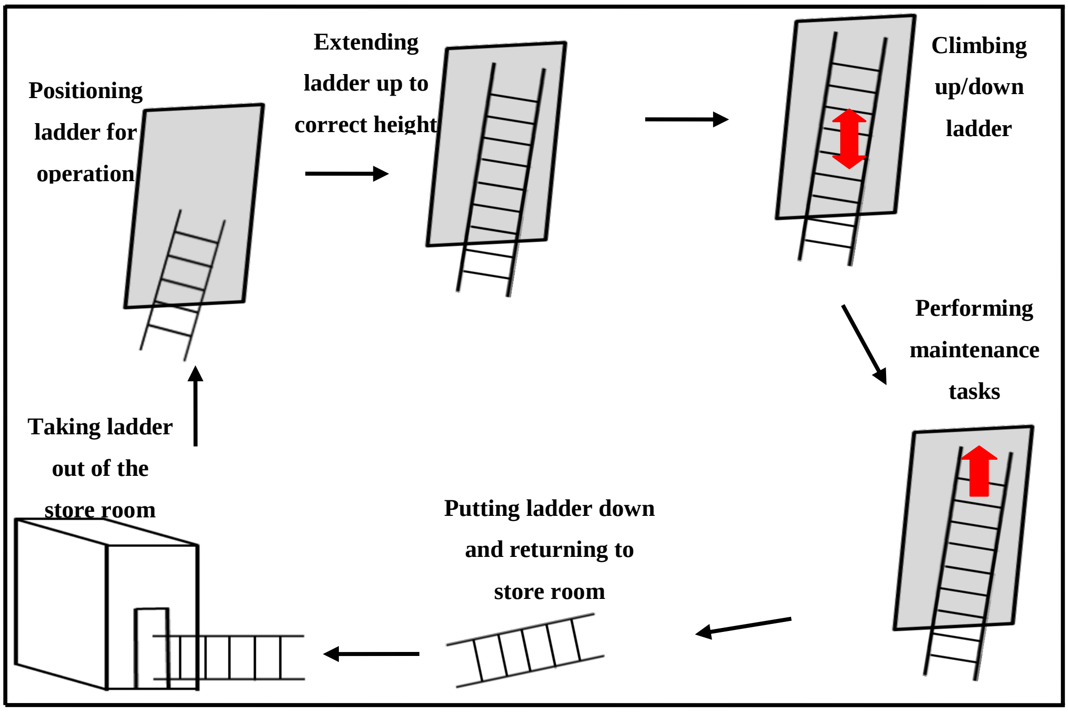

Figure 5: Planned "Use of Ladder for Maintenance Activities" Operational Scenarios (S_o)

The picture above is the pictorial description of the planned "use of ladder for maintenance activities" operational scenarios. Success (as-planned) scenario (S_o) is considered as a trajectory in the state space of the system in risk analysis and this is illustrated in

Figure 6 below:

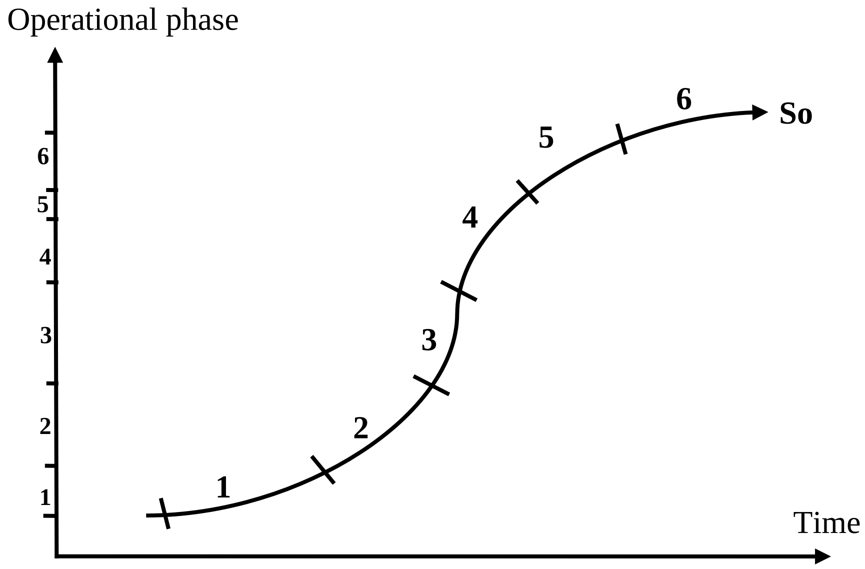

Figure 6: Success Scenario of the Use of Ladder as a Trajectory in the State Space of the System.

Any failure scenarios that deviate from this initially defined success (as-planned) scenario must have a point of deviation from the normal system operation. The point of deviation is a specific point at which an initiating event occurs which could be as a result of internal system failure or an external disturbance that was not anticipated. Some examples of such initiating events are described in

Figure 7 bel

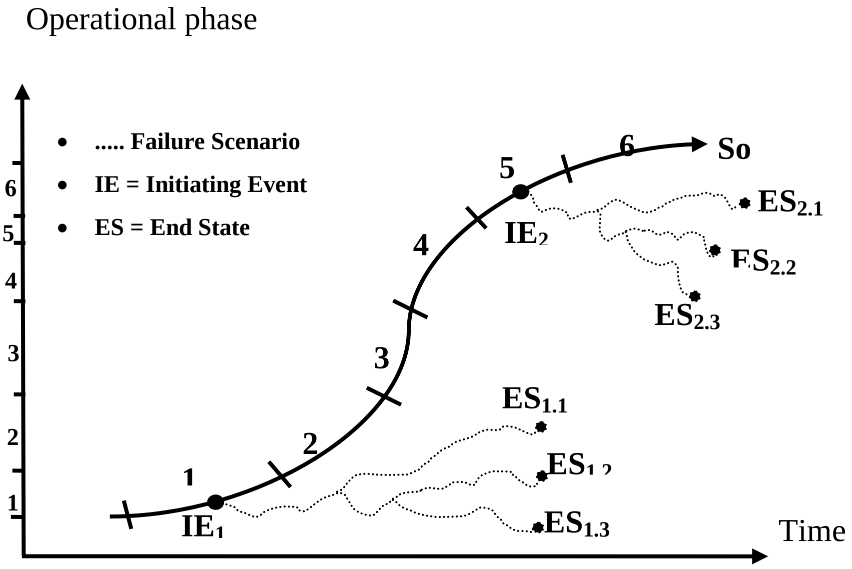

Figure 7: Scenario Tree of Use of Ladder Emerging From the Initiating Event (Engel, 2010).

