CHAPTER 14

Basic Fault Tree Analysis Technique

The fault tree analysis (FTA) technique is proven to be an effective tool for analyzing and identifying areas for hazard mitigation and prevention while in the planning phase or anytime a systematic approach to risk assessment is needed. FTA is used as an integral part of a probabilistic risk assessment. In this chapter we will cover the very basics of FTA. The NASA Fault Tree Handbook with Aerospace Applications (1) is a complete guide to FTA.

14.1 HISTORY

Knowledge of the history of the need for FTA is useful for understanding the simple yet powerful potential of the tool. This history begins with the inception of mechanical vehicles. One common problem that plagued vehicles was malfunction and failures caused by "little things."

Steam engines blew up when pressure relief valves stuck closed. Early autos scattered parts across the countryside as nuts and bolts separated. Airplanes fell to earth because poorly designed fittings tore apart. Always it was the little things that failed and set up potentially deadly chain reactions.

Despite major advances in design and manufacturing techniques, significant numbers of accidents and failures continued to occur. Airplane accidents, attributable to training, accounted for over one-third of the losses during the WWII years 1941–1945. Over 14 000 major accidents were recorded in the United States alone.

Often, the airplane accidents were attributed to "pilot error." However, the majority of crashes should have been linked to a malfunction of little things … a failed hydraulic pump … a broken feathering stop … a missing lock nut.

Risk Assessment: Tools, Techniques, and Their Applications, Second Edition. Lee T. Ostrom and Cheryl A. Wilhelmsen.

Companion website: www.wiley.com/go/Ostrom/RiskAssessment_2e

As technology became more exotic, technological advances exceeded the average skill level for operation and maintenance of advanced air vehicles. Because of the complexity of systems, nuts and bolts errors became even more frequent. An improvement in safety analysis was needed.

This technique had to be capable of handling systems of enormous complexity and allow detailed analysis at the nuts and bolts level. The basic premise behind the development of the tool was LITTLE THINGS CAUSE ACCIDENTS. The first FTA was developed and applied by Bell Telephone Laboratories in 1962, with the requirements in mind. The tool was initially applied to the Minuteman ICBM. As a result of the FTA of that extremely complex system and taking corrective measures, the missile was rated as one of the safest in the USAF inventory (2).

14.2 APPLICATION

Fault trees show graphically the interaction of failures and other events in a system. Basic events are depicted at the bottom of the fault tree and are linked via logic symbols (known as gates) to one or more of the top (TOP) events. These TOP events represent hazards or system failure modes for which predicted reliability or availability data is required. Typical TOP events might be:

- Total loss of production
- Explosion
- Toxic emission
- Safety system unavailable

As indicated, the fault tree begins at the end, so to speak. This top-down approach starts by supposing that an accident takes place. It then considers the possible direct causes that could lead to this accident. Next it looks for the origins of these causes. Finally it looks for ways to avoid these origins and causes. The resulting diagram resembles a tree, thus the name.

Fault trees can also be used to model success paths as well. In this regard they are modeled with the success at the top, and the basic events are the entry-level success that put the system on the path to success.

14.3 FAULT TREE CONSTRUCTION

The goal of fault tree construction is to model the system conditions that can result in the undesired event. The analyst must acquire a thorough understanding of the system before beginning the analysis. A system description should be part of the analysis documentation. The analysis must be bounded, both spatially and temporally, in order to define a beginning and endpoint for the analysis.

The fault tree is a model that depicts graphically and logically represents the various combinations of possible events, both fault and normal, occurring in a system, leading to the TOP event. The term “event” denotes a dynamic change of state that occurs to a system element. System elements include hardware, software, human, and environmental factors.

14.4 EVENT SYMBOLS

The symbols shown in Table 14.1 show the most common fault tree symbols. These symbols represent specific types of fault and normal events in FTA. In many simple trees only the basic event, undeveloped event, and output event are used.

Events representing failures of equipment or humans (components) can be divided into failures and faults. A component failure is a malfunction that requires the component to be repaired before it can successfully function again. For example, when a pump shaft breaks, it is classified as a component failure. A component fault is a malfunction that will “heal” itself once the condition causing the malfunction is corrected. An example of a component fault is a switch whose contacts fail to operate because they are wet. Once they are dried, they will operate properly.

Output events include the top event, or ultimate outcome, and intermediate events, usually groupings of events. Basic events are used at the ends of branches since they are events that cannot be further analyzed. A basic event cannot be broken down without losing its identity. The undeveloped event is also used only at the ends of event branches. The undeveloped event represents an event that is not further analyzed either because there is insufficient data to analyze or because it has no importance to the analysis.

