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Tenerife Accident Analysis: a comparison of Fault Tree Analysis, Failure Mode and Effects Analysis and Causal Analysis based on System Theory

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Highlights

- CAST identified more accident causes than others.
- FMEA found more extensive causes than FTA.
- All methods found that human error was the biggest factor in accident.

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Abstract

Air transport is considered to be the safest means of transport. However, if an accident occurs, it often ends in catastrophe. Thus, significant efforts have been paid to sustain successful operations in aviation. Several studies have been carried out to understand the underlying reasons for accidents. This study used Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA) and Causal Analysis based on Systems Theory (CAST) methods to analyse Tenerife aircraft accident and to compare the findings of different methods. The findings showed that while all three methods provided some overlapping findings, the CAST method led to the identification of all causes that were identified by other methods. Considering the nature of the causal factors, FMEA provided more causal factors that are related to organisation and technology than FTA. This study indicates that CAST has a significant value to identify all causes that can be identified by the use of traditional methods.

1. INTRODUCTION

Air transport is an essential element for the development of modern societies, and safety is one of its key features. Several organisations such as the International Civil Aviation Organization (ICAO), the Federal Aviation Administration (FAA), the European Aviation Safety Agency (EASA) or EUROCONTROL have a primary goal to make aviation the safest transportation mode [1]. In fact, air transport is considered to be the safest means of transport. However, if an accident occurs, it is likely to lead to catastrophe. Approximately 10 fatal accidents occurred per year, leading to 315 deaths between 2012 and 2016 [2].

Following each accident, several organisations and bodies are involved in the accident investigation, and they provide valuable reports on aviation accidents. Additionally, the International Air Transport Association (IATA) summarises the airline industry's safety performance each year [2]. The UK Civil Aviation Authority (CAA) outlines fatal accidents and fatalities worldwide [3]. All these documents contribute to sharing lessons learnt from specific accidents and encourages the airline industry to improve safety.

The investigation of aircraft accidents is challenging due to the complex features of air transport [4,5]. Generally, such investigations require the involvement of a multidisciplinary team with expertise from several related fields. Sujata, Madan, et al. [5] states that "Despite the devastating nature of the wreckage, the investigators need to painstakingly gather bits and pieces of information from all possible sources, analyze them systematically, and stitch them together for arriving at the probable sequence of events that led to the accident". At this point, methods used by the investigation team have a significant influence on

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the analysis. Different accident analysis methods were built on different accident models. The accident models facilitate the identification of causal factors. It is, therefore, the selection of the methods that were built on the accident model would have direct impact on the depth of the analysis.

Domino Model was developed by reviewing health and safety-related accidents. The model identifies accidents with a separate chain of events that are occurring in a specific temporal order. According to [6] the Domino theory belongs to a class of sequential accident models that are ground to most of the accident analysis methods used today, including Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), and Cause-Effect Analysis.

With the changes in the technology and industries, the domino model and so the methods built on them were criticized for being inadequate to investigate accidents in complex systems [7-12]. Thus, different accident models were proposed to understand accidents such as the Swiss Cheese Model [13]. Later on, models that are built on systems theory were introduced such as Accimap [9], Systems- Theoretic Accident Model and Process (STAMP) [14] and Functional Resonance Accident Model (FRAM) [15]. Consequently, methods like FRAM [16] and Causal Analysis using System Theory (CAST) [17] were developed. FRAM and CAST aimed to address the limitations of the traditional accident investigation methods (e.g. FTA and FMEA) by revealing the complex interactions of the socio-technical systems [18,19]. It was claimed that methods like FMEA, FTA and ETA analyses individual system components with a primary focus on human errors [20-22]. FRAM and CAST, however, provide more detail and accuracy in modelling and analysing complex processes with the consideration of human, technology and organizational factors [23-25].

In aviation, FTA has been used for a variety of purposes, including risk assessment [26], development of safety and security requirements [27], and identification of diagnostics [28]. Similarly, FMEA has different uses in the aviation industry, including the analysis of the failure modes of aircraft fuel system parts [28] and the assessment of aviation safety risk factors [29]. STAMP-based CAST has also been used in aircraft security [30], aircraft ground services [31] and air transportation [32] to improve system safety.

Unlike other accident analyses, this study used three accident investigation methods, namely FTA, FMEA and CAST, rather than an accident investigation model. Thus, it aims to determine the success of which accident investigation method in finding the causes of the accident. In this study, Tenerife aircraft accident was analysed by using FTA, FMEA and CAST methods. This study aims to model the Tenerife accident, reveal the causal factors of the accident and compare the findings from three different accident analysis methods.

