A Hybrid Model for Learning from Failures: the Hurricane Katrina Disaster

Abstract:
There is a need to facilitate learning from failures in the context of natural and man-made disasters. This paper investigates the multi-faceted nature of research in disasters and the aspect of hybrid approaches in modelling within this domain. The paper applies a framework of reliability and multiple criteria decision analysis techniques to the case of the Hurricane Katrina disaster of 2005. It is shown how this hybrid model can be used through an integrative approach to perform a systematic analysis that can lead to learning from failures.

The proposed framework incorporates and integrates Fault Tree Analysis (FTA), Reliability Block Diagram (RBD) analysis and the Risk Priority Number (RPN) concept, together with the Analytic Hierarchy Process (AHP) which is used as a simulation model for decision support. It is shown how the proposed integrated framework can contribute to our understanding of failures and enhances the ability to extract lessons from failures or disasters. Such lessons are then mapped into specific decisions for prevention, and resource allocations, to help avoid a repeat disaster.

Keywords: Decision Making, Natural Disasters, Failure Mode Effect and Criticality Analysis, Analytic Hierarchy Process.

1. INTRODUCTION[1]

Previous research has shown that organizations learn more effectively from failures than from successes (Madsen, and Desai 2010) and that failures contain valuable information, but organizations vary in their ability to learn from them (Desai, 2010). It has also been argued that there is a need for a paradigm shift in accidents models due to new challenges that relate to issues such as the fast pace of technological change, the changing nature of accidents, decreasing tolerance to single accidents and increasing complexity and coupling (Leveson, 2004). Pavlou and El Sawy (2011) investigated means of measuring dynamic capabilities and concluded that among its properties are learning, sensing the environment, coordinating and integrating. Also, learning can be enhanced through developing simulations and mental models (Clark, and Kent, 2013).

Research in to disasters and learning from them is multi-faceted in nature (Kulatunga, 2010). Labib and Read (2013) investigated the issue of learning from failures and applied reliability analysis techniques of Fault Tree Analysis (FTA) and Reliability Block Diagrams (RBD) as a framework model for learning from failures. This was based on the analysis of four case studies related to reported disasters, which included the Titanic disaster, the BP Texas City incident, the Chernobyl disaster, and NASA's Space Shuttle Columbia accident. Reliability engineering techniques such as FTA, RBD and Failure Mode, Effects and Criticality Analysis (FMECA) have been used to analyze the case of the Bhopal disaster (Labib and Champaneri, 2012), and it has been shown how such techniques can help in building a mental model of describing the causal effects of the disaster. The same case study of Bhopal was also investigated (Ishizaka and Labib, 2013) and a new logic gate in a fault

[1] This research builds on and extends previous work in chapter 10 of Labib (2014)

tree was proposed for analyzing disasters and the benefits of using hybrid techniques of multiple criteria and fault analysis to evaluate and prevent disasters were demonstrated. **Hybrid modelling has recently been adopted by several authors. For example, Kou *et al* (2014) provided an efficient hybrid model that integrates fuzzy logic, survey questionnaires, Delphi and multiple criteria decision making (MCDM) methods for disaster assessment. Li *et al* (2014a) provided a community-based virtual database for emergency management. Also Li *et al* (2014b) developed a mult-objective optimisation model for oil-importing decisions in extreme events. Zolfani et al (2013) proposed a hybrid MCDM method for the selection of a tunnel ventilation system in the event of automobile accidents. Vaidogas and Šakėnaitė (2010) proposed a hybrid model for fire risk in the form of quantitative risk assessment and multi-attribute selection. Poplawska et al (2014) proposed a hybrid multi criteria decision analysis framework for implementation of corporate social responsibility (CSR) in the extractive sector.**

Tinsley et al, (2012), who investigated near-miss events as well as Hurricane Katrina and other disasters, concluded that "*people may be complacent because prior experience with a hazard can subconsciously bias their mental representation of the hazard in a way that often (but not always) promotes unrealistic reassurance*". This paper extends this work on Hurricane Katrina disaster, by providing and integrating tools that can help in performing a systematic analysis that can lead to learning from failures. It is hoped that this hybrid modelling approach will contribute to the provision of a useful mental representation of disasters.

In this paper, a number of reliability analysis techniques are employed. FTA is used to identify the main direct causes and contributing factors (failure modes) of the Hurricane Katrina disaster, and to show how these direct causes and contributing factors interacted with each other. The interactions identified through FTA are used as an input to an RBD analysis, to demonstrate how overall system reliability could be calculated and improved through, for example, strengthening weak (series) structures revealed by the analysis. The failure modes identified through the FTA analysis are used as input for an FMECA analysis for the identification of a Risk Priority Number (RPN) of each failure mode which can be used to rank the risk of different failure modes.

Leveson (2004) argued that event based accident models, such as FTA, RBD and FMECA, have limitations due to their emphasis on linear causality and inability to deal with non-linear relationships such as feedback, and may give only a superficial explanation about why a disaster may have occurred. In order to overcome this limitation and contribute to the provision of a deeper understanding of the reasons for failure as well as support for decision making, this present paper employs Multi-Criteria Decision Making (MCDM) techniques to structure and analyse the information provided by the reliability techniques. The work presented here utilises the MCDM technique of Analytic Hierarchy Process (AHP) to provide prioritisation, sensitivity analysis and feedback on consistency of the different criteria and the alternative contributing factors. The model helps the decision maker to prioritise different strategies and the allocation of resources. It also provides a sensitivity analysis and a measure of consistency as a form of feedback. Also in this paper we discuss the high level design improvements, and the lessons learned which should be acted upon so as to avoid a repeat disaster.

Figure 1 outlines a flowchart of the structure and relationship between the different techniques used. The three techniques of FMECA, FTA, and RBD belong to the reliability analysis domain, whereas AHP is an MCDM technique.

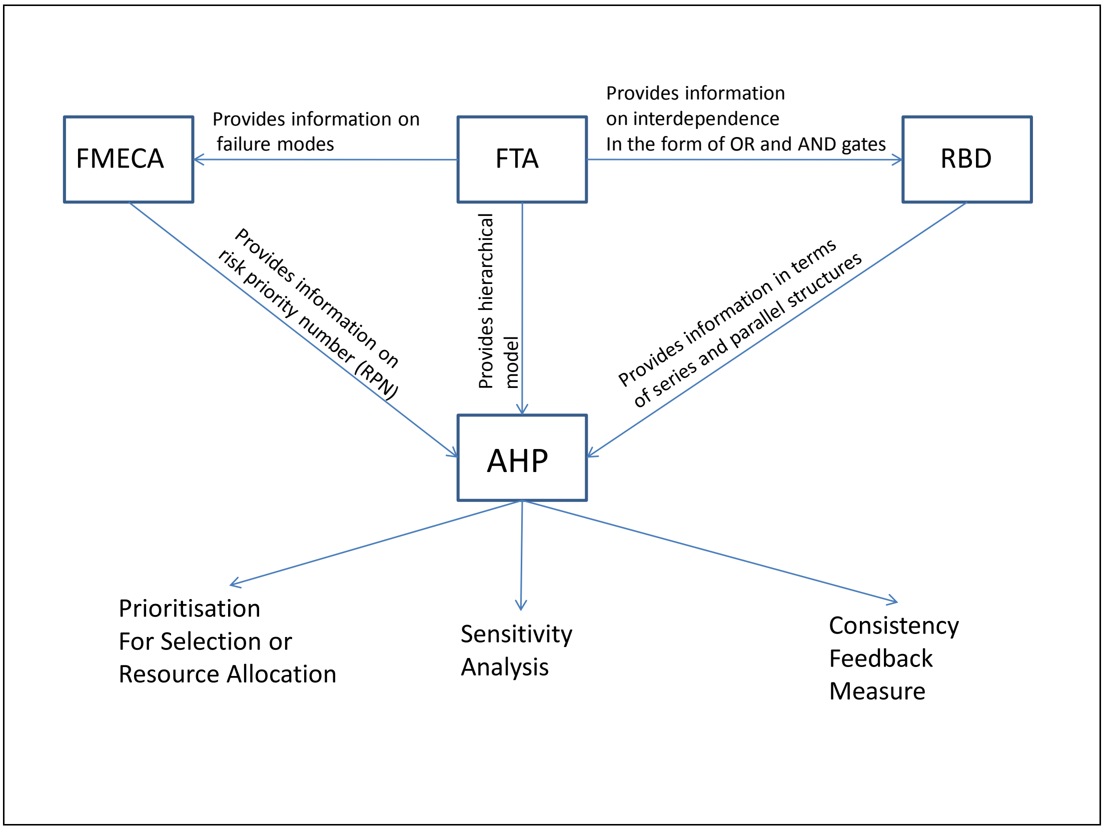

Figure (1): The model structure and the relationships between the different techniques