A related failure scenario originated from each initiating event which is known as a failure scenario tree. The points of deviation within these trees of scenarios are called branch points. The place where all the paths of the scenarios trees terminate are called end states. For example, two failure scenario trees are described in Figure 7. The first failure tree occurred during the operational phase of "getting ladder out of storage room" which originated from event IE_1 "sudden drop of the ladder" and ends at one of three system end states ($ES_{1.1}$, $ES_{1.2}$, $ES_{1.3}$). The second failure tree occurred during the operational phase of "performing maintenance tasks" which originated from event IE_2 "unsafe arrangement of ladder" and ends at one of three system end states ($ES_{2.1}$, $ES_{2.2}$, $ES_{2.3}$).

The end states of the initiating event of "sudden drop of the ladder" are stated as follows:

- $ES_{1.1}$: Property damage
- $ES_{1.2}$: Serious physical injury to self
- $ES_{1.3}$: Injury to others

The end states of the second initiating event of "unsafe arrangement of ladder" are stated as follows:

- $ES_{2.1}$: Falls from height
- $ES_{2.2}$: Falling objects
- $ES_{2.3}$: Property damage

Based on the above philosophy, we are going to illustrate various steps of AFD-2 template with an example of Plastic Recycling Process. What we intend to do is the identification of all the possible initiating events and also all possible scenarios (S_i, $i \neq 0$) that could lead to all failed end states in this process. If done successful, it would help reduce the risk of breakdowns, losses that were not anticipated, surprises, and other significant failures.

4.3.2.1 Application of AFD Technique for Failure Prediction

Plastic Recycling Process

An improvement of a plastic recycling process was performed by some AFD experts. The experts intend to identify all hidden design flaws in the system. The account of the search for potential problems in the plastic recycling process is given as follows:

Figure 8: Plastic Recycling

Source: http://www.balkans.com/open-news.php?uniquenumber=176747

Please note that the main objective of this section is to demonstrate the procedures of failure prediction in AFD but not to accurately predict failure scenarios for this operation. Therefore, I will not recommend this analysis to be used for practical purpose.

Step 1: Formulation of the Original Problem

The original problem should be formulated by clearly naming the system, stating its purpose, as well as describing the potential failures, harmful events, or undesirable phenomena that can occur during the operation.

Exemplary Illustration of Step 1 Using the Plastic Recycling Process

We can formulate the original problem as follows:

a) There exists an operation "Plastic Recycling Process" which its process involves sorting of the plastic, washing of the waste plastic, shredding of the plastic, identification and classification of the plastic, and extruding of the plastic.
b) We wish to identify all possible failures, harmful events, or undesirable phenomena that can occur during the operation.

Step 2: Identify the Success Scenario

Before performing a risk assessment of this operation, the "success" (or as-planned) scenarios of this operation should be properly understood and clearly specified in order to understand the failure scenarios; i.e., the phases of operation and the intended results to be accomplished in each phase" (Kaplan et al., 1999).

Exemplary Illustration of Step 2 Using the Plastic Recycling Process

We will define five phases of a successful “Plastic Recycling Process” operational scenario. The list of success scenarios and their respective intended results for this operation is given in Table 4:

Phases of Operation	Intended Result
Sorting the plastic	Plastic sorted into specific types
Washing Waste Plastic	Plastic free from unwanted particles
Shredding the Plastic	Plastic ripped into small pellets
Identify and Classify the Plastic	Plastics are chemically tested and classified
Extruding	Plastics extruded into form of pellets for the manufacturing of new plastic products

Table 4: Success Scenarios of the Plastic Recycling Process

Step 3: Formulate the Inverted Problem

This step involves the creation or production of all the possible failures that can occur within the system into an inverted problem. By inversion, we mean all failures that we could think of should be restated in the form of creating the observed failures.

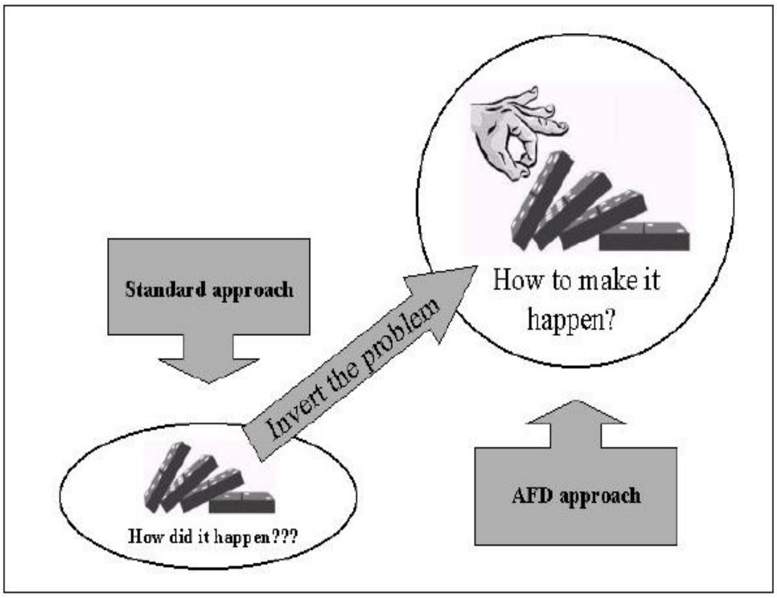

Figure 9: Inverting the problem

The main purpose of inverting these problems is to counter the problem of psychological phenomenon called denial that we human are subjected to. This automatically changed the way an individual thinks about the phenomena. This inversion is formulated as follows:

"It is necessary to produce the specific phenomenon (the observed failure) under the conditions that initiated and/or accompanied the observed failure". (Kaplan et al., 1999).

Exemplary Illustration of Step 3 Using the Plastic Recycling Process

We desire to identify all possible ways in which we could produce all the possible undesirable phenomena that can occur during the plastic recycling process.

Step 4: Apparent or Obvious Ways of Deteriorating the Functioning of the System

This part of the template involves writing down all the obvious possible ways to make the system fail. This process can be done by decomposing the success scenarios into parts or components. We can then look each part thoroughly and ask "What could go wrong in this part?" In this way, we can identify any apparent or obvious ways of making the system fail through all possible IEs, HESs and MSs which can then be combined into complete risk scenarios (Sis.)