14.5 LOGIC GATES

Logic gates are used to connect events. The two fundamental gates are the “AND” and “OR” gates. Table 14.2 describes the gate functions and also provides insight to their applicability.

Electrical circuits are used to illustrate the use of AND and OR gates. Figure 14.1 is a picture of switches in series and the corresponding fault tree. In order for the bulb to be lit, all of the switches must be in the closed position. The logic gate is an “AND” gate.

Figure 14.2 represents the OR gate logic. The bulb will be lit if any of the switches are closed.

TABLE 14.1
Common Fault Tree Symbols

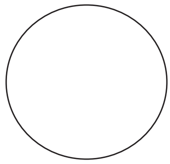
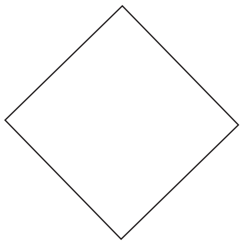
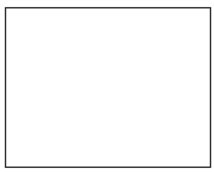
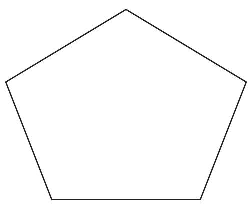
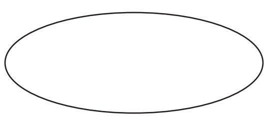
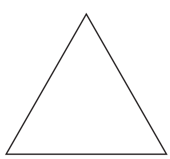
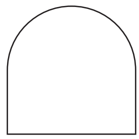
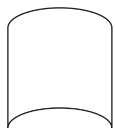
Symbol name	Symbol	Description
Basic event		A basic initiating fault (or failure event)
Undeveloped event		An event that is not further developed. It is a basic event that does not need further resolution
Output event		An event that is dependent on the logic of the input events
External event (house event)		An event that is normally expected to occur In general, these events can be set to occur or not occur, i.e. they have a fixed probability of 0 or 1
Conditioning event		A specific condition or restriction that can apply to any gate
Transfer		Indicates a transfer to a subtree or continuation to another location

TABLE 14.2
Logic Gates

Description	Symbol	Truth table		
AND gate. The AND gate indicates that the output occurs if and only if all of the input events occur		Input A	Input B	Output
		T	T	T
		T	F	F
		F	T	F
		F	F	F
OR gate. The OR gate indicates that the output occurs if and only if at least one of the input events occur		Input A	Input B	Output
		T	T	T
		T	F	T
		F	T	T
		F	F	F

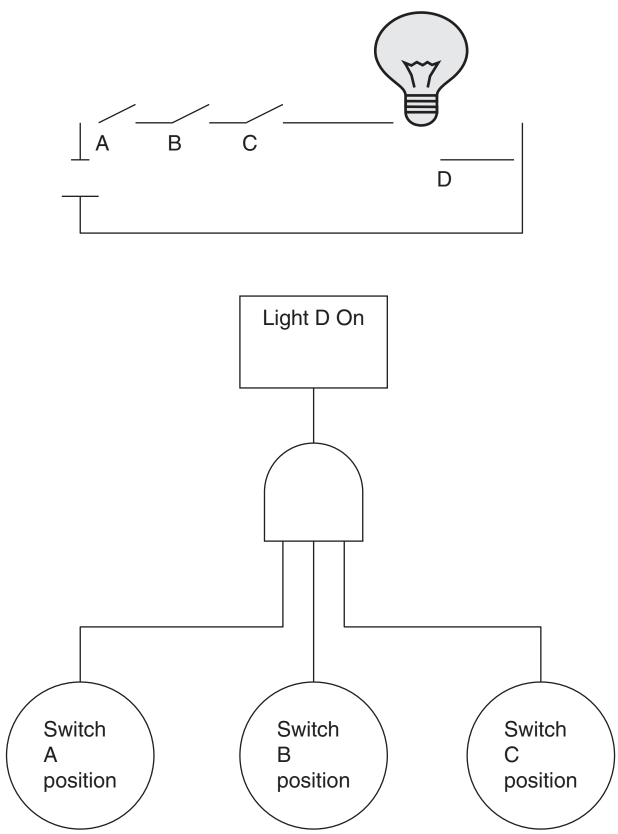


FIGURE 14.1 Switches representing AND gate.