The contributions of the study are both theoretical and methodological. On the theoretical side, it is shown how data - some of which is based on interpretation and judgement and some is more empirical in nature - can be combined in a rich framework that can be used by decision makers to prioritise different strategies and allocation of resources. Although the chosen methods are all normative decision making or assessment techniques, and not inference techniques, by combining them one can illicit useful recommendations for policy making. On the methodological side, it is shown how the two fields of risk analysis and decision science can be combined and utilised in an integrated manner. It also shows that techniques intended for prospective decision making can be utilised to retrospective events. **Finally, our use of hybrid modelling makes a contribution towards demonstration of both the 'interactive and integrative' capabilities of the chosen models.**

According to Cacciabue and Vella (2010) retrospective analysis aims at understanding and extracting lessons from past events through techniques related to data mining and root cause analysis, whereas prospective analysis looks ahead and speculates safety levels of systems through brainstorming initiating events and generation of counter safety measures. They also argue that to ensure consistency and consolidation of the whole safety approach, there is a need to utilise same reference models. Hence, in this paper, the same data, methods and techniques are used for retrospective and prospective analysis.

It may be argued that single techniques have limited capacities to represent complex realities, but simply adding more techniques does not necessarily improve learning. It may make inferences harder to make, and it may introduce contradictions. We demonstrate through the narrative of the case study that the proposed hybrid integrated approach provides better understanding of the causal factors as well as provision of decision support for resource allocation and prevention of similar devastating consequences from disastrous events.

2. ANALYSING DIASASTERS

A disaster may be considered as a Black Swan, a term coined by Taleb (2010) to describe an event which has the three attributes of rarity, extreme impact and retrospective predictability. Taleb (2010) argues that this phenomenon is accelerating as the world is getting more complicated. Globally, natural hazards are increasing at an increasing rate. According to Rougier et al (2010), such increase is due to factors such as environmental change, population growth, new forms of exposure and social vulnerability. The authors of this work believe that the combination of low predictability and large impact makes disasters a great challenge to analyse and hence this paper is both timely and of utility. We accept that hurricanes happen as a rate of 1/100 per year so they are not that rare, but the Katrina disaster is not just an ordinary hurricane in terms of its impact compared to the history of all past hurricanes, which makes it a unique event.

There are two categories of lessons that can be learnt from the Katrina event which are similar to those proposed by Flouron (2011) when describing the BP Deepwater Horizon accident. The first relates to narrow, or specific, lessons while the second relates to broader issues. The former category arises when describing such an event as a 'failure due to human negligence, or having insufficiently high, strong and maintained levees in a hurricane prone area', a type of technical failure, whereas the latter arises from describing such an event as a 'disaster', defined as an occurrence inflicting widespread destruction and distress. Through the latter lens the event is considered broadly in a social science, political, systems theory and management approach, as suggested by the seminal work of Turner (1978) which was then followed up by Toft and Reynolds (1997).

The analysis of disasters can produce four main benefits: First, it can help to identify the root cause of what went wrong and why. Second, it can act as an early warning signal just prior to the event in order to take pre-emptive measures. Third, it can help to institute long term plans to prevent similar events from re-occurring. Fourth, it can provide decision makers with a set of priorities for resource allocation for both recovery and prevention.

Here the term 'root cause' needs to be treated with care. In an accident investigation, if root cause is perceived as for example, 'someone's behaviour' then it may be likely, as argued by Rasmussen (1997), that the accident would occur by another cause at another time. The authors of this work agree that in this example, such root cause is superficial and should be regarded as still part of the symptom rather than the real root cause. A real root cause needs to be plan and policy related with respect to the current status quo. As such, ideally a root cause should lead to initiation or modification of standard operating procedures (SOPs). Also a root cause needs to contribute to the three features of how learning from failures is defined as outlined by Labib and Read (2013), where they argue that learning from failures consists of feedback to design of existing procedures, use of advanced techniques to analyse failures, and generation of interdisciplinary generic lessons.

The innovative aspect of the study presented here is the integration of modelling approaches in a generic hybrid model, since single techniques have limited capacities to represent complex realities. The majority of modelling applications tend to use a single model to analyse a problem, but the issue with this line of approach is that any methodology that relies on just one stand-alone, model has its limitations due to the inherent assumptions that exist in any one particular model and, accordingly, it becomes inadequate in providing an effective and realistic approach. Subsequently, such an approach leads itself into trying to manipulate the problem in hand in order to “fit it” into the method instead of vice versa. So, relying on just one model for analysis may distract people who are carrying out the accident investigation, as they attempt to fit the accident into the model, which, as argued by Kletz (2001) may limit free thinking.

Therefore, what is proposed here is to develop a hybrid model approach which offers richness to the analysis. Moreover, it combines the strengths of the models used, and the limitations that exist in each model tend to cancel each other; in other words, they complement each other. The proposed hybrid models are fully integrated to provide an effective and efficient approach, firstly for identifying and prioritising important features that led to the disaster and need improvement, and secondly for optimising the allocation of resources to prevent or mitigate the consequences of future disasters.

3. THE HURRICANE KATRINA DISASTER

The Hurricane Katrina disaster has been studied in detail by the American Society of Civil Engineers - ASCE (2007), Select Bipartisan Committee (2007) – a Committee of the US Senate, Jonkman et al (2009), Crowther et al (2007), Griffis (2007) and van Reeet al (2011). Although it could be argued that this section could be made much shorter by simply referring the reader to the abundant information in the above reports it is suggested that such a primary data collection would be of lower quality as over time memories would have faded and key individuals may no longer be available. Therefore, a secondary data analysis (which is a proven and widely used research method) will be used for the problem structuring. Such a secondary analysis also gives the possibility of triangulating sources. Moreover, the information can be easily checked by other researchers.

New Orleans is situated near where the Mississippi River flows into the Gulf of Mexico in south eastern Louisiana. It was built on low-lying marshland between the Mississippi River, Lake Pontchartrain, Lake Borgne and the Gulf of Mexico. The New Orleans region and its busy port, which is one of the most important ones in the United States, are part of Louisiana’s extensive petroleum infrastructure which supplies oil and other petroleum products to the rest of the country. The state of Louisiana itself is ranked fifth in United States oil production, is home to a network of pipelines, storage facilities, seventeen petroleum refineries and two of the US’s four Strategic Petroleum Reserves. Also New Orleans serves as a business centre for BP, Shell Oil, Chevron and ConocoPhillips.

Sinking Region

New Orleans is built on a foundation of thousands of feet of soft sand, silt and clay. Subsidence (settling) of the ground surface occurs naturally due to consolidation, oxidation and groundwater pumping influences. Large portions of Orleans, St. Bernard and Jefferson parishes (counties) are therefore below sea level and continue to sink.

Prior to 1946, flooding and subsequent sediment deposition counterbalanced natural subsidence leaving south eastern Louisiana at or above sea level. However, due to major flood control structures being put in place, fresh layers of sediment are not being deposited so as to replenish ground lost to flooding. Also groundwater withdrawal, petroleum production, development and other factors are all contributing to the subsidence which is estimated by the US Geological Survey to occur at a rate of between 0.15 and 0.2 inches per year with rates of up to 1 inch per year occurring in some places.

Hurricane Protection System

Responsibility for design and construction of most of the flood and hurricane protection levees along the Mississippi River and in the New Orleans region rests with USACE (United States Army Corps of Engineers). Their strategy was to build levees or floodwalls around segments of New Orleans. Typical USACE flood protection structures constructed in and around New Orleans were: i) Earthen levees, ii) I-Walls (used to raise the level of flood protection), and iii) T-Walls (shaped like an upside-down T with substantial armoured foundations).

Other agencies own and operate further flood protection systems such as the interior drainage and pumping stations, the Mississippi River Levee Flood Protection System, and non-USACE levee features.