Exemplary Illustration of Step 4 Using the Plastic Recycling Process

Obvious Possible Initiating Events: In this example, I assume the knowledge of the manufacturing process of bicycle fender presented by Kaplan. Now, our intention is to make the system fail by asking the inverted question "How can we create deterioration of the system?" With respect to the above stated phases of the success scenarios, we define the following Initiating Events:

IE1: Improper sorting process.

IE2: Bad washing of waste plastic.

IE3: Improper shredding of the plastic.

IE4: Poor identification and classification of the plastic.

IE5: Poor extruding.

Obvious Harmful End States: we then imagine what the harmful end state (HESs) would be and this is stated as follows:

HES1: Increased cost of recycling

HES2: Damage to worker health and environment

HES3: Sales reduction

HES4: Damage to plant and equipment

HES5: Low quality product

HES6: Unhappy customers

Obvious Mid-States Scenarios: We also need to include any emerging scenarios that are important. The following are mid-state scenarios that immerged so far:

MSS1: Increased waste

MSS2: Ingestion of harmful bacteria

MSS3: Ruin recyclables

Obvious Possible Risk Scenarios: Finally, we should identify what the risk scenarios would be and put it together as follows:

S1. **IE1** → MSS1 → **HES1**→ **HES4** → **HES3**

S2. **IE2** → MSS2 → **HES2**

S3. **IE3** → MSS3 → **HES6** → **HES3**

S4. **IE4** → HES4

S5. **IE5** → MSS1 → **HES1** → **HES5** → **HES3** → **HES6**

The above scenarios are the obvious ones showing initiating events, mid-states and end states. The complete set of predicted failure scenarios are not limited to the obvious ones defined above as there may be other factors that could bring about more failure which we are still going to still figure out. Let us not forget that the IEs and HESs represent large categories of events which should be broken down into subcategories in order to identify more specific scenarios. This process can be very complicated because it leads to a profusion of initiating events (IEs), harmful end states (HESs), and mid-states (MSs) and complete risk scenarios (Sis) (Kaplan et al., 1999). The checklists in AFD software can be helpful in carrying out this task; however, since this AFD software is not within our reach, we will have to depend strictly on our creative thinking in this thesis by looking through all available resources so as to identify potential failure scenarios that we can create.

Step 5: Identification and Utilization of Available Resources

This step involves becoming aware of the "Resources" available in the system and its surroundings that are necessary for creating harmful effects. This follows from the recognition that "Any of the identified methods for producing the desired phenomenon will require certain resources" (Kaplan et al., 1999). This same concept was used in AFD-1 in terms of the original problem that "For any failure or drawback to occur spontaneously, all the necessary components must be present within the system or its environment" (Kaplan et al., 1999).

Therefore in order to search for the necessary resources, one should identify resources that are required for the actualization of the operation and also find the necessary resources within the system or its environment that might be instrumental in contributing to failure. Kaplan further described an example of applying acid to an object. Implementation of this requires that you have an acid available as a resource within the system or its surroundings as well as the means of applying the acid to the object in question (Kaplan et al., 1999).

Although mission demands are made at the top level of operations, however, failures initiated at the lowest level can never be ruled out. Therefore to be able to properly identify the resources available to us, we should consider all the phases of operations as well as breaking the whole operation down to the six layers presented in Figure 10. This will enable us identify all resources that could contribute to the failure of the operation.

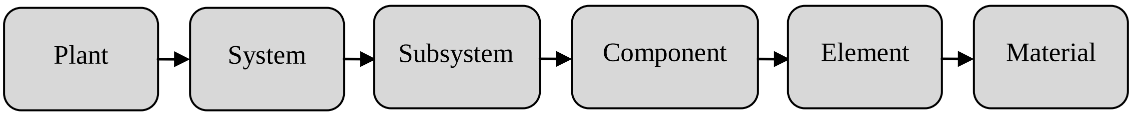

Figure 10: Six-Layer Hierarchy for Predictive Diagnostics of a System

Kaplan stated five different ways that resources are utilized in the AFD process and these five ways are presented as follows (Kaplan et al., 1999):

1. "Identifying the elements of the system that can directly contribute to causing the negative effect
2. Revealing the indirect influence(s) of available resources on the failure, through their interaction (in effect creating new resources from those already present)
3. Answering the question: "What can help to destroy the system?" (This is the way that ideas are generated in Failure Prediction)
4. Assessing the likelihood of various hypothesized mechanisms of an observed failure. (If all the resources necessary for a failure mechanism are present, then it is 100% probably that that mechanism occurred. If all the necessary resources are not present in some fashion, then that mechanism could not have occurred)
5. Selecting the most effective (or inexpensive) methods to prevent the repeat of an observed failure, or the occurrence of an identified possible new failure" (Kaplan et al., 1999).

What item 2 presents is the possibility of creating resources in such a way that two existing resources from those that are already present in the system or its close environment can react together and create another necessary resource useful for the creation of failure phenomenon. For instance, Kaplan explains if acid is needed, we need to look for the existing resources that can generate acid through chemical reaction. For sure, it is not an easy way of generating failure hypothesis but it demonstrated the main idea of resource utilization, as it pave way for the successful identification of the most tricky and subtle failure phenomena (Kaplan et al., 1999).

The six main methods described by Kaplan for obtaining new resources without having to introduce elements outside the system are (Kaplan et al., 1999):

1. "The direct combination of available resources to provide a new result. This implies the possibility of combining different fields such as electrical, magnetic, thermal, chemical etc. which are already available in the system, or creating combinations of different substances by mixing, adjoining, etc

2. Combining pre-selected properties of available resources to provide a required interaction between them
3. Using physical effects that can be performed through system elements or elements available in the nearby environment
4. Using chemical reactions and other chemical effects that can spontaneously occur via system elements or elements from the nearby environment
5. Using geometric effects (i.e., specific properties of different lines and shapes)
6. Using "clever" technologies and other inventive tricks that can be performed via system elements or elements from the nearby environment" (Kaplan et al., 1999).