2. MATERIAL METHOD

2.1. Tenerife Accident

The terrorist attack that took place at Gran Canaria Airport on March 27, 1977, caused many planes, including the two planes involved in the accident, to be diverted to Los Rodeos airport on the Spain island of Tenerife.

The Los Rodeos airport quickly got stuck as parked aircraft blocked the single taxiway and instead forced the outgoing aircraft into a taxi on the runway. Unfortunately, shortly after that, KLM and Pan Am aircraft were crashed, leading to 583 deaths and 61 survivors (see Figure 1). Tenerife accident remained to be the worst aircraft crash in world aviation history [33,34]. The chronology of the Tenerife accident is shown in Table 1

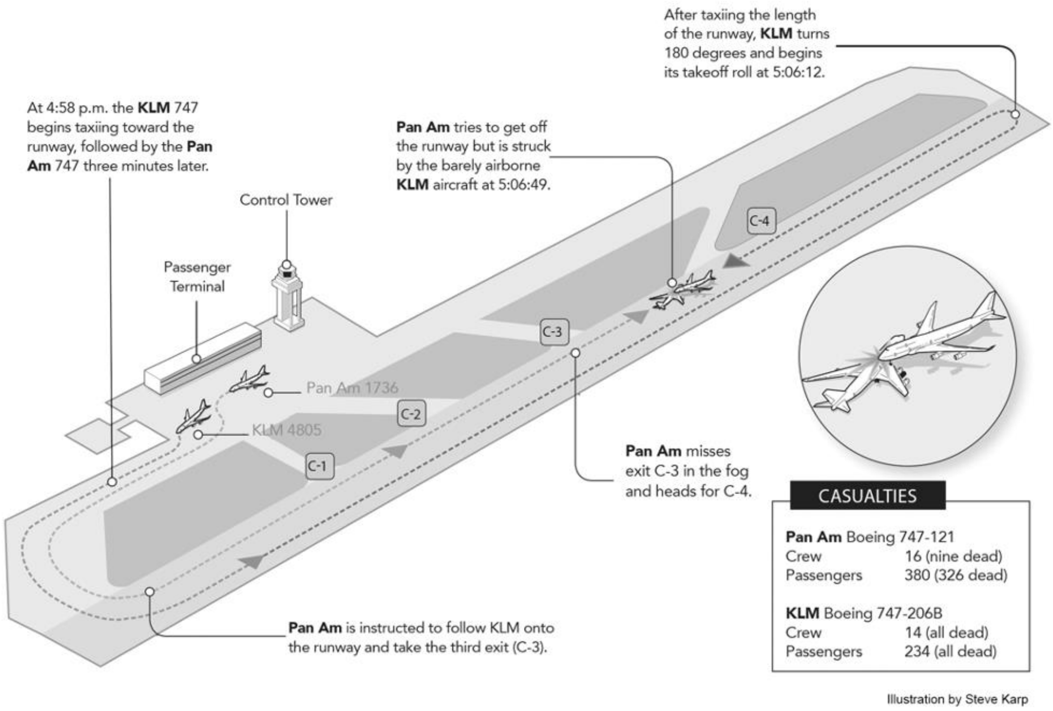

Figure 1. *An illustration of the collision at Los Rodeos airport, obtained from [35]*

Table 1. *Chronology of the Tenerife accident adapted from [3], [36]*

Time	Event
12:30	KLM flight 4805, a Boeing 747, from Amsterdam to the Canary Islands and Pan Am flight 1736, another Boeing 747 bound for Los Angeles and New York to the Canary Islands, were diverted to Los Rodeos airport in Tenerife due to a bomb threat.
13:38	The KLM aircraft landed at Tenerife airport.
14:15	The Pan Am aircraft landed. Pan Am aircraft had to park behind the KLM flight in such a way that it could not depart until the KLM aircraft left.
14:30	Las Palmas airport reopened, Pan Am aircraft was ready to take off for flight as its passengers remained on the aircraft. KLM's passengers had abandoned the aircraft, so there was a delay in their re-boarding and refuelling to shorten the return time to Las Palmas. Meanwhile, the weather conditions started to get worse, and visibility on the runway decreased due to fog.
16:56	The KLM aircraft began taxiing for takeoff and initially headed towards a runway parallel to the take-off runway. This directive was changed shortly after, and KLM was asked to taxi on the take-off runway and eventually make a 180-degree turn and wait for further instructions. Pan Am was asked to follow KLM on the take-off runway and leave the take-off runway via taxiway C3, use the parallel runway for the remainder of the taxi, then pull behind the KLM flight. Pan Am's request to stay away from the take-off runway and remain on the runway until KLM left was denied.
17:06	Despite being instructed to wait, the KLM plane started to move after making a 180 degree turn at the end of the take-off runway and said "we are now taking off". Neither the air traffic controllers nor the Pan Am crew were sure of what this vague statement meant, but Pan Am