Hurricane Katrina

Hurricanes are not a new phenomenon to south east Louisiana; there have been 13 major hurricanes in the last 155 years. Hurricane Katrina started out in the Bahamas as a tropical storm on 23rd August 2005. It crossed south Florida on 25th August as a Category 1 hurricane before entering the Gulf of Mexico. The hurricane intensified as it tracked westward.

Hurricanes are categorised based on their maximum wind speed according to the Saffir-Simpson Hurricane Scale. On 28th August, the hurricane began tracking toward the northwest, and intensified from a Category 2 (96-110mph) to a Category 5 (>155mph) in just 12 hours. As it approached land, the warm, moist air and energy that it could draw from the Gulf of Mexico decreased, and Hurricane Katrina was degraded to a Category 3 hurricane (111-130mph).

On 29th August 2005 Hurricane Katrina, which was one of the strongest storms ever to hit the coast of the United States, brought intense winds, high rainfall, waves, and storm surges that caused widespread devastation in New Orleans and along the coasts of Louisiana, Mississippi, and Alabama. Levees and floodwalls were overtopped and several were breached, allowing billions of gallons of water from the Gulf of Mexico, Lake Borgne, and Lake Pontchartrain to flow into New Orleans, flooding major portions of the city.

Consequences of Failure of Protection System

The following statistics in relation to the Hurricane Katrina disaster identify the devastation that was caused:

- **Fatalities:** As of 2nd August 2006,1,118 people confirmed dead
- **Damage to residential and non-residential property:** $ 21 billion
- **Damage to public infrastructure:** $ 6.7 billion
- **Population displaced:** Approximately 50%
- **Regional economy:** Approximately 124,000 jobs lost and the region's economy crippled

Technical Causes of Failure

From the many causes identified in previous studies (ASCE, 2007; Select Bipartisan Committee, 2007;Jonkman et al, 2009; and Crowther et al, 2007) as being responsible for the disaster the high level ones can be categorised as either direct or contributory.

Direct Causes:

a) **Levees breached:** Authorities used I-walls to raise levee elevations instead of increasing width and height with earth, wrong elevation datums were used and they did not account for soft I-wall foundations resulting in overtopping and I-wall collapse. Also many infrastructure penetrations were made through levees.
b) **Ineffective pumping stations:** Under-rated pumping stations which were not hurricane resistant required the presence of an operator and power to function, resulting in only 16% utilisation of the limited pumping capacity for the region.

Contributing Factors

c) **Hurricane protection management policy:** Poor risk management approach, uncoordinated construction, maintenance and operation of levees, and also no levee subsidence correction program all contributed to the unfolding of the disaster.
d) **Inadequate emergency response:** Lack of a mandatory evacuation order, unprepared local and state emergency response agencies and a late national response impacted rescue efforts.

4. METHODOLOGY OF THE HYBRID MODELLING APPROACH

As mentioned in Section 1, the innovative aspect of this paper is the integration of modelling approaches in a generic hybrid model. In order to show how the different tools and techniques of the hybrid model are co-ordinated, both Figure 1 and Table I show how the integration of the methods is developed and describes the tools used in terms of their input requirements, expected outputs and sources of information. It also shows how each tool relates to another. The AHP methodology was used as a prioritisation method rather than the Analytic Network Process (ANP) although the later allows interaction between the different criteria, due to the fact that AHP is hierarchical in nature which corresponds to the architecture of FTA. Furthermore the simplicity in computation of AHP compared to ANP justifies its use especially in a situation where hybrid modelling is used.

As stated before, single techniques have limited capacities to represent complex realities, so simply adding more techniques does not necessarily improve learning. It may make inferences harder to make, it may introduce contradictions, and it may impede efforts to assemble a systemic, rather than reductionist understanding. Also uncertainty can arise from limitations in different models which may be of three types (Rougier et al, 2010); parametric uncertainty in terms of not knowing the correct settings of the parameters, input uncertainty in terms of not knowing the value of the data, and structural uncertainty in terms of failure to represent the natural system. The emphasis in this paper is on the structure aspect of modelling, and uses the Katrina Disaster as an example to demonstrate the approach.

Table I: Integration of tools with the proposed hybrid model.

Tools and associated Figures and Tables that discuss results of the tool	Data used by each tool	Tool's outputs
Fault Tree Analysis (FTA). Identifies causes of failure (failure modes) and interactions between causes Figures (2) and (4)	• Data related to technical causes of the failures based on understanding of the problem and based on previously published research (e.g. ASCE, 2007)	• Information on failure modes and their root causes in the form of basic events, for input into FMECA tool. • Information on interdependence in the form of OR and AND gates, for input into RBD tool. • Hierarchical model, for input into AHP tool.
Reliability Block Diagram (RBD) Provides better understanding of the reliability of the system Figure (3)	• Basic events from the FTA tool. • Relationship between basic events from FTA i.e. every OR gate in FTA is mapped as a 'series' structure in RBD, and every AND gate in FTA is a 'parallel' structure in RBD.	• Information in terms of 'series' and 'parallel' structures to inform about the relative weights assigned in the AHP tool. • Demonstrates how the overall system reliability can be calculated and improved by strengthening weak (series) structures in the diagram.
Failure Mode Effect and Criticality Analysis (FMECA) Analyses probability of failure modes against severity of consequences and difficulty of detection Tables (II - V)	• Failure modes from the FTA tool.	• Risk Priority Number (RPN)
Analytic Hierarchy Process (AHP) Provides prioritisation of alternative decisions and sensitivity analysis for a decision maker. Figures (5), (6) and (7)	• Risk priority number (RPN) from FMECA tool. • The hierarchical model from the FTA tool. • Series and parallel structures from the RBD tool. • Judgments from questionnaire completed by decision makers and informed by structure of FTA and RBD tools.	• Prioritisation for Selection or Resource Allocation. • Sensitivity analysis - 'What if' analysis. • A measure of consistency • Feedback measure to the decision maker.

5. FAULT TREE ANALYSIS (FTA)

A fault tree is a logical diagram which shows the interactions of failure events which lead to system failure, i.e. a specific undesirable event in the system, as well as failures of the components of the system. It is considered as a *deductive logic model* in which a system failure is postulated and reverse paths are developed to link the system failure with all subsystems that can contribute to that failure (Vesely et al, 1981) and (Ekaette et al, 2007). The undesirable event constitutes the 'TOP' event of the tree and the different component failures constitute the basic events of the tree. The causes of the TOP event are "connected" through logic gates; we only consider AND-gates and OR-gates. Basic events are those associated with human errors, equipment failure and environment interference. FTA provides a logical representation of the relation between the top event and those basic events. In order to explain how the component failures of the direct causes and contributing factors interact with each other, an FTA was constructed by the authors (Figure 2) guided by the technical causes of the failures and our understanding of the problem based on previously published information as identified in Section 3 above.

In order to build a mental model of possible causal factors, it is useful to start by categorising such factors into two or more broad classifications. In process industry, and especially in nuclear energy, one can attribute failure to one of two main reasons; either a design integrity failure or an operational and maintenance failure. For example in the case of Fukushima nuclear disaster, failure was clearly caused by the former rather than the latter, whereas in the case of Chernobyl nuclear disaster, the failure was attributed to a combination of both categories at varying degrees (Labib, and Read, 2013). In a natural disaster such as Hurricane Katrina, it is proposed to categorise possible causal factors into *direct causes* (such as levees breeched and ineffective pumping stations), and *contributing factors* (existing hurricane protection and management policy or inadequate emergency response).

Starting at the top event or system failure (the Hurricane Katrina Disaster), the fault tree was built downwards from the undesired event to intermediate events (rectangular boxes) and then to basic events using logical AND/OR gates and deductive logic, i.e. repeatedly asking 'what are the reasons for this event?' The basic events of the fault tree in this case refer to the component failures and human errors in the circular/elliptical shapes at the bottom of the diagram.

The AND/OR gates describe the fault logic between the events, i.e. the logic gate underneath the intermediate event 'Levees breached' is an 'OR' gate. The inputs to this gate are 'I-wall collapse', 'Overtopping' and 'Infrastructure breaches'. As these events are connected using OR logic this means that if any of these intermediate events occur, then they will cause the output event to occur i.e. 'Levees breached'. If the type of gate used was instead an AND gate, then this would indicate a level of redundancy in the system in that all three basic events/component failures would have to occur before the output event would occur. For both AND gates and OR gates, the minimum number of inputs required to make these gates valid is two.