Pictorial description of the utilization of resources is presented in Figure 11 below:

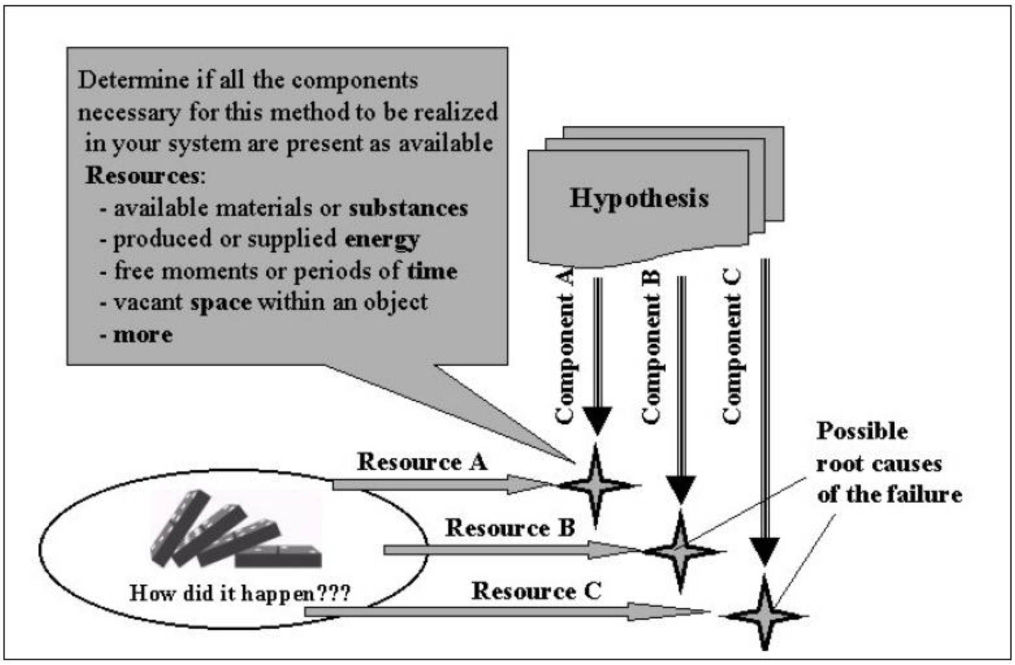

Figure 11: Utilization of Resources

Kaplan also suggests an effective way of carrying out risk analysis process by checking the "List of Resources" several times as it will provides the opportunity of identifying new failure hypotheses at every new level of the system analysis (Kaplan et al., 1999).

The typical lists of different types of resources and their combinations presented by Kaplan are stated in Table 5:

• **Substance resources** - Waste - Raw materials or unfinished products - System elements - Inexpensive substances - Substance flows - Substance properties	• **Field resources** - Fields (energy) in a system - Fields (energy) from the environment - Sources of fields - Fields of dissipation – energy waste
• **Space resources** - Occupy vacant space - Use another dimension - Arrange vertically - Use the reverse side - Nesting - Travel through	• **Time resources** - Preliminary action - Partial preliminary action - Preliminary placement of an object - Create pauses - Eliminate idling - Concurrent operations - Group processing - Staggered processing - Use post-process time
• **Informational resources** - Fields of dissipation - Substance properties - Substance flows from a system - Substance/field flows passing through - Alterable properties of substances	• **Functional resources** - Functions of the system or its elements - Find an application for harmful functions - Super-effects (effects provided through the cooperative action of different parts of the system)

Table 5: Lists of Different Types of resources (Kaplan et al., 1999).

Exemplary Illustration of Step 5 Using the Plastic Recycling Process

The categories of resources that are available in the plastic recycling process are presented in Table 6 as follows:

RESOURCES	CATEGORY	DESCRIPTION
Substances	Waste	Contaminated plastic waste.
	Raw materials/products	Plastic fume and dust. Washing detergent and chemical used for identification and classification of plastics.
Field	Fields (energy) in the system	Mechanical energy of the shredder and electrical energy of the shredder.
	Fields (energy) from the environment	Air flow for drying washed plastics.
Space		Contaminants that can remain inside the plastic.

Functional		Noise from shredder, hot extruder
Organizational		Improperly trained or inexperienced work force
Hazardous Elements		Chemically active substances used in the recycling process.

Table 6: Categories of Available Resources in the Plastic Recycling Process.

Now that the resources available to us have been identified; in the next step, we will seek more details of the failure scenarios listed above as well as identify additional failure scenarios by considering the use of AFD checklists. The way to go about this is to commence by drawing outgoing scenarios tree for each IE that are stated above, and tagging the additional IEs and MSs that emerges.

Step 6: Utilization of the Knowledge Base

This step of the template involves utilizing the knowledge base which is a store of information or data that is available to draw on. This implies that another set of checklists which are incorporated in the AFD software should be studied in order to look for items that might be associated with additional IEs, MSs, and HESs. Any scenarios that arise as a result of this procedure should be numbered and included in the trees (Kaplan et al., 1999). “These checklists essentially tabulate mankind’s experience with failures in such a way that a user can go down the list item by item, considering how each might apply to the users’ own system or operation (Kaplan et al., 1999).

In order to be able to understand the use of checklists in AFD process, we should recall Figure 6 in which the success scenarios of the use of ladder as a trajectory in the state space of the system was presented, with time, t, as the parameter along the trajectory. If we wanted something to go wrong; firstly we should identify those times that has the greatest vulnerability along the trajectory (Kaplan et al., 1999).

The checklists that Kaplan says AFD offers are presented as follows:

1. **Time-Oriented Checklists**: there are two types of checklists under this time-oriented checklist and they are:

- **Checklist 3 - Typical Stages in the life Cycle of a Technical System**: Carrying out a thorough hazard identification and risk analysis during all stages in the life cycle of a technical system is vital in identifying failure scenarios. Checklist 3 identifies the stages where failure scenarios can be identified as (Kaplan et al., 1999):

1.1 Manufacturing
1.2 Testing
1.3 Packaging
1.4 Transportation
1.5 Sales and Purchasing
1.6 Installation
1.7 Maintenance
1.8 Repair
1.9 Disassembly and Salvaging

"Each of these stages is associated with a sub-list of things that can go wrong during that stage. For example, stage 3.7 which is the maintenance stage is associated with the following possibilities" (Kaplan et al., 1999):

3.7.1 "Violation of maintenance specifications
3.7.2 Inactivation of safety, backup, or redundant systems
3.7.3 Use of the system under conditions other than those for which it was designed, or for a purpose inconsistent with the systems original function
3.7.4 Undesirable influence on the system during maintenance
3.7.5 Incorrect or ill-timed service/maintenance
3.7.6 Dangers that can emerge during maintenance (i.e., dangers to maintenance personnel)" (Kaplan et al., 1999).

- **Checklist 5 - Typical Dangerous Periods in a System's Functioning:** This checklist provides the following list of typical dangerous periods in a system's functioning:

5.1 Periods of departure from usual routine
5.2 Periods of stressful change
5.3 Periods of change in personnel (e.g., shift changes)
5.4 Periods of high stress in an individual worker's personal life
5.5 Periods when tests and maintenance occur
5.6 Periods of crowding and vulnerability to panic
5.7 Periods when security is weak

Each of these listed items can further be broken down into sub-lists and can be illustrated using real-life examples to make it more realistic.