	reassured the controllers that it would report once it had moved away from the take-off runway when a message was heard in the KLM cockpit. When the engineer asked the pilot of KLM flight, "Is he not clear then, that Pan Am?" the pilot replied "yes", and there was no further conversation. The collision of the two planes occurred 13 seconds later at 17:06. None of the 234 passengers and 14 crew members of the KLM aircraft survived and died. Of the 380 passengers and 16 crew members on board the Pan Am flight, 70 survived, but later 9 died, resulting in a total of 583 fatalities.

2.1. Study Design

This study analysed the Tenerife accident by using FTA, FMEA and CAST methods. In this study, each method is applied by authors, and, then, the findings were revised by all authors. First, all authors reviewed the official accident reports and the related news and watched several accident simulations videos. Authors arranged two meetings to discuss the accident. Next, three authors individually applied a method that was assigned to them. After that, the authors had several meetings to revise the findings and compare the findings from different methods. The comparison focused on the capability of methods to identify human, organisation, environment and technology-related causal factors. Figure 2 shows the design of this study.

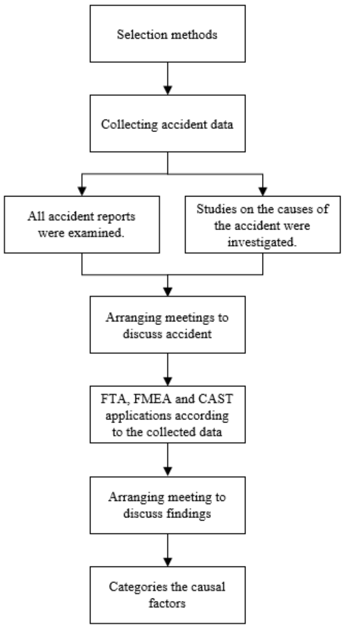

Figure 2. *Study design*

2.3. Fault Tree Analysis

As a quantitative method, the FTA method is widely used in many sectors such as aviation, nuclear engineering, human engineering and safety management [37-40].

FTA is an important method for estimating the reliability of a complex system by identifying the relationships between components or subsystems in a system. With FTA, the frequency or probability of occurrence of dangerous events for the system can be estimated and the root causes of dangerous events in the system can be easily determined. This makes FTA a useful method. [41-43].

FTA is a deductive analysis technique, and it consists of a series of events and logic gates. As seen in Figure 3, FTA formation is done as follows: the unwanted peak event in the error tree is called "Top event", which is indicated by the letter 'T'. The middle event is the parent event that is the cause of the subsystem or component failure event. The basic event is a subsystem or component failure event and the cause of the middle event. FTA has two logic gates: 'AND' is used if all input events of an AND gate are the cause of the event above, and 'OR' is used if at least one of the input events of the OR gate is the cause of the event above [44].

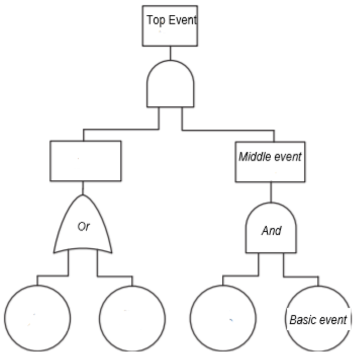

***Figure 3**. A sample FTA model*

In this study, FTA is applied in four steps: (1) top event is identified, (2) possible causes leading to the top event are identified, (3) each cause is determined until the identification of each basic event and (4) basic events are categorised as being related to human, technology, organisation and environment.

2.4. Failure Mode and Effects Analysis

In 1949, FMEA was initially applied on a military project in the United States to assess the effects of potential failures. In the applied study, two aspects were determined to identify and order failure modes: the impact on the success of the task and the safety of those involved [45]. FMEA has been used in manufacturing, aerospace, computer software design, healthcare, and other industries to evaluate system security [46-49].

FMEA is a method that can systematically evaluate processes to identify potential failure modes at each system component, causes of the failures and their potential impacts on the system and to determine the components that require change or improvement. The FMEA application is suitable for the processes having sequential dependent interrelated steps [50].

A thorough FMEA requires the involvement of a team [51]. The FMEA application mainly consists of four steps: planning for the analysis, executing the FMEA, reporting the analysis and updating the FMEA [51].

In this study, the FMEA execution is applied in four steps: (1) accident is modelled, (2) failure modes are identified, (3) the effects and causes of the failure modes are identified, and (4) causes are categorised as being related to human, technology, organisation and environment. This study will not calculate the risk priority numbers as it is out of the scope of the analysis.