A fault tree analysis can be used to define the undesired event to study, and obtain an understanding of the system. It can also provide a useful graphical representation of a hierarchical analysis of failure modes, as it provides a mental map that can help to understand the logic of the failure concerned.

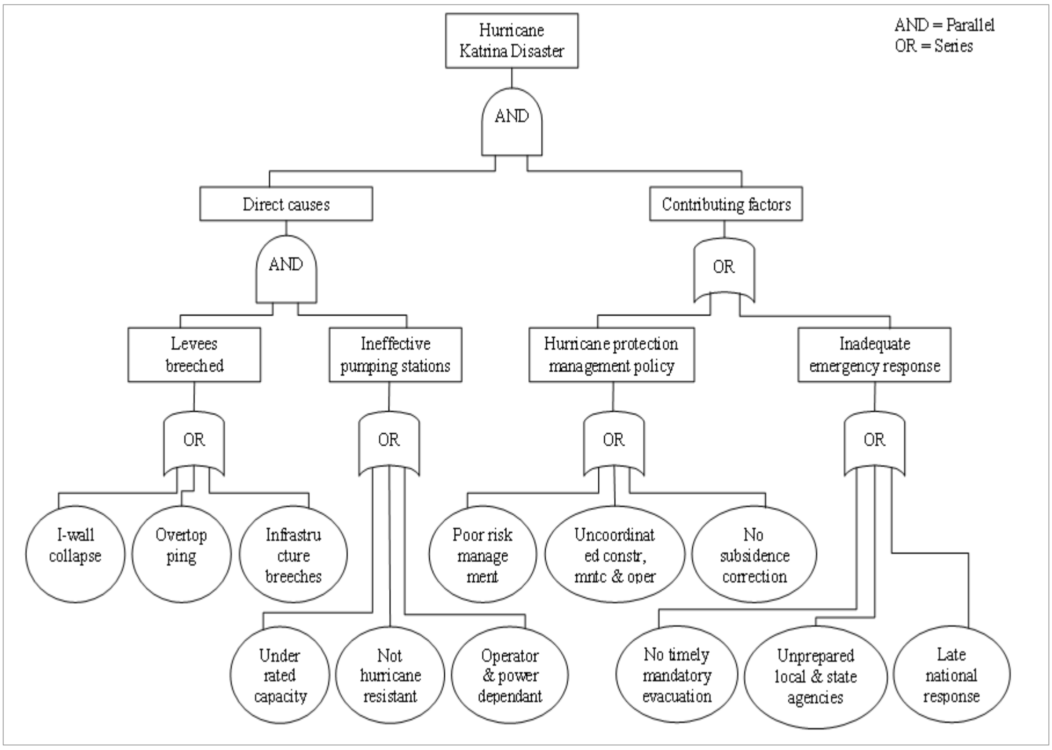

Figure (2) Fault Tree Analysis (FTA) of the Hurricane Katrina Disaster

Therefore, from the FTA we can obtain information on the degree of interdependence in the form of OR and AND gates, which are translated in series and parallel structures respectively and are described further in Section 6 through the RBD model. Also, from the FTA we can extract the different failure modes and their root causes in the form of basic events (the bottom circles in the FTA in Figure 2) and subsequently analyse their criticality as will be shown later in Section 7 using the FMECA model. Finally, as a mental model, it provides valuable information to structure the hierarchical AHP model for multiple criteria prioritisation in Section 8.

6. RELIABILITY BLOCK DIAGRAM (RBD)

A Reliability Block Diagram (RBD) is constructed to assess and improve the overall system reliability, as shown in Figure (3)**.**

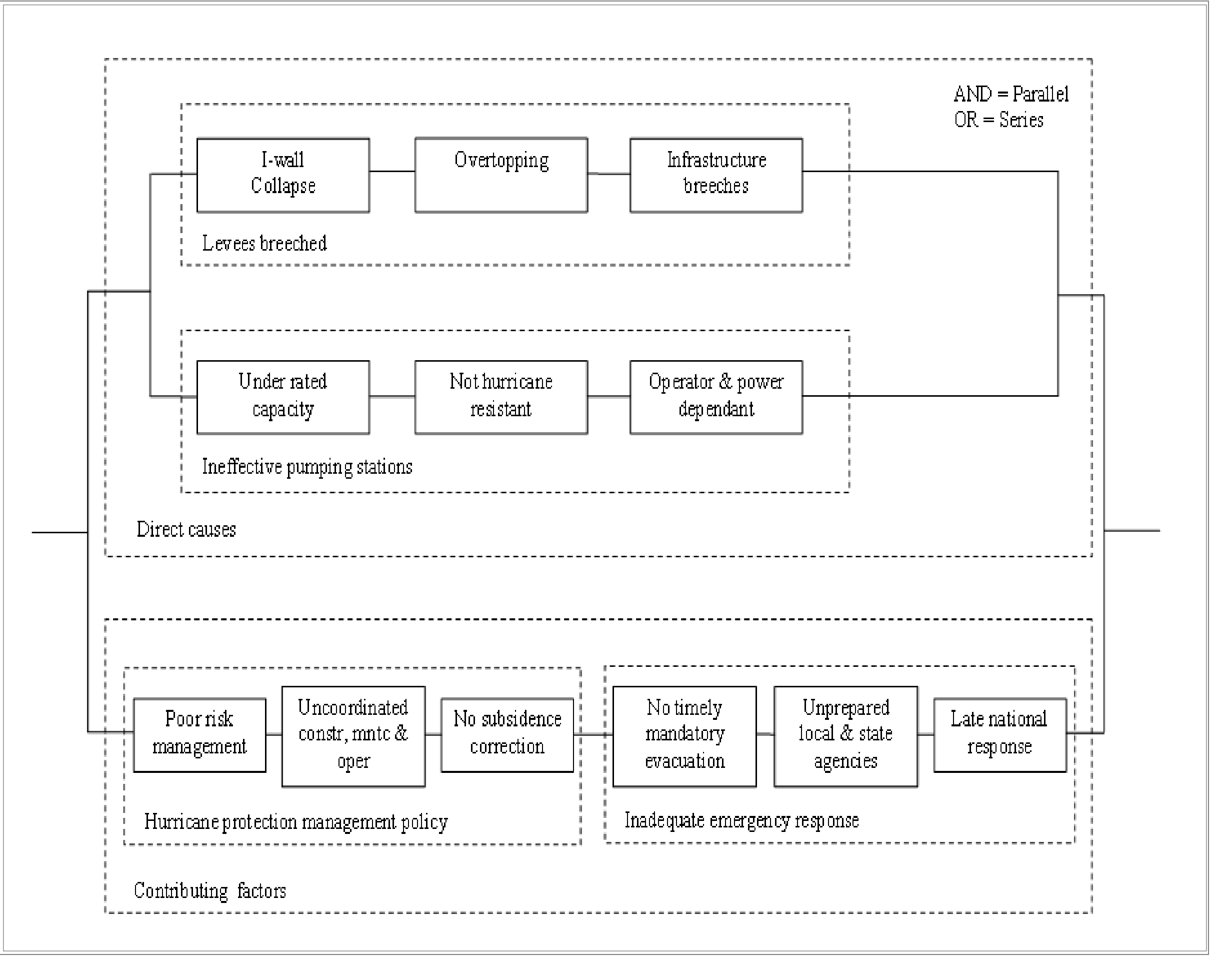

Figure (3) RBD (Reliability Block Diagram) of the Hurricane Katrina Disaster

The Reliability Block Diagram gives additional value to the analysis, as it provides the decision maker with a better understanding of the overall reliability of the model by highlighting vulnerable aspects of the model, where series structures exist, and relatively safe areas where there is either redundancy or parallel structures. Moreover, given reliability values of different boxes (components), one can calculate the whole system's reliability. So, in order to maximise system reliability and minimise system failure rate, then the number of series dependencies (components in series) should be kept to a minimum.