2. Space-Oriented Checklists

Kaplan states that after becoming accustomed of the vulnerable times, we should seek regions in the space that is within this vulnerable time in which failures could be created. AFD software provides the following checklist for this purpose;

- **Checklist 4 - Typical Weak and Dangerous Zones:** The typical weak and dangerous zones are listed as follows:
    - 4.1 Flow concentration zones
    - 4.2 Zones subjected to the action of high-intensity fields
    - 4.3 Conflict zones
    - 4.4 Bad history zones
    - 4.5 Zones containing junctions of different systems
    - 4.6 Multi-function zones
    - 4.7 Tool-work piece contact zones
    - 4.8 Zones of concentrated potential energy

Each of these listed items can also be broken down into sub-lists and can be illustrated using real-life examples to make it more realistic.

3. Types of Failure Checklists

The next thing to do is to further seek the types of failures we could create. AFD software provides the following checklist for this purpose:

- **Checklist 2 - Typical Harmful Impacts:** This checklist provides the opportunity of generating failures by considering impacts from the following:
    - 2.1 Mechanical
    - 2.2 Thermal
    - 2.3 Chemical
    - 2.4 Electrical
    - 2.5 Magnetic
    - 2.6 Biological

2.7 Electromagnetic
2.8 Information
2.9 Psychological/emotional

- **Checklist 6 - Typical Sources of High Danger:** This checklist provides the chance of generating failures that could have serious impact on the operation.
- **Checklist 7 - Typical Disturbances of Flows:** This checklist has to do with ways of interfering with the flows going on in the operation.
- **Checklist 1 - Typical Functional Failures:** Since failure can happen at the top level or at the lowest level; therefore this checklist address the issue of identification of functional failures that can be produced at the following level:
    1. System Level
    2. Device Level
    3. Component Level
    4. Material Level

4. Other Checklists

We can further think critically to identify any other available resources at various phases of operation that we could use in creating failure scenarios. Again, the commercially available AFD software provides the following checklists for this purpose:

- **Checklist 8 - Typical Resources Capable of Producing Harmful Impacts:** This category of checklist constitutes an expatiated collection of possible resources that could production harmful impacts.
- **Checklist 9 - Patterns of Typical Failure Scenarios (Including Human Errors):** This checklist has to do with the identification of patterns of failure scenarios that has been experienced before, or failure scenarios that could occur in different situations. These patterns are categorized with respect to the situation under which it occurred or could occur so that users can look for those patterns that are relevant to his/her process.

5. Failure Intensifying Checklists

Failure intensifying checklists has to do with failures that are regarded as the most dangerous harmful effects due to the fact that they have the possibility to intensify with respect to time, or those that started slowly at the initial stage but later appear with full force. Two checklists were created in order to generate this kind of failure hypotheses and they are:

- **Checklist 10 - Methods of Intensifying a Failure:** In this checklist, the suggestions that Kaplan said we should try to do as regards intensifying a failure and preventing it from decreasing or escaping with time are:
  1. Increase the failure with the help of the system itself.
  2. Break the system’s natural compensatory processes.
  3. Eliminate the possibility of damage correction.
- **Checklist 11 - Ways of Masking or Hiding the Failure:** In this checklist, Kaplan mentioned that we can try to do the following listed action so as to mask the failure:
  1. Cause the failure to appear in a place that is rarely monitored.
  2. Cause the failure to appear in a place that is difficult to access.
  3. Cause the failure to appear only when it is not observed.
  4. Divert the sensor’s attention from the failure.
  5. Decrease the sensor’s level of sensitivity.

Exemplary Illustration of Step 7 Using the Plastic Recycling Process

We begin the prediction of all possible failure scenarios that can happen in the plastic recycling process by first checking against the checklist called Typical Weak and Dangerous Zones in a system. The description of the type of zones under this checklist and its possible sources of danger is presented in Table 7:

CHECKLISTS	TYPE OF ZONE	POSSIBLE SOURCE OF DANGER
Typical Weak and Dangerous Zones in a system	Flow concentration zones	Washing zone – Flow of lubricant, mechanical force, impacts. Drying zone – Flow of electrical energy. Washing and drying zones – Flow of air and water.
	Zones subjected to the action of high intensity fields	Stamping zone – Mechanical forces, impacts vibrations. Drying zone – High amplitude electric current.
	Conflicts zones	Plastic waste washing zone – A strong chemicals such as anionic detergents or cationic surfactants is added to washing water which is a threat to health.

	Bad history zones	Harmful effects: Rejections are usually related to the washing zone.
	Zones of junctions between different systems	Storage zone (where washed plastics are kept for shredding).
	Multi-function zones	Extruder: feed zone at hopper end, compression zone (transition) at the middle and melt zone (melting zone) at the die end.
	Tool-article contact zones	Shredding zone – Mechanical forces, impacts vibrations. Extruding zone – Mechanical forces, impacts vibrations.

Table 7: Types of Zones under the Checklist of Typical Weak and Dangerous Zones

After utilization of the resources through the use of checklists, our attention is drawn to a zone that had not been identified earlier. This zone is the storage zone which is between the washing of the waste plastic and shredding of the plastic.

This storage zone gives rise to another IE which is as a result of using chemicals for the washing of the waste plastic. Improper washing of the waste plastic could make the plastic become toxic contaminated and when recycled into another form of container or packaging, it may likely be unsafe, especially in the case of using it for food, medicines or baby products. We should now define the new IE as IE6; that is waste plastic becomes contaminated as a result of improper use of chemicals for washing of the waste plastic. In Table 8, we will further describe other checklists available to be analyzed.

CHECKLISTS	FAILURE LEVEL	SUGGESTION
Typical Functional Failures	Technological system (i.e., failure of function at the system level)	Bad washing of waste plastic suggest harmful impact on workers and the environment (HES2) Application of high quantities of chemicals for washing waste plastic suggests harmful effects on workers and consumer (HES2.1).
	Devices (failure at the device level)	Low quality of product suggests poor extruding (HES5).
	Materials	Low quality of product suggests improper sorting process (HES1).
		Deformation of finished product after slight use suggests poor identification and classification of plastic
	Object of nature	Increased waste suggests environmental pollution.