2.5. Causal Analysis based on Systems Theory

CAST was developed by [17] to undertake in-depth accident analysis. CAST is built on STAMP. With STAMP, safety is treated as a control problem, and accidents are determined to be as a result of inadequate controls or the violation of safety constraints [17]. CAST has already been used in different contexts to analyse accidents, including pipeline ferry and deep-water blowout accidents [52].

CAST focuses on the identification of controls and controllers to highlight their roles in the accident. CAST does not focus on blaming individuals; instead, it shifts the focus to why the specific accident occurred [53]. The CAST application involves five-parts: (1) assemble basic information (e.g. system and hazards), (2) model safety control structure, (3) analyse each component in loss, (4) identify control structure flaws and (5) provide safety improvement recommendations [17]. CAST initiates the analysis by modelling the control structure as in Figure 4. CAST takes into account the physical, organizational and social components of the entire system and the interactions between them [17, 54].

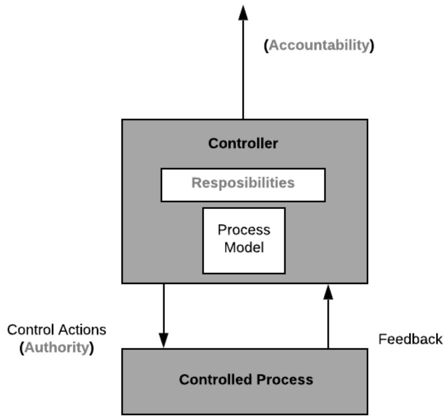

Figure 4. *The basic building block for a safety control structure [17]*

In this study, CAST is applied to identify the causal scenarios, and so this study only followed the first four steps, as mentioned above.

3. RESULT

3.1. FTA Application

FTA identified 22 basic events for the cause of the Tenerife accident, as shown in Figure 5. Adverse weather conditions, inadequate airport conditions, Air Traffic Controllers (ATCs) errors, conditions at the aircraft and pilot errors were main factors leading to the accident. Adverse weather conditions on the day of the accident reduced visibility. Airport was located in a challenging position for flight safety. The fact that the accident occurred on Sunday and the presence of two personnel at the airport posed a problem in itself. The absence of lights in the middle of the runway and the absence of a radar system to show the location of the aircraft on the ground constitute a chain of negligence. There were only two ATCs working at the tower. One of them changed the radio frequency, which resulted in poor communication between ATCs and pilots. Accident reports highlighted that Pan Am aircraft captain request for waiting for the KLM aircraft take-off was not heard at all. While pilots at both aircraft made errors, KLM aircraft captain was also rushed to take-off, and this decision was the last chain of the event for the Tenerife accident.

FTA revealed that stress and poor communication were of great importance in the causes of the accident. With the FTA application, 4 causes were related to organisational factors, 12 to human, 3 to technology and 5 to environmental factors.