An RBD can usually be constructed on the basis of information provided within an FS (Functional Specification) document, Schematic Drawing or a Piping and Instrumentation Drawing. RBD's can be constructed using a two-state assumption, i.e. either fully operational (up) or totally failed (down), which renders subsequent analysis much easier than it otherwise would be if a third state existed, i.e. partially failed (e.g. reduced output from pumping station). Also this two-state assumption, which is conservative, makes reliability evaluations desirably cautious when safety assessments are involved

Reliability Block Diagrams can be used to symbolise the way in which the system functions as required and is determined by the reliability dependencies. It can also be used to perform quantitative analysis. In our case we also use it for understanding that the '*Direct Causes*' are modelled in a relatively safer parallel structure when compared to the '*Contributing Factors*' which are modelled in series structure which is more vulnerable (Aven, 2011). Such information will be used in assessing the priorities using the AHP model in Section 8.

7. FAILURE MODES, EFFECTS AND CRITICALITY ANALYSIS

Taking the direct causes only for the Hurricane Katrina disaster, it is possible using a basic FMECA (Failure Modes, Effects and Criticality Analysis) template, as shown in Table V, to document for each component mode of failure its effects (symptoms), cause of failure and how the failure can be eliminated or reduced.

For example, the Levee: I-wall Collapse component mode of failure in the FMECA template (Table V, item nr 1) would be populated as follows:

- **Component and Mode of failure**= Levee: I-wall collapse.
- **Effect i.e. symptoms** = Immediate flooding of protected areas.
- **Cause of failure** = Low safety margin used based on meteorological conditions for area, i.e. maximum category 3 barometric pressure and wind speed assumed (inherent effects of reduction from category 4/ 5 to 3 not factored in).
- **How can the failure be eliminated or reduced** = 1. Strengthen/replace I-walls and 2. Segregate areas by use of internal levees to contain breaches.

Next, by constructing word models for probability of occurrence, severity and difficulty of detection (Table II to IV) and applying these to the failure mode effect and criticality analysis (FMECA) template, it is possible to rank each component mode of failure in terms of each of these and to arrive at an overall Risk Priority Number (RPN) which can then be used to focus attention on the highest risk items. The information in Table (V) and its associated numerical probabilities were produced based on the authors' understanding from the related literature published about the Hurricane Katrina disaster as outlined above, using the word models in Tables II to IV.RPN numbers have no units and the objective of FMECA is to reduce the RPN, which can be calculated as follows:

- **RPN = Probability of occurrence of failure (O) x Severity (S) x Difficulty of Detection (D)**
- Remaining with line item nr 1 example, the rankings would be populated and RPN calculated as follows:
- **Probability of occurrence of failure (O)** = 3 i.e. Possible in time interval 10 – 20 years
- **Severity (S)** = 5 i.e. Loss of life, major property and economy damage
- **Difficulty of detection (D)** = 3 i.e. Moderate
- **RPN** = 3 x 5 x 3 = 45

A FMECA can be used to achieve the following:

- It is a straight forward step-by-step technique almost universally accepted as a method for systematically determining the ways in which failure can occur and also the effects (from minor to catastrophic) that each such failure can have on overall functionality
- The objective of FMECA is to anticipate failures and prevent them from occurring
- A good FMECA will: identify known and potential failure modes, identify cause and effect of each failure mode and provide for problem follow-up and corrective action, and prioritises the identified failure modes according to the RPN

Bradley and Guerrero (2011) have acknowledged the wide use of FMECA in both product design and industry. However, they have identified two prominent criticisms of its traditional application viz. that according to measurement theory RPN is not a valid measure for ranking failure modes, and that it does not weight the three decision criteria used in FMECA. They have proposed a new ranking method that can overcome this criticism. Here, however, we use traditional FMECA and then use AHP to deal with the ranking issues.

Table (II) RPN Word Model for FMECA of Direct Causes of Hurricane Katrina in terms of Probability of occurrence of failure (O)

Keyword	Time interval	Score
Very unlikely	>50 years	1
Unlikely	20 – 50 years	2
Possible	10 – 20 years	3
Probable	5 – 10 years	4
Frequent	<5 years	5

Table (III) RPN Word Model for FMECA of Direct Causes of Hurricane Katrina in terms of Severity (S)

Keyword	Score
Repair cost only	1
Minor property damage	2
Significant property and minor economy damage	3
Major property and significant economy damage	4
Loss of life, major property and economy damage	5

Table (IV) RPN Word Model for FMECA of Direct Causes of Hurricane Katrina in terms of Difficulty of detection (D)

Keyword	Score
Almost certain	1
High	2
Moderate	3
Low	4
Absolute uncertainty	5

Table (V) FMECA of Direct Causes of Hurricane Katrina

Item Nr.	Component and Mode of failure	Effect i.e. symptoms	Cause of failure	O	S	D	RPN	How can the failure be eliminated or reduced?
1	Levee: I-wall collapse	Immediate flooding of protected areas	Low safety margin used based on meteorological conditions for area i.e. maximum category 3 barometric pressure and wind speed assumed (inherent effects of reduction from category 4/5 to 3 not factored in)	3	5	3	45	1. Strengthen/ replace I-walls 2. Segregate areas by use of internal levees to contain breaches
2	Levee: Overtopping	Initial slow flooding of protected areas, followed by fast flooding on erosion and destruction of foundations	Soft soils beneath and adjacent to levees unprotected	3	4	4	48	1. Harden soils beneath/ adjacent to levees by mixing in/ replacing with aggregate 2. Protect soils adjacent to levees with concrete
3	Levee: Overtopping	Fast flooding of protected areas	Incorrect design elevations (1 to 2 feet) due to use of wrong datum	3	5	2	30	Raise levees to correct elevation
4	Levee: Infrastructure Breaches	Initial slow flooding of protected areas, followed by fast flooding on further erosion of breach	Many penetrations through levees for roads, railroads and utilities	4	4	2	32	Eliminate/ redesign levee penetrations
5	Pumping Stations: Underrated capacity	Floodwaters in protected areas continue to rise	Underrated i.e. only suitable for storm water runoff and routine seepage water from interior drainage system	3	4	4	48	Increase pumping capacity to cope with storm surges from surrounding bodies of water
6	Pumping Stations: Location	Floodwaters remain in protected areas	Stations not located in areas worst hit by floods	3	4	3	36	Build pumping stations in areas likely to flood
7	Pumping Stations: Piping design	Floodwater recirculation back to body of water where it came from	Discharges hard piped back into canals and waterways	4	4	2	32	Re-route discharges away from city and bodies of water so that recirculation cannot occur
8	Pumping Stations: Backflow	Water back flowed to city through inoperable pumps/ discharge pipes	No automatic backflow preventers in place	3	4	2	24	Install automatic backflow preventers
9	Pumping Stations: Building design	Pumping stations became inoperable	Not designed to withstand hurricane forces and hence damaged by hurricane	3	3	4	36	Reinforce/ rebuild so as to withstand hurricane forces
10	Pumping Stations: Operation	Pumping stations became inoperable	Dependant on operators who were evacuated and no automatic control	3	3	3	27	Automate pumping stations so that they can operate without operators present
11	Pumping Stations: Power	Pumping stations became inoperable	Dependant on electricity which was knocked out early on and no backup generation	4	3	2	24	Install redundancy in power supply lines and onsite backup generation

(O) - Probability of occurrence of failure, (S) - Severity, (D) - Difficulty of detection, (RPN) - Risk Number

The item numbers in Table (V) of the FMECA correspond to the items in the FTA in Figure (2) as shown below in Figure (4) below.