Typical Harmful Impacts	Mechanical	Mechanical stress, impacts suggests improper shredding of the plastic (IE3)
		Mechanical stress, impacts suggests poor extruding (IE5)
	Electrical	Impacts of electrical field, discharges and currents suggest poor extruding (IE5.1).
		Impacts of electrical field, discharges and currents suggest bad shredding (IE3.1).
Typical Disturbances in Flows of Substance, Energy and Information		Insufficient handover/communication between shift personnel suggest improper communication (IE6)
Typical Resources	This checklist, if applied will lead us to some scenarios that had been identified previously as well as new set of scenarios.	

Table 8: List of Other Checklist Available in the Plastic Recycling Process

Step 7: Invent New Solution

What we have been doing so far in step 4, 5 and 6 is trying to find ways in which we can create all possible undesired phenomena by swinging back and forth in the way we ask the following questions: “What physical effect or principle can create the undesired phenomena?” “What resources do I need to implement this principle?” and “What resources do I have?" (Kaplan et al., 1999).

In this step, we will now identify of the important HESs and MSs among those that have been identified; once this is done, it can then be tagged as secondary failure scenarios and we should seek additional ways in which these events can be created. Again one can apply the commercially available AFD software which uses I-TRIZ tools to solve the secondary problem. Any of the I-TRIZ tools listed below can use employed:

- Identifying the ideal solution,
- The Innovation Guide,
- Targeting the technical and physical contradictions,
- Applying the separation principles,
- Substance Field Analysis,
- The operator method.

Kaplan stresses that “the utilization of ARIZ is the best way to invent the most complicated and non-trivial failures that can be associated with the system or operation” (Kaplan et al., 1999).

Exemplary Illustration of Step 7 Using the Plastic Recycling Process

ARIZ for Failure Prediction

Description of the Secondary Problem or Obstacle: one of the most important problems identified is the plastic becoming toxic contaminated. Some of the chemicals used for washing and cleaning of recycled plastics in order to remove all foreign matters that are no wanted are so strong; that it could pose a serious threat to those working in the recycling facility and also could contaminated finished products meant for storage of food or drug.

Description of Ideal Conditions for Realizing this Harmful Effect: The ideal conditions are: improper washing of the waste plastic or application of high quantity of the chemicals during washing.

Is There Any Known Ways of Providing this Ideal Condition? There are several ways in which this ideal condition can be provided. One way is the improper washing of the waste plastic. Another way is by using high quantity of chemical substances during washing. We can also point to bad sorting because it is very possible that there could be toxic substances remains in a recycled plastic bottle initially used for keeping gasoline or pesticide; which is surely not safe to be used as food container. This can be linked to improper training of personnel or typical human error.

Step 8: Intensify (Amplify) and Mask Harmful Effects

After identifying the HESs and failure scenarios, amplification is suggested to be done. The amplification is very important because it allows us give full attention to failure scenarios with negligible probability of occurrence which can prompt a surprise. Once such failure scenarios are intensified, cautionary measures intended to arrest or minimize the consequences of failures would definitely be in place.

Exemplary Illustration of Step 8 Using the Plastic Recycling Process

Let us assume that the contamination of the waste plastic happens rarely or has a negligible probability of occurrence. We should therefore reverse this using expression such as repeatedly, constantly or assign a significant probability of occurrence. This will automatically put cautionary measures in place to arrest such events from springing up surprises.

Step 9: Analyze the Revealed Harmful Effects

This step involves analyzing and organizing the scenario trees in order to properly understand them. The combination of these scenario trees will make up our set of Sis for our problem.

Exemplary Illustration of Step 9 Using the Plastic Recycling Process

All the set of failure scenarios that have been identified can be presented in form of outgoing scenario trees or incoming trees as illustrated in Figure 7 in the example of the use of ladder for maintenance activities.

Step 10: Failure Prevention

The prevention of the failures should be a function of the failure hypotheses or scenarios that are considered. Careful study and understanding of this failure hypotheses or scenarios should be the starting point to identifying measures of preventing the failures. Kaplan states that one can seek help of checklists or some other TRIZ-tools to develop more effective and reliable solution.

Exemplary Illustration of Step 10 Using the Plastic Recycling Process

Toxic contamination of the waste plastic is the most interesting harmful scenarios identified in this operation. It involves improper washing of the waste plastic, by using high quantity of chemical substances during washing as well as bad sorting of the waste plastic. General ways or methods suggested by Kaplan of eliminating or mitigating the causes of this undesired phenomenon are stated as follow:

1. Eliminate the causes, for example, eliminating the conditions that bring about the undesired action.
2. Introduction of a process that eliminates or reverses the effect of the undesired action.

4.4 Strengths and Weaknesses of AFD

We have done the analysis of the AFD procedure for failure prediction and as well illustrated this procedure with one simple example. Based on this analysis, we therefore seek to identify the strengths and weaknesses of AFD in determining the Black swan events or the unforeseen events.

4.4.1 Strengths

1. The Invention of Failure

One of the overwhelming strength of AFD technique lies in the "inventive philosophy" to generate risk scenarios under TSS. In ordinary failure analysis, risk analyst would ask: "Why did the observed failure occur?" However, in AFD-1 and AFD-2, risk analyst would instead ask "How can I create such a failure?" and "How can I make things go wrong?" respectively. This process of deliberately "inventing" failures helps the risk analyst in predicting as many failures as possible through the development of failure scenarios. "The advantage to this approach is analogous to a defence attorney becoming a prosecutor. The system's potential flaws are viewed from a perspective that allows for full exploitation of a system's weaknesses. It is obvious that, when all system deficiencies are made explicit, the team or individual can take more effective countermeasures" (Inc., 1999).

How does the failure invention help in identifying black swan type of events? Considering the category B of the black swan type of events; the unknown knowns which are events that were not on the list of known events from the perspective of those who carried out a risk analysis (or another stakeholder) due to the fact that there was no awareness of such events, or there was limited consideration, one would say that inventing failures through the process of prediction could help in adding some failure events that had never occurred before to the list of known events when carrying out risk analysis. For sure, it may not capture the complete set of failure scenarios or accurately predict the future but it is very possible that it produces a number of credible and significant future occurrences that may be useful in revealing the black swans which may pose as a threat to the safety of a system or process.

There are two additional advantages that the concept of inversion adds to the factors that can minimize the occurrence of black swan type of events; they are:

2. The Phenomenon of Denial

At times, we human tend to resist thinking about things that are not pleasant because of a psychological phenomenon called denial. We have the tendency of ignoring obvious things by saying “It cannot happen here,” “Things will turn out all right,” “It has never happened before,” etc (Kaplan et al., 1999). This altitude could make us refuse to critically investigate our system for any obvious evidence. Kaplan stated that “ the presence of the denial phenomenon is clearly seen in the historical evidence of various disasters, accidents, and failure (Kaplan et al., 1999). Once we put ourselves in this frame of mind, our system becomes vulnerable; therefore prone to surprises.