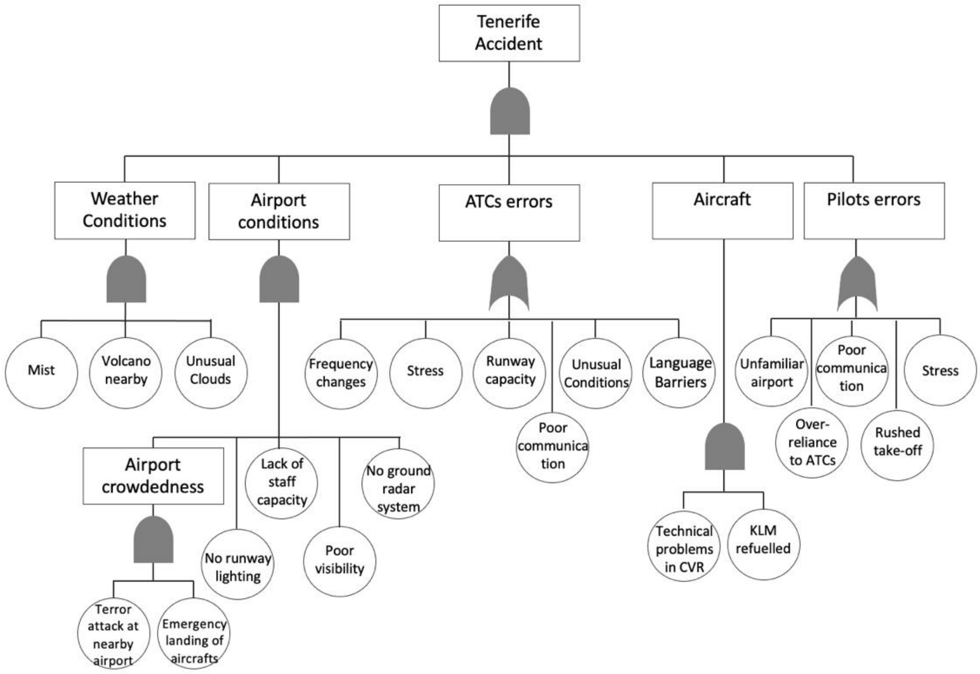

***Figure 5**. Accident analysis with the FTA method*

3.2. FMEA Application

Tenerife accident occurred while KLM aircraft was taking-off and Pan Am aircraft was taxing on the runway. Thus, FMEA was applied by considering the take-off process, which is modelled in Figure 6.

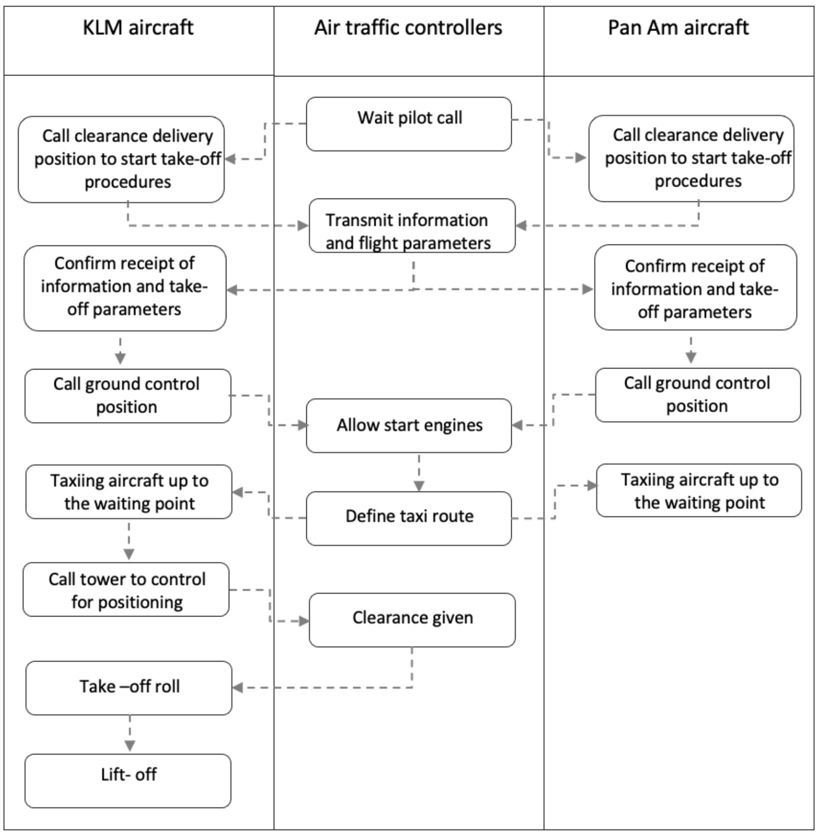

***Figure 6.** Take-off process adapted from [55]*

FMEA application was undertaken by considering each system component as well as key stakeholders (i.e., aircraft crew and air traffic controllers). FMEA investigated each system component. In total, 15 different failure modes and 23 different causes were identified.

***Table 2**. FMEA application findings*

Sub-system	Function	Failure Mode	Effects	Causes
KLM aircraft	Call clearance delivery position to start take-off procedures	Delays on the call	Putting extra pressure on the KLM and Pan Am crew and passengers Delays on the flight	Captain decided to take fuel to fly back to Amsterdam
	Confirm receipt of information and take-off parameters	Delays on receiving the parameters	Putting extra pressure on the KLM and Pan Am crew and passengers Delays on the flight	Coordination problems among the various centres
	Call ground control position	Delays on the call ground control position	Extra pressure on the crew	The airport is not designed to accommodate such aircrafts A third controller is not in present
	Taxiing aircraft up to the waiting point	Wrong taxiing	Confusion to both approach controller and captain KLM missed turning at Taxiway C3	Miscommunication Runway size is small for such a large aircraft
	Take-off roll	Wrong take-off initiated	KLM aircraft started releasing its brake too soon	No light available runway centreline No ground radar system Released its break without clearance Captain rushed to take-off Poor visibility at the runway Poor communication among the crew Poor communication between the captain and the controller A high pitched sequal overlays controller's sound and it is distorted.
	Lift-off	Inadequate lift-off	Aircraft collision	Initiated the take-off too soon
Air traffic controllers	Wait for the pilot call	Delays on the call	Increased stress	KLM captain decided to take fuel to fly back to Amsterdam KLM aircraft blocked the way of Pan Am aircraft
	Transmit information and flight parameters	Delays on transmitting information	Putting extra pressure on the controllers and pilots at two aircrafts	Coordination problems among the various centres
	Allow start engines	Delays on the allowance to start engines	Delays on the flight Putting extra pressure on the pilots and controllers	Delays on the prior steps