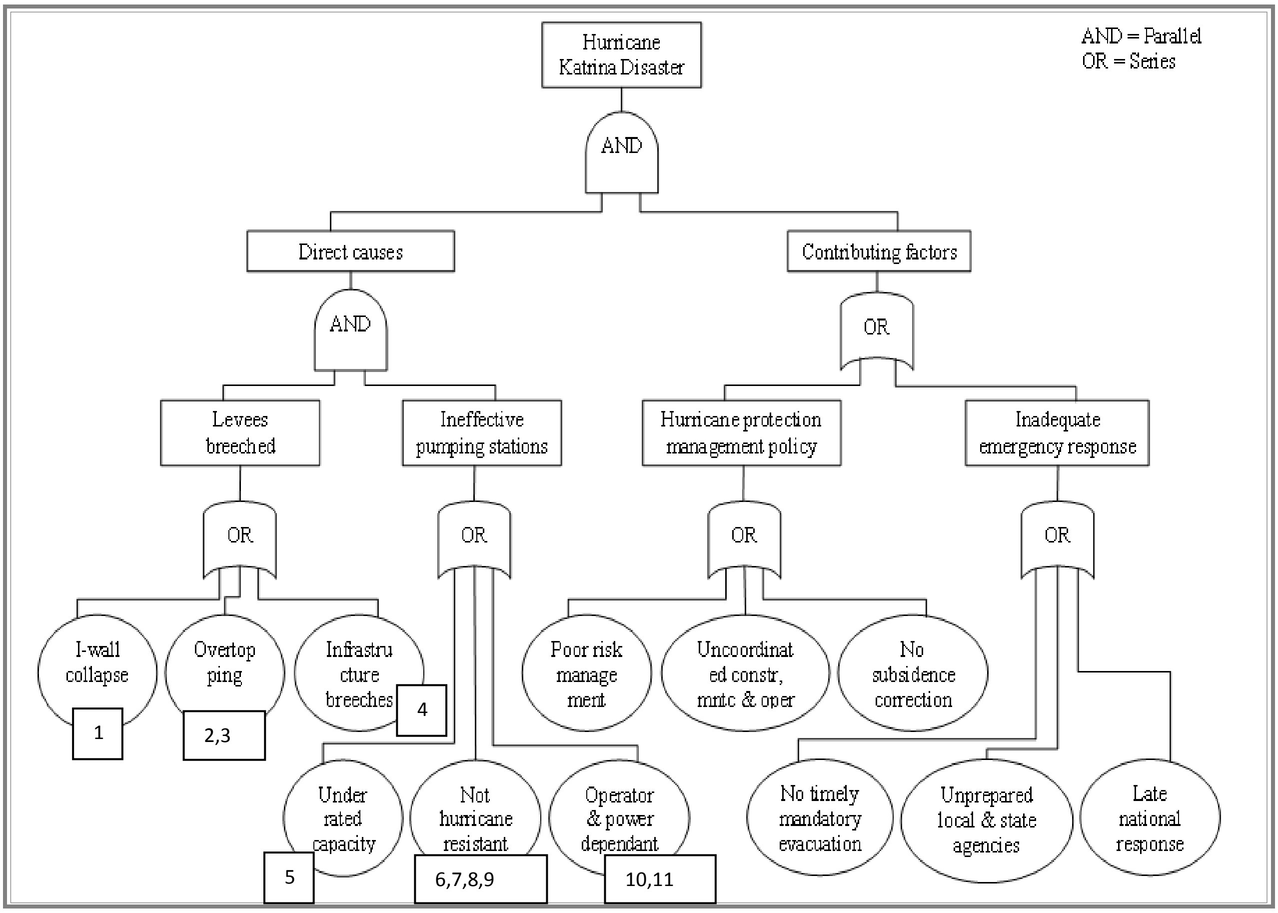

Figure (4) Fault Tree Analysis (FTA) of the Hurricane Katrina Disaster with item numbers shown from Table (V)

8. ANALYTIC HIERACHY PROCESS MODELLING

The Analytic Hierarchy Process (AHP) is a multi-criteria decision making (MCDM) method. The objective of AHP is to act as a mental model and for prioritisation. Mental models such as AHP, and FTA, help the decision makers to understand the environment (Porac and Thomas, 1990). Prioritisation is then useful for either a selection decision – choose the highest priority alternative, or as a portfolio resource allocation decision – allocate resources according to the percentage of weights allocated to different alternatives. The AHP helps the decision-maker facing a complex problem with multiple conflicting and subjective criteria. For a review reporting the applications of AHP, please consult Forman and Gass (2001), whereas for a review of methodological developments of AHP the reader can consult Ishizaka and Labib (2011). This approach has been originated by Saaty (1997, 1980, and 1994) and requires the decision maker(s) to provide judgements about the relative importance of each criterion and then specify a preference on each criterion for each decision alternative.

The FTA model shown in Figure (2) is used as the hierarchical model in AHP, where the higher levels are criteria and sub-criteria, and the basic events (root causes) are considered as the alternatives. This paper then translates the diagram shown in Figure (2) into an AHP hierarchy as shown in Figure (5), where the second and third levels are criteria and sub-criteria, and the third level identifies the different alternatives (basic events).

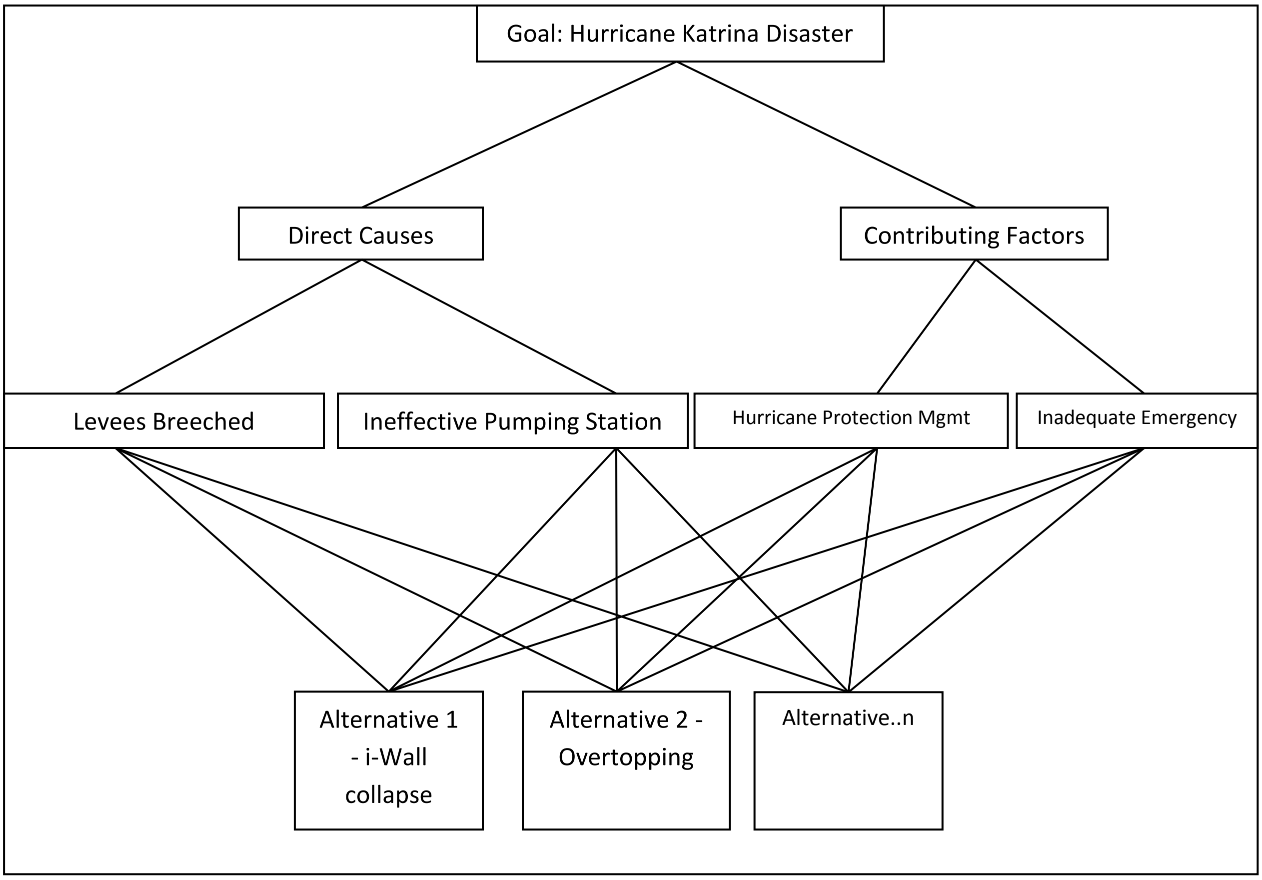

Figure (5): A Hierarchical Model Based on AHP

Using the software package Expert Choice, pair-wise comparison is then performed on each level with respect to the level above. The pair-wise judgement is informed by the FTA model in Figure (2). For example, when comparing '*Direct Causes*' to '*Contributing Factors*' more relative weight is given to '*Contributing Factors*' than to '*Direct Causes*'. The rationale behind this is the interdependence of the events below those two factors. Under '*Direct Causes*' there is an AND gate, which implies that there are two factors that have *simultaneously* affected the direct causes namely; '*Levees Breached*' AND '*Ineffective Pumping Stations*' and this implies an element of redundancy. Whereas under '*Contributing Factors*' there is an OR gate, which implies that either '*Hurricane Protection Management Policy*' OR '*Inadequate Emergency Response*' can have a direct effect on the '*Contributing Factors*'. This is also clearly demonstrated in the RBD model in Figure (3) where the '*Direct Causes*' are modelled in a relatively safer parallel structure as compared to the '*Contributing Factors*' which are modelled in series structure which is more vulnerable (Aven, 2011).