The advantage of asking the inverted question “How can I make something go wrong” is that it helps in making an offensive and proactive decision. This makes the identification of many set of failure scenarios likely; therefore minimizing the occurrence of black swan type of events.

3. The “Production” Effect

If we would like to respond to the question “What can go wrong” with our system or operation, we would generally seek solution by searching through history data for related failures. “However, the recorded database associated with failures is relatively poor” (Kaplan et al., 1999), and this is because there is shortage of documented information of failures.

This shortage of documented information about failures within a system or its environment is blamed on the denial phenomenon because people tend to be unwilling to document data that has to do with failures. It is possible to link some of the surprises that can happen as a result of black swan events of “category B” (events that were not captured when carry out risk assessment due to the fact that there was no awareness of such events) to the unwillingness to document failures.

When it comes to what human are proud of, as in “how to produce something or create some effect, there are lots of information available. Therefore we can take advantage of this, by carrying out the process of inversion. This will simply make vast amount of information available to which could minimize the occurrence of black swan type of events.

4. The Amplification of Failure

Step 8 of the AFD Procedure for Failure Prediction deals with intensifying failures through exaggeration of the extent of damage or occurrences. This is another strong strength of AFD technique because if we consider the category C of the black swan type of events; the known knowns which are events that are on the list of known events in the risk assessment but are judged to have negligible probability of occurrence, and therefore not believed to occur, we would realise that the application of failure amplification will definitely reverse the negligibility probability of occurrence of these types of events and therefore pave way to judging it as events that has significant probability of occurrence. Once it has been judged as events with significant probability of occurrence, cautionary measure that would prevent or mitigate the risk of occurrence of black swan type of events would be put in place.

5. The Concept of the Use of Resources and Checklists

One of the most important strength of AFD tool is the concept of "Resources" which is based on the following:

"*For any failure or drawback to occur spontaneously, all the necessary components must be present within the system or its nearby environment. If all those components are present, the failure will necessarily occur*" (Kaplan et al., 1999).

Resources are essential part any successful system or operation. For example, man power, equipments, raw materials etc. are all required, in order to get a business started. What is so important about resources is that, if we could make a good list of all resources that our system or operations are associated with; we would see that the list will go on lengthening. Although in the first instance, many of these resources are hidden and not visible therefore, putting the list of resources together could reveal hidden ones. For example, preparation of food in the kitchen requires resources such as stove, lighter, vegetable, salt, oil etc. if we base failure prediction only on these obvious resources without making proper list of resources, hidden resources such as air could give rise to surprises.

The idea of using resources available in or around the system or operation makes a lot of sense in identifying failure scenarios. It will enable thorough risk assessment of the system/operation from the system level down to the component level and as well review failures that might be associated with resources.

4.4.2 Weaknesses

1. Complex Database/Report

Since there are no limitations as to the number of failure scenarios that can be predicted, analysts can always continue predicting failure scenarios and adding as many scenarios as possible that he or she thinks are applicable. The prediction that would include complete set of failure scenarios that had happened before as well as those that have never happen before. This process is more complicated, therefore, leading to a profusion of initiating events (IEs), harmful end states (HESs), and mid-states (MSs) and complete risk scenarios (Sis) (Kaplan et al., 1999). A key task that arises here is: how do we effectively manage this profusion? This is a major problem in failure prediction and it will require an effective huge data base for it to be managed properly.

However, it can also make the database more complex in the sense that the more information you add to it, the more you make it difficult to initially set up. An attempt to simplify or reduce the complexity of the database/report may give rise to the possibility of ignoring some failure scenarios deemed to be insignificant. This could result to a black swan event.

2. Overlook Human Factor

In any complex system, human operators are one of the major sources of errors. Even the well-trained operators can be a victim of nature, for instance prone to boredom, feeling sleepy during night-shift. AFD tends to put too much attention on mechanism or technical issue of the system and ignore errors that can surface as a result of human failure.

3. Uncertainties

It is normal that all predicted data, assumptions, hypotheses made or even measured data will have some level of uncertainty. As we all know that risk and uncertainty are in almost every activity we do; the same thing applies to all activities we did when carry out the failure predictions. Some assumptions, hypotheses and predictions were made in the process of identifying events/scenarios that can cause system or operational failure. We cannot guarantee that these assumptions, hypotheses and prediction are completely accurate; they may differ from the actual state. Uncertainty can only be reduced but can never be completely eliminated.

4. Rely on Experts’ Knowledge and Experience

Kaplan stated that the process of generating failure scenarios is more art than science which often relies on the analyst’s background knowledge. Knowledge is the key factor in predicting risk scenarios. For example, some analyst may believe that an operation will fail due to the set of data and information, modelling and analysis available to them. There is possibility that their belief can be wrong, resulting to wrong prediction because knowledge in this case can only be subjective but not objective.

Some assumptions and hypotheses were made when predicting failure scenarios in the AFD process. These assumptions and hypotheses are conditioned on background knowledge in which their credibility and reliability will always be an issue to question.

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5. Conclusion

5.1 Final Remarks

The new tool for failure and risk analysis called Anticipatory Failure Determination has been presented along with its strengths and weaknesses in identifying the black swan type of events. There is no doubt that the AFD is a powerful tool for failure and risk analysis as it goes a step further when compared to the traditional approaches for failure analysis. The process of deliberately inventing failure events and scenarios is where the strength of the technique lies. (Masys 2012).

From the analyses of the strengths of AFD, it is very easy to identify that AFD makes a significant contribution in revealing only category B and C black swan type of events through the process of failure inversion, failure amplification. However, failure inversion and failure amplification are steps of AFD-2 template that follows after successful identification of failure modes which is the most important part of the template.

In this event/scenarios identification, the theory of scenario structuring coupled with some assumptions and hypotheses were used in predicting failure scenarios. These assumptions and hypotheses remain an issue for debate and could be challenged because it strongly depends on the background knowledge of the analyst. The stronger the knowledge, the more you increase the likelihood of predicting valuable set of failure scenarios. The weaker the knowledge, the lesser your chance, and this increases the possibility of surprises and black swan springing up.

5.2 Area for Further Study

This thesis sought to analyze the Anticipatory Failure Determination in a bid to identify its strengths and weaknesses in identifying black swan type of events. It is obvious that the most vital aspect of AFD as regards black swan type of events is the hazard/threat identification. The knowledge that the hazard/threat identification methods depend on, should be the area for further study. Therefore, in order to meet the three categories of black swan, more study should be channelled on strengthening the knowledge dimension.