	Define the taxi route	The inadequate direction is given	KLM required to make 180 degrees turn at the end of the runway Pan Am missed turning at Taxiway C3	Miscommunication between pilots and controllers No ground radar system A third controller is not in present A lack of personnel No runway number signs
	Clearance given	Confusing clearance is given	KLM released its brake and initiated the take-off before the clearance given	Miscommunication between controllers and KLM pilots Stress on both parts Different frequencies gave the clearances to both aircraft
Pan Am aircraft	Call clearance delivery position to start take-off procedures	Delays on the call	Putting extra pressure on the KLM and Pan Am crew and passengers Delays on the flight	KLM aircraft blocked the way of Pan Am aircraft
	Confirm receipt of information and take-off parameters	Delays on receiving the parameters	Putting extra pressure on the KLM and Pan Am crew and passengers Delays on the flight	Coordination problems among the various centres
	Call ground control position	Delays on the call ground control position	Extra pressure on the crew and passengers	The airport is not designed to accommodate such aircrafts A third controller is not in present A lack of personnel
	Taxiing aircraft up to the waiting point	Wrong taxiing	Pan Am missed turning at Taxiway C3 Aircraft remained in the runway while KLM taking-off	The controller's transmission blocked pan Am's transmission Poor visibility at the runway No runway number signs Miscommunication between Pan Am crew and the controller Heavy Spanish accent of the controller

As in Table 2, communication problems and poor visibility at the runway were identified causes of several failure modes. Additionally, several factors, such as poor airport design for large aircraft, a lack of personnel available at the control tower, and stress were revealed to be the contributory factors of the accident. In the FMEA application, several causes were repeated in different cases. Among 23 causes, 7 were related to organisational, 13 to human, 6 to technology and 1 to environmental factors. Clearly, some causes were identified under two or three categories.

3.3. CAST Application

Two aircraft collided on the runway at Los Rodeos airport, Tenerife. In this accident, three systems-level hazards and safety constraints were identified as:
Hazard 1: Aircraft enters into a wrong area (*Safety constraint 1: Aircraft has to enter the correct area*)
Hazard 2: Aircraft prepares to take off from the wrong taxiway (*Safety constraint 2: Aircraft has to be in the right taxiway on time)*
Hazard 3: Aircraft violate minimum separation standards (*Safety constraint 3: Pilots have to obey the minimum flight standards*)
In this study, the safety control structure is shown in Figure 7. Considering the safety control structure and proximal events (see Table 1), each component was analysed as in Table 5.

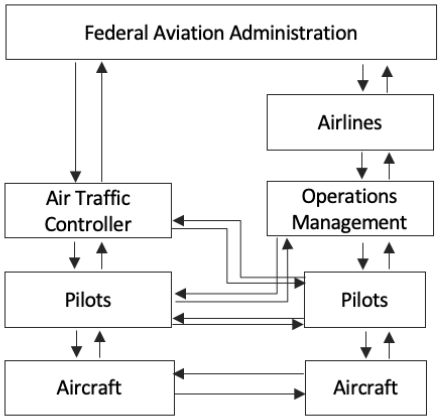

Figure 7. *Safety control structure*

Table 5. *CAST results of Tenerife aircraft crash adapted from [56]*

Upper Management Level Analysis
FAA (Federal Aviation Administration) **(1) Safety Related Responsibilities** Registration of aircraft, certification of aircraft airworthiness (FAR) & operating manuals, issuing airworthiness directives, certification of airline operating procedures, certification of aircrew training, certification of ATC training, certification of maintenance, and checking compliance with regulations **(2) Context** Pressure for airlines/manufacturers to effectively address safety issues in a way that minimizes costs **(3) Unsafe Decisions and Control Actions** Issued AD that emphasized information already in-flight manuals. Added explanation, but insufficient and incorrect. Initial FAR requirements insufficient for safe operation **(4) Process model flaws** Act quickly to fix a known problem. Changes to operating procedures are believed to be sufficient and are handled in the same way as necessary action against previous accidents was addressed and closed. **KLM/Pan Am Airlines** **(5) Safety Related responsibilities** Train aircrew on aircraft operation and emergency procedures, follow FAA regulations and create a safety culture **(6) Context** The safe flight is valued **(7) Unsafe Decisions and Control Actions** Pressure aircrews to minimise delays **(8) Process model flaws**