The pair-wise judgement is also informed by the FMECA model in Table (V). However FMECA is only applicable for failure modes and hence RPN values are only provided for items under '*Direct Causes*'. Items under '*Contributing Factors*' are subjectively assessed. The risk priority number (RPN) in Table (V) provides useful information about the rankings of different risks (failure modes) associated with the Hurricane Katrina disaster.

We know from the FTA in Figure (2) that under '*Levees Breached*', the three items of '*I-Wall Collapse*', '*Levee Overtopping*', and '*Infrastructure Breaches*' are the most relevant and hence take the highest weights of the value of 9 (extreme) compared to the rest of the items. We also know from the RPN values in Table (V) combined with information in Figure 4 (which contains FTA with failure mode numbers from Table V at the bottom left side of the figure) that '*I-Wall Collapse*' (45 RPN value) is slightly higher than '*Levee Overtopping*' (combined average of 39 i.e. half way between 30 and 48) which is in turn slightly higher than '*Infrastructure Breaches'* (32 RPN value). This sort of logic for elicitation for the prioritisation of alternatives is shown in Figure (6).

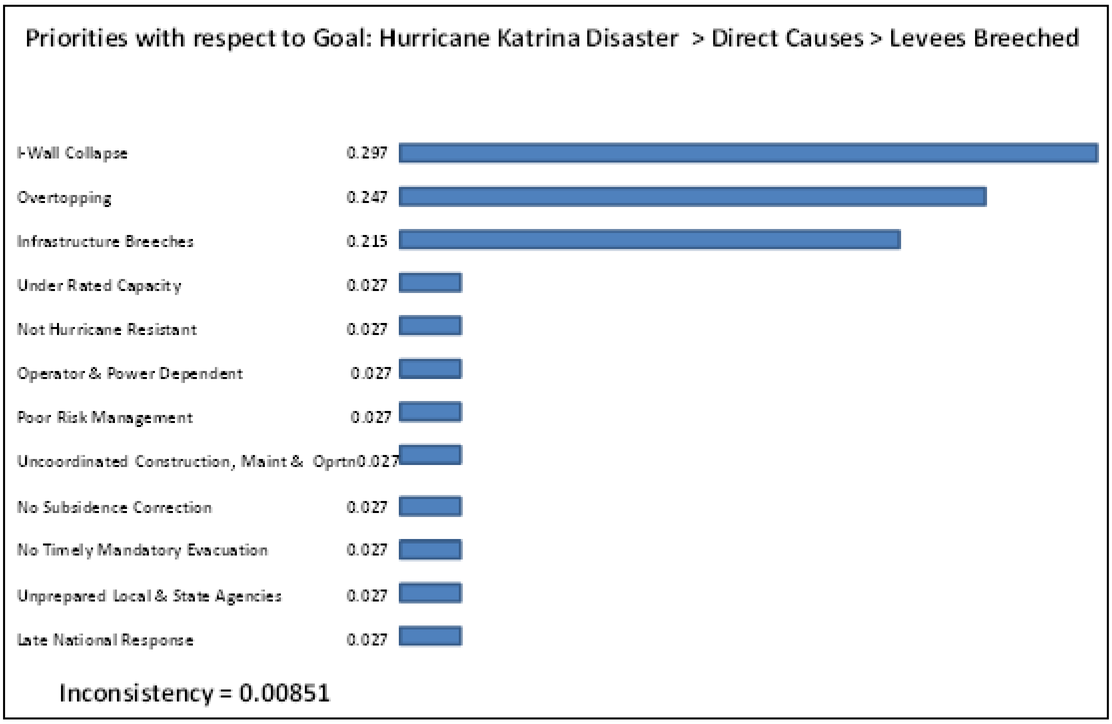

Figure (6): Priorities of Alternatives under '*Levees Breached*'

The same comparison is then carried out across the rest of the hierarchy. Once the pair-wise comparisons are completed, the calculations of the overall basic events (alternatives) ranking is obtained as shown in Figure (7).

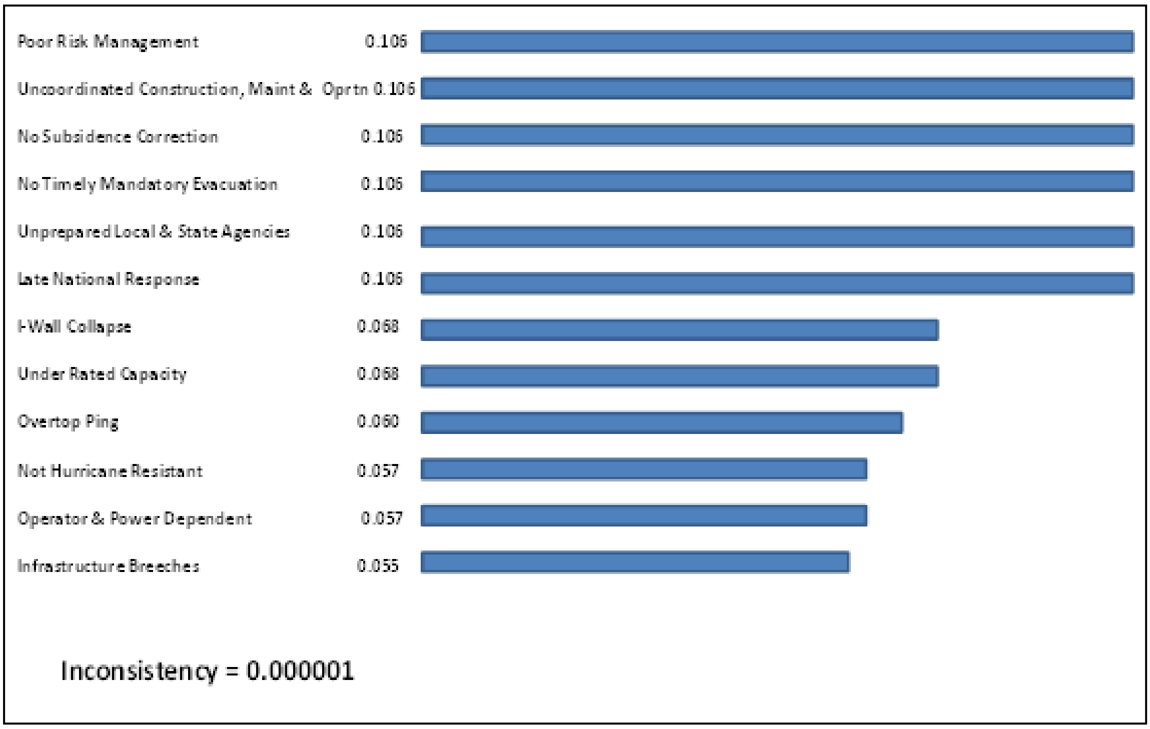

Figure (7): Overall priorities of alternatives (basic events)

There are three outputs that can be produced from the AHP model as shown below:

1. An overall ranking as shown in Figure (7) where the summation of rankings is equal to unity. This helps in case one needs to allocate resources among alternative basic events. It also helps in understanding how each basic event is compared to the other.

2. A measure of Overall Inconsistency of the decision maker's preferences which is a useful feedback for validation of consistency, as explained before. Overall consistency less than 10% is normally acceptable as a measure of consistent preferences. Saaty (1980) has developed a random generated matrix for each matrix dimension which is called consistency index (CI). Essentially consistency is measured by providing a degree of closeness to a random generated matrix of judgments in the form of consistency ratio (CR). So the further away from randomness the more consistent we are.

3. A facility to perform sensitivity analysis (what-if analysis) which provides information about the causal relationships among the different factors. This capability can help us to explain and predict the different relationships among criteria and alternatives. This aspect has not been demonstrated in the current work due to size limitation.