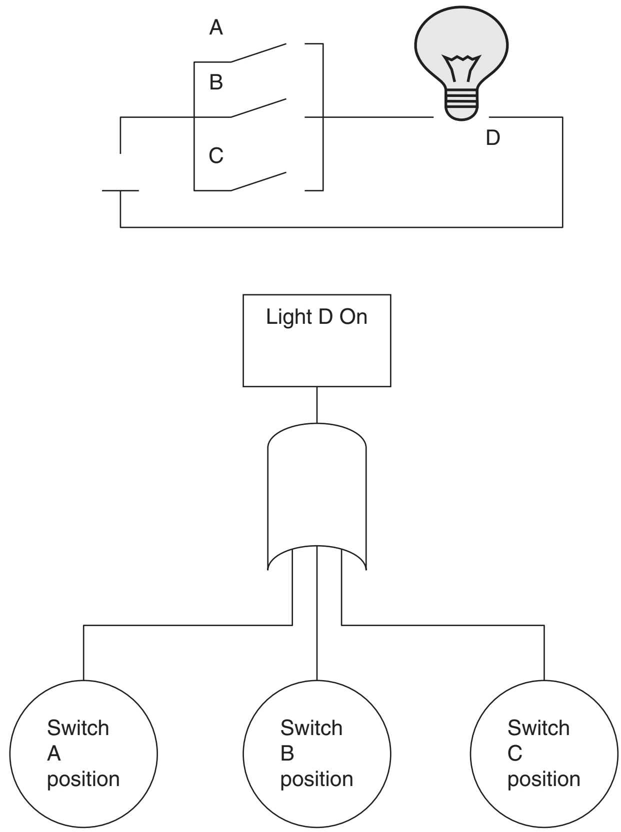


FIGURE 14.2 Switches representing OR gate.

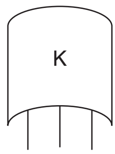
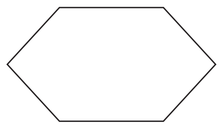
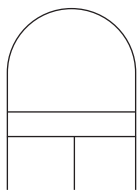
Other gates that can be used in more complicated trees are shown in Table 14.3. These logic gates are used when representing complex systems. Other gates can be used as well. These are usually very specialized in nature and do not have widespread application.

14.6 ANALYSIS PROCEDURE

There are four steps to performing an FTA:

1. Defining the problem.
2. Constructing the fault tree.
3. Analyzing the fault tree qualitatively.
4. Documenting the results.

TABLE 14.3
Fault Tree Symbols

Symbol name	Symbol	Description
Voting OR (*k* out of *n*)		The output event occurs if *k* or more of the input events occur
Inhibit		The input event occurs if all input events occur and an additional conditional event occurs
Priority AND		The output event occurs if all input events occur in a specific sequence

14.6.1 Defining the Problem

A top event and boundary conditions must be determined when defining the problem. Boundary conditions include:

- System physical boundaries
- Level of resolution
- Initial conditions
- Not allowed events
- Existing conditions
- Other assumptions

Top events should be precisely defined for the system being evaluated. A poorly defined top event can lead to an inefficient analysis.

14.6.2 Constructing the Fault Tree

Construction begins at the top event and continues, level by level, until all fault events have been broken into their basic events. Several basic rules have been developed to promote consistency and completeness in the fault tree construction process. These rules, as listed in Table 14.4, are used to ensure systematic fault tree construction (excerpted from *Guidelines for Hazard Evaluation Procedures*, Center for Chemical Process Safety of the American Institute of Chemical Engineers (3)).

TABLE 14.4
Rules for Constructing Fault Trees

Fault tree statements	Write the statements that are entered in the event boxes and circles as malfunctions. State precisely a description of the component and the failure mode of the component. The "where" and "what" portions specify the equipment and its relevant failed state. The "why" condition describes the state of the system with respect to the equipment, thus telling why the equipment state is considered a fault. Resist the temptation to abbreviate during construction
Fault event evaluation	When evaluating a fault event, ask the question "Can this fault consist of an equipment failure?" If the answer is yes, classify the fault event as a "state-of-equipment" fault. If the answer is no, classify the fault event as a "state-of-system" fault. This classification aids in the continued development of the fault event
No miracles	If the normal functioning of equipment propagates a fault sequence, assume that the equipment functions normally. Never assume that the miraculous and totally unexpected failure of some equipment interrupts or prevents an accident from occurring
Complete each gate	All inputs to a particular gate should be completely defined before further analysis of any other gate. For simple models, the fault tree should be completed in levels, and each level should be completed before beginning the next level. This rule may be unwieldy when constructing a large fault tree
No gate to gate	Gate inputs should be properly defined fault events; that is, gates should never be directly connected to other gates. Shortcutting the fault tree development leads to confusion because the outputs of the gate are not specified.