Relied on FAA certification and inspections to ensure safe operating procedures

Middle Management Level Analysis

Operations Manager:
Safety Related responsibilities

Develop company operating procedures that ensure safety, provide aircrew training on safety, and update operations procedures to meet FAA requirements

Context

Under pressure and all operating procedures must meet or exceed FAA requirements to ensure efficiency

Unsafe control actions
Pressure on pilots to minimise delays, and there were no ATC constraints in the training simulators

Process Model Flaws
Focused on efficiency, poor feedback from aircrews on safety, and assumption that compliance with FAA regulations ensures the safety

Air Traffic Controller:
(1) Safety Related responsibilities

Maintain aircraft separation, inform pilots of weather in area (ATIS) and PIREPs, efficiently prioritise and move aircraft and assist in emergency landings and procedures

(2) Context

Mist at the runway, a single runway in use, pressured to expedite operations, knew KLM and Pan Am executing an emergency landing, unsure of the situation, air traffic control was provided by two controllers (ground and approach), airport facility does not have ground radar, and so the controllers were required to provide aircraft, the airport did not designate the taxiways by numbers, separation under deplorable visibility conditions, and controllers were stressed

(3) Unsafe Decisions and Control Actions

Made a quick decision due to time pressure, ground controller and approach controller used different frequency, poor use of English on the radio

(4) Process model flaws

Believed that KLM could execute the takeoff

Pilots:
(5) Safety Related responsibilities

Maintain safe flight, follow emergency procedures, report status inconsistencies, report safety hazards and challenge other pilots on checklists/decisions

(6) Context

Highly experienced/ confidence, pushed to minimise delays/avoid missed approaches, mist, unsure of the situation, stressed, pilots were unfamiliar with the airport, and KLM aircraft took fuel prior to the accident.

(7) Unsafe Decisions and Control Actions

KLM aircraft captain called ground control for start clearance instead of 1st officer, KLM captain called for clearance before checklist was complete, taxi on the runway under heavy mist, poor communication between air traffic controllers and pilots at both aircraft, KLM captain made a quick decision to take-off, and the KLM pilots dismissed KLM flight engineer's question

(8) Process model flaws

Believed that could execute the rapid take-off, Pan Am aircraft captain expressed the desire to hold short of the runway and wait for the KLM to take-off. However, the tower never received that information, believed that controllers provided the correct instructions, and Pan Am did not receive any information from the ATC regarding the exit 3rd taxiway. In contrast, they informed the caption on the 1st and 2nd ones.

↓↑

Physical Aircraft Safety Controls

Safety Requirements and Constraints Violated:

• Maintainability to navigate, remain within airport operating limitations, inform passengers of emergency state and procedures, execute emergency procedures, and safely egress

Emergency and Safety Equipment (Controls) Partial List:

• Crew emergency procedure training, passenger emergency procedure pre-flight summary, passenger emergency exit procedure card and emergency procedure checklists

Failures and Inadequate Controls:

• Inadequate navigation tools to maintain situational awareness, inadequate information concerning conditions at the runway, inadequate protection against weather condition, inadequate specificity with a warning system, and no emergency brake, and on the KLM CVR, the tone of the controller’s voice was distorted

The CAST method was able to detect 50 different causal scenarios. Among these, 14 causes were related to organisational, 31 to human, 16 technology and 5 environmental factors.

As seen in Figure 8, the implementation of CAST was able to cover the largest number of factors in all categories when the findings of all three methods were analyzed for their ability to identify organizational, technology, environmental and human causal factors. Additionally, CAST led to the identification of all factors that were identified by FTA and FMEA applications.