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7. List of Appendix

1. Appendix 1

Template for Failure Analysis (AFD-1)

STEP 1: FORMULATE THE ORIGINAL PROBLEM

Describe the original situation associated with the undesired phenomenon:

> There is a system called [name of system] for [describe purpose of system]. An undesired effect occurs under the conditions [describe]. It is necessary to find the cause of this phenomenon.

STEP 2: IDENTIFY THE SUCCESS SCENARIO

Operations or Phases	Results

STEP 3: LOCALIZE THE FAILURE

STEP 4: FORMULATE AND AMPLIFY THE INVERTED PROBLEM

> Step 1: It is necessary to produce [describe inverted problem] under the given conditions [describe].
>
> Step 2: It is necessary to produce [describe inverted problem] under the given conditions [describe amplified conditions].

STEP 5: SEARCH FOR SOLUTIONS

> The same phenomenon is intentionally created in the following areas:
>
> The resources (available or derived) are:
>
> The way(s) to produce the desired phenomenon as found in the Innovation Guide are:

ARIZ for Failure Analysis

> Step 1: The general way to produce the desired phenomenon is:

The secondary problem is:

Step 2: The ideal conditions for realizing this harmful phenomenon are:

Step 3: The known way to provide the ideal conditions is: The way to change the system, recommended by the Innovation Guide is:

Step 4:

A - Limitations to providing the ideal conditions are:

B - Contradiction: There is a way to produce the harmful effect but it cannot be realized for the following reason:

C - According to the Separation Principles, this contradiction may be resolved in the following way:

STEP 6: FORMULATE HYPOTHESES AND TESTS FOR VERIFYING THEM

The hypotheses are:

Tests required to verify the hypotheses:

STEP 7: CORRECT THE FAILURE

The way to prevent / eliminate this kind of failure in the future is:

2. Appendix 2

Template for Failure Prediction (AFD-2)

STEP 1: FORMULATE THE ORIGINAL PROBLEM

Describe the original situation associated with the undesired phenomenon:

> There is a system called [name of system] for [describe purpose of system]. We wish to find all possible undesired effects or failures that can occur within, or as result of, this system, and to identify the ways in which these undesired phenomena can occur.

STEP 2: IDENTIFY THE SUCCESS SCENARIO

Operations or Phases	Results

STEP 3: FORMULATE THE INVERTED PROBLEM

> There is a system called [name of system] for [describe]. It is necessary to produce all possible undesired effects or failures that can occur within, or as a result of, this system.

STEP 4: APPARENT WAYS TO DETERIORATE THE SYSTEM FUNCTION

Obvious possible Initiating Events are:

Obvious Harmful End States are:

Obvious Possible Risk Scenarios are:

STEP 5: IDENTIFY AVAILABLE RESOURCES

Substance resources:

Field Resources:

Space resources:

Time resources:

Functional resources:

Systemic resources:

Change resources:

Differential resources:

Inherent resources:

Organizational resources:

Small failures disturbances:

Hazardous elements:

Control devices:

Protection systems:

STEP 6: UTILIZE THE KNOWLEDGE BASE

Typical weak and dangerous zones in a system:

Typical functional failures:

Typical harmful impacts on systems (humans included):

Typical life cycle stages of technological systems:

Typical dangerous periods in system functioning and evolution:

Typical sources of high danger:

Typical disturbances in flows of substance, energy and information:

Resources:

STEP 7: INVENT NEW SOLUTIONS

The way(s) to produce the harmful effects according to the Innovation Guide are:

ARIZ for Failure Prediction

Step 1: The general way to produce the desired effect is:

The resulting secondary problem is:

Step 2: The ideal conditions for realizing this harmful effect are:

Step 3: The known way to provide the ideal conditions is:

Step 4: The way to change the system, as recommended by the Innovation Guide, is:

A - Limitations to providing the ideal conditions are:

B - Contradiction – There is a way to produce the harmful effect but it cannot be realized for the following reason:

C - According to the Separation Principles, this contradiction may be resolved in the following way:

STEP 8: INTENSIFY AND MASK HARMFUL EFFECTS

Typical ways to intensify harmful effects:

Typical ways to mask harmful effects:

STEP 9: ANALYZE THE REVEALED HARMFUL EFFECTS

STEP 10: PREVENT/ELIMINATE THE HARMFUL EFFECTS

Typical ways to prevent harmful effects:

Results of working with I-TRIZ operators:

3. Appendix 3

Anticipatory Failure Determination Software Features

There are two software products for Anticipatory Failure Determination: Ideation Failure Analysis and Ideation Failure Prediction. Both products include the following features:

1. Templates and Suggestions for Failure Analysis and Failure Prediction Hypertext templates to guide you through the failure analysis or failure prediction process, along with explanations and suggestions for each step.

2. Problem Formulator, which provides:

- A means to create a graphic model of the system, its environment, and related failures (either existing or hypothesized).
- Automatic generation of problem statements to support the development of failure hypotheses. These include:
    - For Failure Analysis – the Inverted Problem Statement for any failure or drawback whose cause you aim to reveal.
    - For Failure Prediction – a set of Directions for each function (activity, action, process, operation, condition, or effect) included in the system model.
    - A set of Directions for Failure Prevention/Elimination for each verified failure or failure scenario.
- Embedded links from each Direction to the applicable section of the AFD knowledge base.

3. AFD Knowledge Base

The AFD Knowledge Base includes:

- System of Operators – The I-TRIZ principles, methods and standard solutions in the form of recommendations for changing a system. In AFD failure analysis and prediction, operators are used to help generate hypotheses and ideas for corrective action.
- AFD checklists

  - Typical functional failures
  - Typical harmful impacts
  - Typical stages in the lifecycle of a technical system
  - Typical weak and dangerous zones
  - Typical dangerous periods in a system's functioning
  - Typical sources of high danger
  - Typical disturbances of flows
  - Typical resources capable of producing harmful impacts
  - Patterns of typical failure scenarios (including human errors)
  - Methods of intensifying a failure
  - Ways to mask or hide a failure
- Innovation Guide – a hypertext encyclopedia of technological effects useful for failure analysis and failure prediction.

4. AFD Report

The AFD Report offers the ability to document your creative work with the software. Reports can be converted to rtf files for use with other applications.

5. Illustrations

Each operator is accompanied by one or more illustrations describing how the operator was applied to a specific technological situation.