14.6.3 Analyzing the Fault Tree

Many times it is difficult to identify all of the possible combinations of failures that may lead to an accident by directly looking at the fault tree. One method for determining these failure paths is the development of "minimal cut sets." Minimal cut sets are all of the combinations of failures that can result in the top event. The cut sets are useful for ranking the ways the accident may occur and are useful for quantifying the events, if the data is available. Large fault trees require computer analysis to derive the minimal cut sets, but some basic steps can be applied for simpler fault trees:

Uniquely identify all gates and events in the fault tree. If a basic event appears more than once, it must be labeled with the same identifier each time.

Resolve all gates into basic events. Gates are resolved by placing them in a matrix with their events.

Remove duplicate events within each set of basic events identified.

Delete all supersets that appear in the sets of basic events.

By evaluating the minimal cut sets, an analyst may efficiently evaluate areas for improved system safety.

14.6.4 Documenting the Results

The analyst should provide a description of the system. There should be a discussion of the problem definition, a list of the assumptions, the fault tree model(s), lists of minimal cut sets, and an evaluation of the significance of the minimal cut sets. Any recommendations should also be presented.

14.6.5 Examples of Fault Tree Analysis

Simple Example

The following examples will show the fundamentals of FTA. We will start with analyzing a simple cooling system flushing procedure. This procedure can also be analyzed using human reliability analysis (HRA) techniques, but we will use FTA at this point. The procedure reads as follows:

Warning – Cooling system must be below 100 °F prior to draining

1. Begin with the engine cold and ignition off.
2. Remove the radiator pressure cap.

Warning – Ethylene glycol coolant is toxic and must be disposed of in an appropriate manner.

3. Open the petcock at the bottom of the radiator and drain the coolant into a bucket.
4. Close the petcock and fill the radiator with water.
5. Start the engine and turn the heater control to hot. Add cooling system cleaner and idle the engine for 30 minutes (or as per the instructions on container).

Warning – Cooling system must be below 100 °F prior to draining.

6. Stop the engine and allow it to cool for five minutes. Drain the system.
7. Close the petcock, fill the radiator with water, and let the engine idle for five minutes.
8. Open petcock and drain the water.
9. Repeat Step 6–8.
10. Close the petcock.
11. Fill cooling system with 50/50 mixture of water and *nontoxic* antifreeze/coolant.

The first step will be to determine the credible top events. In this case it will be:

Mechanic is Burned
Cooling Flushing Failed

In fact, the “Mechanic is Burned” top event can be grouped under the “Cooling Flushing Failed” top event because if the mechanic were burned, then the task would fail in a sense.

From the procedure we can identify several basic events. These are shown in Table 14.5, along with their credibility.

TABLE 14.5
Car radiator Failures

Failure	Description	Credible failure
Engine not below 100 °F before beginning flushing procedure	In this failure the mechanic begins the coolant draining process without ensuring the engine is cool enough	This is a credible error. It happens all the time to professional as well as amateur mechanics. Since the system is under pressure, a severe burn can occur
Failure to remove radiator cap	As it says, the mechanic fails to remove the radiator cap	This is not a credible error, unless we are modeling the fact that the mechanic does not do the task at all
Failure to drain radiator	The mechanic fails to drain the radiator	This is not a credible error, unless, again, we are modeling the fact that the mechanic does not do the task at all
Failure to close petcock valve	This failure involves the mechanic not closing or incorrectly closing the petcock valve. This error can occur at least four times in the procedure	This is a credible error and can lead to an environmental spill
Failure to add flushing agent	The mechanic fails to add the flushing agent	This is a credible error because the mechanic can get busy and forget where they are in the process
Failure to remove flushing agent	The mechanic fails to remove the flushing agent	This is a credible error because, once again, the mechanic can get busy and forget where they are in the process. OR a shift change occurs or job change over and the second mechanic does not know where in process they are. This happens in the airline industry every day
Failure to rinse engine	The mechanic fails to rinse the remaining flushing agent from the engine	This might not be a catastrophic error, once the engine is drained of the flushing agent. It depends on how corrosive the flushing agent is
Failure to fill engine with 50/50 nontoxic antifreeze mix	The mechanic fails to fill the cooling system with the proper mixture, the right amount of coolant, or coolant at all	This again is a credible error