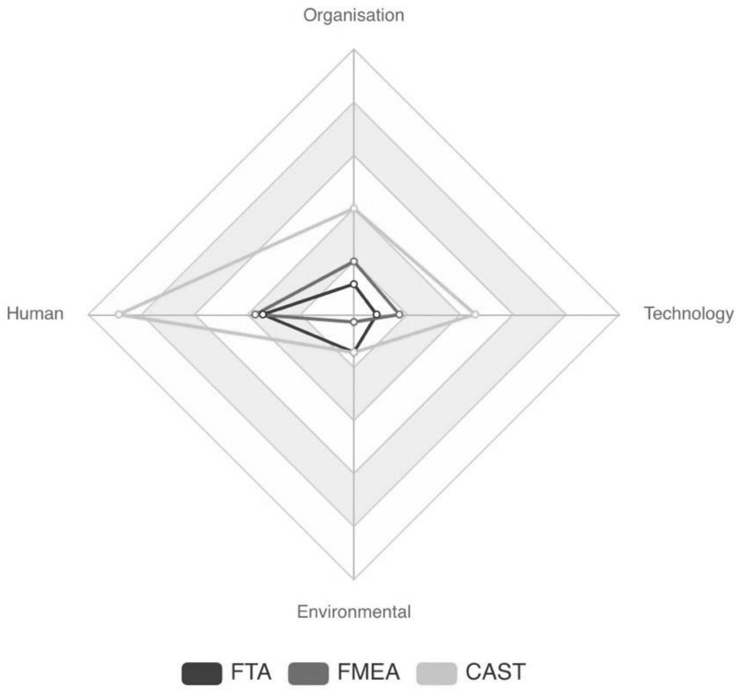

Figure 8. *The radar chart for categorising the causal factors identified from FTA, FMEA and CAST*

4. DISCUSSIONS

In this study, Tenerife aircraft accident was analysed by using FTA, FMEA and CAST. The findings indicate that the CAST application provided the most comprehensive analysis, but yet there were some overlappings on the findings from different methods. For instance, all methods identified a lack of communication as a primary cause for the accident. Indeed, all passengers on the KLM aircraft and 335 passengers on the Pan Am aircraft died as a result of a misinterpretation or misinterpretation of standard terminology used in communication between the pilots and the tower controller [57]. In aviation, the necessity of strong communication between crew and between pilots and air traffic controllers has been highlighted by several researchers [58,59].

All methods predominantly identified human-related causes. This was due to the nature of the accident and the analysis as focusing on the actions taken by the pilots and air traffic controllers. However, different methods had different approaches when identifying human-related causes. For instance, FTA application referred to it as “human error”, and FMEA explained it as part of a “wrong action”. In contrast, CAST provided a scenario where unsafe human actions were provided due to inadequate controls in the system. Apart from human-related factors, the FTA application revealed environmental conditions (referring to weather and external factors) the most, and FMEA and CAST revealed technology and organisation-related factors. Similar conclusions were made different researchers [21,36,60]. Methods enforce its users to focus on different causal aspects due to the different science behind them [61]. Nevertheless, all methods have their own strengths and weaknesses [53,62].

In a study, it was stated that the highest control failure rate in the Tenerife accident was the failure of action controls (44%), and it was stated that one of the important causes of the accident was communication disorder. This highlights the need for well-established formal organizational relationships that define behavioral, pre-action review, and action responsibility controls. [63]. In another study, it was stated that there are many causes of the accident and that the lack of coordination is an additional factor [64]. Another study examining the Tenerife accident stated that the main cause of the accident was human error, as in this study, and in parallel with this study, ineffective human behaviors were shown as the main causes of the accident along with organizational factors [65]. Other accident studies have examined the accident as human and organizational, but in this study, the environmental and technological factors have been examined with an in-depth analysis of the accident and the advantages of the CAST system in finding the cause have been seen.

The FTA application in this study required less time in comparison to FMEA and CAST, and it was also easy to apply. However, it must be noted that different individuals might end up with the identification of different basic events by using FTA [66]. Despite FMEA having a more systematic approach than FTA, both methods provided almost the same number of causal factors with having different focuses. FMEA provided factors in all categories in a more equally weighted way.

The FMEA application was considerably less time-consuming in comparison to the CAST application. Additionally, FMEA enabled the identification of design flaws as well as inadequate feedback loops between components despite the nature of the method focusing on the individual system components.
FMEA is a tool that allows for the identification of potential problems and continuous improvement in complex intertwined processes [50].

5. CONCLUSION

Here, it is noteworthy that FTA and FMEA aim to reveal the causes of failures that contribute to accidents, whereas CAST aims to identify inadequate controls leading to the accident. In this study, the CAST was found to be a valuable method to identify causes at different categories. [17] said that "*an accident where innocent people are killed is tragic, but not nearly as tragic as not learning from it*". This study demonstrated that the CAST application was able to cover all failure modes that were identified in FTA and FMEA applications. Additionally, while all methods have value in analysing accidents, CAST appears to be more useful and convenient to analyse major accidents.

The limitations of this study must be mentioned. In this study, each method was applied by an individual author as the aim was not to apply the methods thoroughly; the study rather aimed to identify the causes of the Tenerife accident. It is; therefore, the individual's different levels of skills and knowledge might well have an influence on their findings. However, all authors reviewed the same reports, and several meetings were arranged to discuss the findings and revise them accordingly.

There are deficiencies in the literature regarding accident investigations. Based on this study, it is necessary to provide data to find the most comprehensive method by examining and comparing different accident reports using FTA, FMEA, CAST or other accident analysis methods in future studies.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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