It is worth noting here that pair-wise comparisons between failure mechanisms could have been done by comparing limit state functions of strength and loading variables, instead of subjective scoring on a scale of 1 to 9. However, it is argued that the ability to handle subjectivity is the strength of the AHP method. Moreover AHP offers both sensitivity analysis and feedback on consistency. This sensitivity analysis can help to predict the importance of criteria in changing environments that will subsequently affect the importance of different alternatives.

9. DISCUSSION AND LESSONS LEARNED

It has been argued by some critics that such an analysis cannot be realistically calculated and that results are irrelevant when there is a high degree of subjectivity. It should be emphasised here that in this paper the incorporation of FTA and RBD methods are intended for a *risk-informed* rather than a *risk-based* decision making as outlined by Apostolakis (2004). Hence the approach proposed here is intended to address the nature of the risk rather than attempting to quantify the risk per se.

Apostolakis (2004) provides a balanced approach with respect to benefits and limitations of such techniques and argues that these tools are not perfect but represents a considerable advancement in rational decision making. Our approach is in line with the three questions posed by Kaplan and Garrick (1981): 1) what can go wrong? 2) How likely is this? And 3) what are the consequences? So our approach in using reliability analysis is stronger on relativities (i.e. relative comparisons and trends) but weak on absolutes. Nevertheless it is believed that a candle in the dark is better than no light at all.

Using the overall hierarchical structure of Figures 2, 4 and 5 it is possible to see that broadly speaking there are strategic measures that need to be undertaken with the focus on addressing both the direct causes, in terms of design of levees and pumping stations, and the contributing factors, in terms of hurricane protection management policy and a more adequate emergency response.

From the main recommendations of the published investigation reports cited at the beginning of Section 3 in this paper, the following operational and high level design improvements/lessons learned are identified for action, so as to eliminate or reduce the possibility of failure of the hurricane protection system in the future:

1. Assign single entity responsibility for managing critical hurricane and flood protection systems, ensuring:
    i. The entity is organised and operated to enable, not inhibit, a focus on public safety, health and welfare.
    ii. Public safety, health and welfare are the top priorities.
2. Establish a mechanism for a nationwide levee safety program, similar to that in place for dams.
3. Quantify and periodically update the assessment of risk.
4. Determine the level of acceptable risk in communities through quality interactive public risk communication programs, and manage risk accordingly.
5. Establish continuous engineering evaluation of design criteria appropriateness, always considering the impact of individual components on the overall system.
6. Correct hurricane and flood protection system physical deficiencies by establishing mechanisms to incorporate changing information.
7. Implement more effective mechanisms to ensure co-ordination and co-operation between designers, maintainers and operators, e.g. apply concurrent engineering techniques.
8. Engage independent experts in high level review of hurricane and flood protection systems.

At a more detailed level, the global priorities of alternatives shown in Figure (7) identifies the top six causal factors, which are: Poor Risk Management (PRM), Uncoordinated Construction, Maintenance and Operation (UCM&O), No Subsidence Correction (NSC), No Timely Mandatory Evacuation (NTME), Unprepared Local and State Agencies (UL&SA),and Late National Response (LNR).

Using the notion of the House of Quality (Vanegas and Labib, 2001) where the 'Whats' are correlated to the 'Hows', Table VI shows the relationship between most important alternative causal factors as identified above (the 'Whats') and the suggested actions from the main recommendations of the published investigation reports (the 'Hows').

Table VI: The relationship between the 'Whats' and 'Hows' using the House of Quality notation.

		Columns represent 'Hows', i.e. suggested actions							
		1) Assign single entity.	2) Nationwide levee safety	3) Quantify risk assessme	4) Level of acceptable risk	5)Engineering evaluation of design	6) Hurricane & flood protection	7) Co-ordination and co-	8) Engage independent experts.
Rows represent 'Whats' i.e. requirements	PRM	M	M	H	H	M	M	H	M
	UCM&O	H	H	M	M	H	H	H	M
	NSC	M	H	M	M	H	H	M	M
	NTME	H	M	H	H	M	M	M	M
	UL&SA	H	M	M	M	M	M	M	M
	LNR	H	M	H	H	M	M	M	M

M: Medium impact, H: High impact

10. CONCLUDING REMARKS

The main contribution of this analysis of the causes of the Katrina disaster is that it shows that the proposed methodology can produce better information for policy makers. This is achieved through the utilisation of selective operational research and reliability analysis related techniques in an integrated approach. Such methodology supports modelling of the factors that lead to a disaster and then provides a facility for taking rational decisions. So this prompts the question: What is new in the proposed theory? Is it novel relationships? Or is it better decisions? It is probably both of these, but with emphasis on mental modelling, as it is believed that formulating a problem normally solves 80% of it. This is in line with the argument posed by Einstein and Infeld (1938) "*The formulation of a problem is often more essential than its solution, which may be merely a matter of mathematical or experimental skill*". It is acknowledged that every technique has its own limitation, and hence the originality of the approach lies in utilising a hybrid of techniques that tend to cancel the limitations inherent in any one of the used techniques when used on its own.

The novelty of this work is three-fold; firstly through the demonstration of the interactive and integrative nature of the chosen hybrid tools. Secondly, such integration is presented in a novel way where each tool is first explained in the form of related figures and tables, then categories of different types of data used by each tool is outlined, followed by identification of the specific outputs from each tool. Finally, the

relationship between most important alternative causal factors for the disaster are mapped against suggested decisions for resource allocation utilising the concept of the house of quality notation to map the 'whats' against the 'hows'.

This work has indicated how some current ranking and sensitivity analysis methods might be applied to the example of the Katrina disaster. It is believed that such an approach can significantly improve the objectivity of risk management decision making.

In terms of reliability analysis, FTA has been employed to show how some of the direct causes and contributing factors of the disaster interacted with each other. It provided information on the failure modes that have been used in the FMECA model. Also, it provided information on interdependence, in the form of OR and AND gates, which was useful for the RBD model, and finally it provided a hierarchical structure which improved our understanding of the problem, and which formed the basis for the developed AHP model. RBD representation has then been used to demonstrate how overall system reliability can be calculated and improved. RBD provided information, in terms of series and parallel structures, which has been used to inform our elicitation of judgements in the AHP model. The FMECA model has then been used to determine Risk Priority Number which has been used to rank the risk of different failure modes. Subsequently, this has informed our judgements in the pair-wise comparison within the AHP model.

In terms of MCDM, we have utilised an AHP analysis which was able to provide prioritisation, sensitivity analysis and feedback on consistency of the different criteria and alternative contributing factors. Finally, some of the high level design improvements/lessons learned, which should be acted upon so as to avoid a repeat disaster, have been discussed.

A generic approach has been offered that can be used for risk and safety analysis in order to learning from disasters. This approach can also be applied to previous research studies of process and nuclear disasters such as those of Pate-Cornell (1993), and Vaurio (1984).

It can be argued that the Fault Tree in Figure 2 is a more general logic tree rather than a strict classical Fault Tree as traditionally used to analyse failures at equipment level. The reason is that the "Hurricane Katrina Disaster" is depicted as a top event (which is not strictly traditional in the usual fault tree sense, i.e. is not a well-defined subset of a sample space, to which a binary indicator variable can be attached – 1 for occurrence, 0 for non-occurrence). The advantage of using the proposed approach is that it offers richness to the model, so that both subjective judgement and objective evaluation measures are taken into account in a mental model.

More empirical research is needed on how (or whether) ranking and sensitivity analysis, as proposed in this paper, will improve risk management decisions more than other approaches. Also more research is needed in the field of expert and intelligent systems in terms of investigation of the degree of compatibility of tools when considering hybrid modelling approaches. Another related area of future research is the assessment of interdependencies among failure modes and the impact of simultaneous hazards. Modelling of combination of hazards is now an area that is attracting much research in the wake of Fukushima nuclear power disaster in Japan (Labib 2015) and the interest in such phenomena is expected to grow. Also future research is needed in the fields of coping with beyond design scenarios (Labib, and Harris 2015), and the impact of

human factors in dealing with disasters. An interesting variation to this theme can relate to research into the impact of cultures on perception of risk and response to disasters as highlighted by Kulatunga *et al* (2006), and Kulatunga (2010). Capacity building for post-disaster infrastructure as highlighted by Haigh and Amaratunga (2009) is an area that needs more empirical research. Finally, the impact of resource shortage and su[ply disruptions during pot-disaster reconstruction as highlighted by Chang et al (2010) is an area that also needs more empirical research.

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