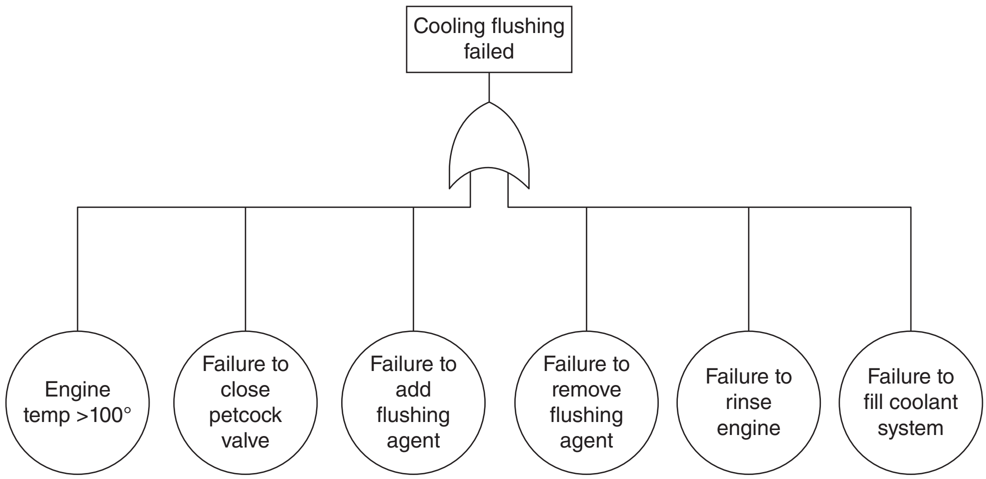


FIGURE 14.3 Fault tree analysis of coolant flushing task.

Once done assessing the credibility of the failures, we next construct the fault tree. We will not include errors that were deemed to be credible. Our top event will be the Cooling Flushing Failed. All the basic events will be entry points into the tree. The tree is shown in Figure 14.3.

Notice that we were able to build the fault tree only using an OR gate and the basic events. That is because only one of the credible failures can lead to the failure of the task.

Next we will model a simple hardware system failure, one that most homeowners have experienced. That is of the sprinkler system failure. The top event is Sprinkler System Failure. Table 14.6 contains the credible failures that can lead to the top event.

In Figure 14.4 we have constructed a partial fault tree from these failures. A full tree was not constructed to save space.

14.6.6 Modeling Success Using Fault Tree Analysis

One of the useful attributes of FTA is that it can also be used to model success paths as well as its more traditional use of modeling failure paths. For instance, say that a hiker wants to climb Mt. Everest. What must happen in order to do such a climb? Or say that someone wants to pass a certification examination or even complete a project on time. What does that person need to do to succeed in those goals? Obviously, there are many project management techniques that are great at modeling success paths for projects. Network diagrams are one example of a tool that can be used. However, FTA can also be used to model this type of process.

So, let’s say our goal is to write a technical book that has 12 chapters and meet the contractual requirements of the publisher. As with modeling in the failure space,

TABLE 14.6
Sprinkler Head Failures

Failure	Description	Credible failure
Sprinkler head failure 1	Sprinkler head fails because it wore out	Yes – it is a credible failure
Sprinkler head failure 2	Sprinkler head fails because neighbor hits it with their lawn mower	Yes – it is a credible failure
Sprinkler valve failure 1	Sprinkler valve wears out	Yes – it is a credible failure
Sprinkler valve failure 2	Sprinkler valve breaks due to freezing	Yes – this failure though is contingent on the system not being properly drained the fall before. So, we will model it in this manner
Sprinkler controller failure 1	The battery that backs up the memory fails, and after a power failure the system has lost its mind	Yes – it is a credible failure
Sprinkler controller failure 2	The sprinkler controller fails	Yes – it is a credible failure
Sprinkler pipe failure 1	The sprinkler pipe breaks due to freezing	Yes – this failure though is contingent on the system not being properly drained the fall before. So, again, we will model it in this manner
Sprinkler pipe failure 2	The sprinkler pipe breaks due to digging in the yard	Yes – it is a credible failure

we need to develop the list of credible events that must occur to succeed. Table 14.7 lists these.

Though in real life an event tree is probably a better tool to model this with, we will develop the model using a fault tree. Chapter 16, Event Trees and Decision Analysis Trees, will show how this process can be modeled using an event tree. Figure 14.5 will show a fault tree for this process.

14.6.7 Fault Tree Analysis for Use in Accident Investigation

The following provides a description of an actual accident involving TAM Linhas Aéreas Flight 3054. An FTA will be constructed from the information provided (4–7).

On 17 July 2007 TAM Linhas Aéreas Flight 3054, an Airbus A320-233 aircraft, left Salgado Filho International Airport in Porto Alegre, only to land in wet conditions and crash at Congonhas-São Paulo International Airport in São Paulo, Brazil. When the flight first touched down, it was raining, causing the plane to overrun the runway, cross a highly busy main road during rush hour traffic, and crash into the TAM Express warehouse, which happened to be next to a gas station that exploded with the force of

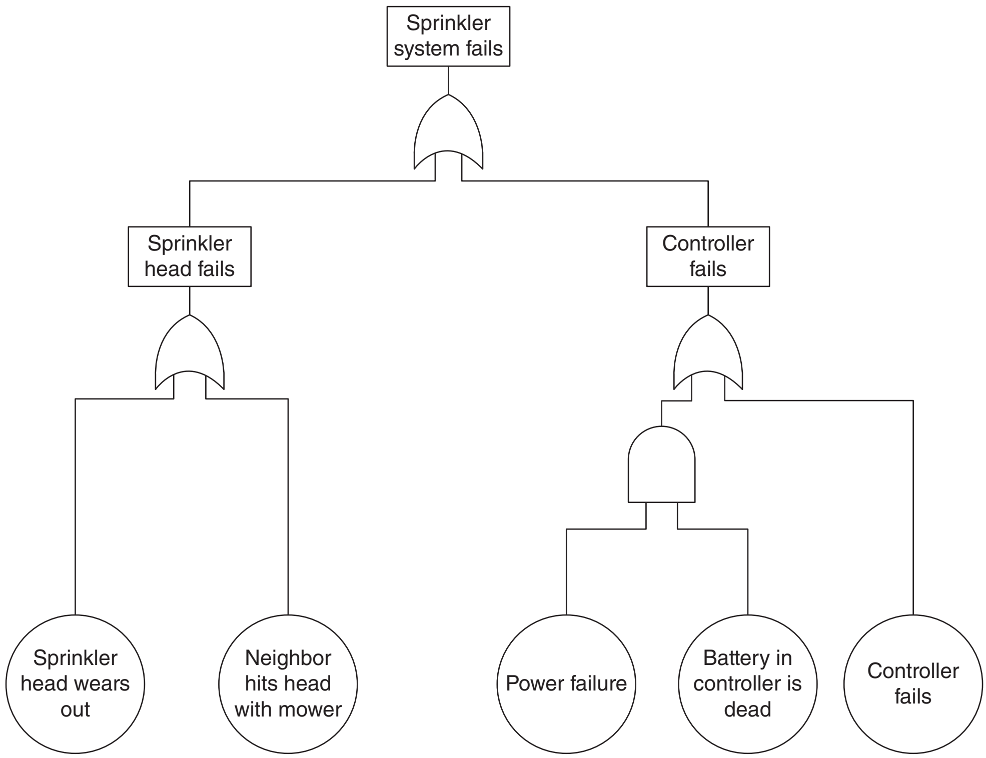


FIGURE 14.4 Partial fault tree of sprinkler system failure.

TABLE 14.7
Author Failures

Success	Description	Credible
Author 1 completes six chapters	Author 1 completes the chapters assigned to him/her	Yes – this has to occur to succeed
Author 2 completes six chapters	Author 2 completes the chapters assigned to him/her	Yes – this has to occur to succeed
Editor's changes are appropriate	The editor's changes must not change the technical content of the book and must be grammatically appropriate	Yes – this has to occur to succeed
Artwork meets requirements	The artwork has to meet the publisher's requirements to be included	Yes – this has to occur to succeed
Manuscript is formatted correctly	Besides the book needing to meet technical and grammatical requirements, it also has to be formatted correctly	Yes – this has to occur to succeed
Manuscript is submitted on time	The manuscript has to be submitted on time to be accepted	Yes – this has to occur to succeed

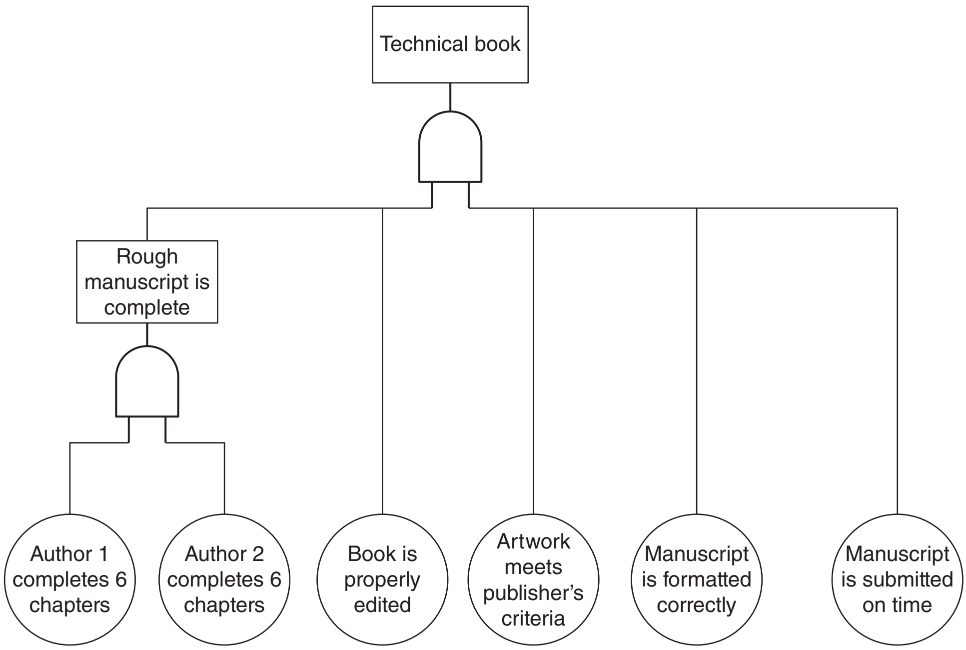


FIGURE 14.5 Fault tree for success modeling.

the impact of the Airbus A320-233, #789 (4). With 187 people on board, and 12 people on the ground, there totaled 199 fatalities (5), causing this crash to be the highest in deaths of any Latin American aviation accident. Not only was it the most devastating in Latin America, but it was the world's worst Airbus A320 crash involving fatalities anywhere in the world (6).

Airbus A320-233 was registered as PR-MBK and had the manufacturer's serial number of 789. The A320-233 was powered by two International Aero V2527E-A5 engines. The A320-233, #789 was built in February 1998 and took its first flight in March of 1998 and had its last flight in July of 2007 (7). TAM Linhas Aéreas was the last of four companies to operate the A320-233, #789, in less than a decade. TAM Linhas Aéreas did not come into position of the A320-233, #789, until December of 2006. Data collected from *Flight International* shows that as of April 30, the A320-233, #789 had mounted up to 20 379 flying hours and 9313 cycles (7).

The aircraft was dispatched for the Flight 3054 with a jammed thrust reverser, a braking device on the aircraft. According to TAM, the fault in the thrust reverser did not make the landing any more dangerous, and the mechanical problem was not known of at the time. It was later reported that the plane had trouble braking on the São Paulo runway on 16 July, the day before the crash, indicating that they had prior knowledge that something was wrong with the braking system (7).

Once the aircraft touched down in São Paulo, the pilots were unable to slow the aircraft down at a normal rate. The aircraft was still traveling at approximately 90 knots toward the end of the runway. The aircraft took a hard left and overshot the runway where it cleared the major roadway since the runway was elevated but eventually collided with the TAM Express building. Surveillance videos showed that the aircraft touched down at a normal speed and at a normal spot on the runway but the aircraft failed to properly slow down (www.News.com).

Authorities uncovered the flight data recorder, which contained information about what happened in the plane during flight. The data showed the following information. The thrusters had been in the climb position just prior to touchdown as the engines were being controlled by the computer system (4). An audio warning was given by the computer two seconds before touchdown warning the pilots that they should manually take control of the throttle. When the aircraft touched down, it was found that one thruster was in the idle position while the other was stuck in the climb position. In order for the spoilers to deploy and assist in slowing the aircraft down, both thrusters must be in the idle position. With different forces being applied to each side, it created a force that caused the plane to veer off to the left uncontrollably (4, 7).

Prior to the accident, the airport became under increased scrutiny due to a mid-air collision in September of 2006. The airport was known to have safety issues regarding operations in the rain as well as runway characteristics for the traffic going through it. One of these characteristics involved the length of the runway (7). There are so many variables that can affect the landing distance of an airplane that the airport had failed to consider.

For example, if the aircraft's approach speed is 20 knots higher than normal, it will take the aircraft 25% longer to slow down. The runway had been seen as a problem prior to the incident, and in February 2007, a judge had actually banned flights using Fokker 100, Boeing 737-700s, and Boeing 737-800s, stating that the runway needed an additional 1275 ft in order to operate safely. The A320 was not banned because the manufacture stated a shorter braking distance than the banned aircraft. However, the ban was quickly lifted as the airline industry stated that they would be inconveniencing thousands of passengers (6).

The root causes for the crash were that one of the reverse thrusters was known to be out prior to the flight, the runway was wet, and the runway should have been longer. While TAM claims that the thrusters should not have caused the crash, it is obvious that had the reverse thruster been functioning, the aircraft would have most likely been able to stop. Having grooves cut into the pavement to help reduce the risk of hydroplaning could have prevented the moisture on the runway, and had the runway been longer, the aircraft would have had more time to stop (4).

Pilot training might have also contributed to the accident even though both pilots were very well trained and had plenty of experience. Commander Kleyber Aguiar Lima, from Porto Velho, was born on 22 March 1953, and worked for TAM from November 1987 to July 2007 and had over 14 000 flight hours in his career, and Commander Henrique Stephanini Di Sacco, from São Paulo, who was born on 29 October 1954, joined TAM in 2006 and also had over 14 000 flight hours in his career (5). They knew that one thruster was not functional and should have planned the landing as if neither thruster would work. They knew that the landing strip was short; they also knew that the strip was wet. The combination of the short landing strip and the wet landing strip along with the malfunctioning thrusters should have alerted the pilots to take a different course of action.

Precautions should be taken to improve traction during wet weather. This includes cutting grooves in the pavement to allow the water to flow off of the runway increasing the traction when an aircraft lands. This airport just finished with major renovations on the landing strip; it should have been mandatory that the strip be 100% finished before being allowed for use.

Also, warnings from the government stating that the runway was much too short for larger airliners to land on were passed off way too quickly. Governmental rulings should be respected, and with that, the changes must be made no matter how necessary to ensure the safety of all the passengers on all the planes. The airport officials knew that the runways were too short to handle such large planes, and yet they continued to allow those planes to fly to not disrupt the economy.

As with most aircraft crashes, there are several factors that lead to the crash. The following is a list of items that contributed to the crash. This list is then used to construct the fault tree that is depicted in Figure 14.6:

- Runway was wet.
- Rain in area.

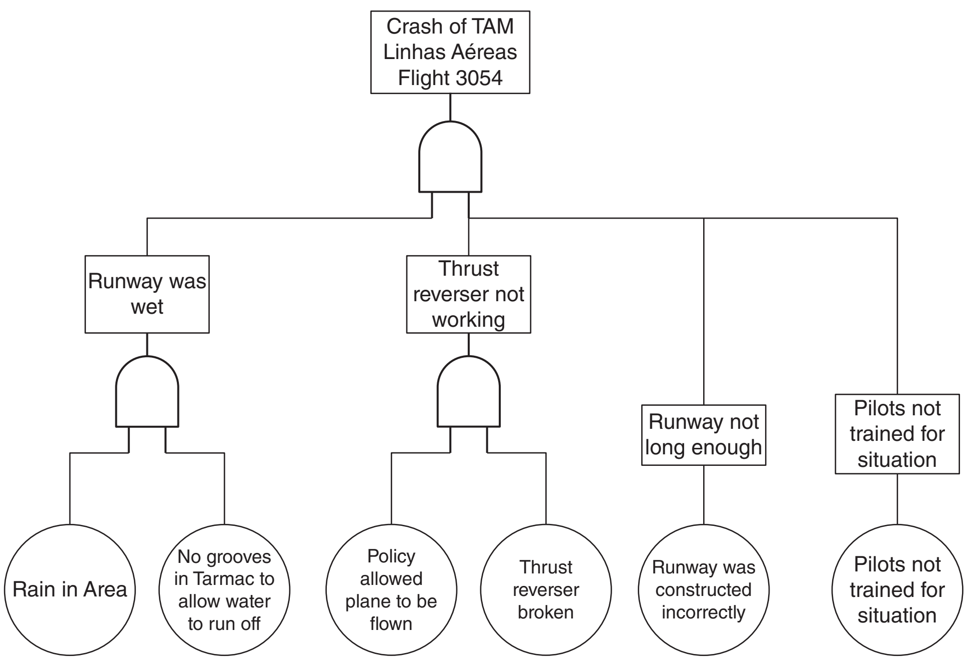


FIGURE 14.6 Fault tree for TAM Linhas Aereas Flight 3054.

- No grooves cut in runway.
- Thrust reverser broken.
- Airline policy allowed aircraft to be flown with broken thrust reverser.
- Runway too short.
- Airport policy allowed larger planes to land on runway.
- Experienced pilots had not had training in this situation.

The fault tree is very useful to showing how all the individual factors come together to cause the flight to crash. Is this all of them? No, there are some decision processes that the pilots went through that are not shown. These can be better modeled using HRA techniques. These are discussed in Chapter 12.

14.7 SUMMARY

The FTA technique has proven to be a very rigorous and valuable tool for analyzing complex systems. Strengths include an ability to analyze down to a great level of detail, a simple presentation, and a systematic method for analysis. Fault trees are used in a variety of disciplines and can model many types of systems.

The Probabilistic Risk Assessment (PRA) chapter will discuss how FTA is used in conjunction with other techniques to analyze complex systems.

Self-Check Questions

1. What advantage does FTA have over other risk assessment techniques?

2. What disadvantages does FTA have?

3. Pick a recent accident or event and develop an FTA for it.

4. FTAs can be used for financial events as well. How could an FTA be used to determine how a business might overspend their resources.

5. How can FTA be used in enterprise risk management?

6. Describe how an FTA can be used in conjunction with an FMEA or PHA.

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