CHAPTER 2

An Example of Practical Risk Analysis

2.1 Risk with Volcanic Ash Clouds and Commercial Aviation

Risk Analysis (RiskAn) is not only performed when designing or developing a system. Many systems require ongoing RiskAn during operations, in particular when the environment of operations changes. Not only risk analysis but risk management is a complex and subtle business. It is not just a matter of taking some numbers, multiplying and adding them together, and making a decision on the result. Many of those numbers don't exist; uncertainty is often rife. Coping with that uncertainty is part of risk management. This may be shown through a practical example.

Commercial civil aviation is a sociotechnical system. A sociotechnical system is one in which system operations are partly accomplished through engineered technology, and partly through human operation involving many participants/operators. Participants are required to file flight plans with the airspace sovereign authority at the starting point of the flight ("instrument flight plans"). Flight plans involve routing (straight-line segments along "airways"), altitudes, and times. A plan is confirmed by the airspace authority after international coordination and modification as needed. The plan is modified during the flight through real-time radio communication between aircraft and "air traffic controllers" (ATCOs), who work for the airspace authority on the ground, and are cognisant of who is occupying the airspace for which they are responsible, and coordinate its use. The goal of air traffic control is safety of flight – ATCOs are to ensure adequate physical separation between all airspace users, ideally to eliminate the possibility of collision.

A sudden change in the environment of civil aviation operations occurred in mid-April 2010, when the volcano Eyjafjallajökul in Iceland erupted and spewed clouds of ash into the upper atmosphere. Volcanic ash can be very abrasive and can cause extensive damage to jet engines. There is a hazard, namely, having engines fail in flight [2]. Much airspace over Northern Europe was closed on 2010-04-15 by the sovereign authorities due to the eruption.

Besides the safety hazards of such an event, there are also economic hazards. Economic risks and safety risks are conceptually similar. Both are the expected value of the loss. (This is so with informal as well as formal meaning - “expected value” is also a technical term in probability theory.) But what counts as a loss is different: for safety, it is human or physical damage; for economics, it is money.

One economic hazard is the cost of ceasing operations, said to be cumulatively £130m per day for the commercial air travel industry and £5.5m for HMG in lost passenger duty [**?**]. Various airlines complained about the airspace closure. According to them, the situation wasn’t so bad that they couldn’t fly safely. But there is another economic hazard to consider. What if airlines flew in the ash cloud, and some engine somewhere had a problem. What would then happen? And what would the cost of that be?

So, what were the risks, both for safety and for economics, and how were they analysed?

2.2 Considerations From Tuesday 2010-04-20 (After Five Days Of Closure)

[a comment on what the environment was like on that day] ... I must say that in Bielefeld it is wonderful to see the sky without the usual 15 or so condensation trails and the ensuing cirrus, but my wine&tea merchant and his son are stuck in Namibia at the end of a hunting holiday and desperately need to get back to work, so I understand well the economic side of this .....

In order to understand what volcanic ash can do to gas turbine engines, it is instructive to read about Speedbird 9 in 1982 [**?**] as well as the NASA report of damage to the engines of an aircraft which flew through the ash cloud of Mt. St.

Helens in 2000 on its way to Europe [12]. The Mt. St. Helens cloud was not visible to the NASA pilots, and visual inspection of the engines on landing revealed no damage. But the engines were nevertheless severely damaged.

Volcanic ash contains a high proportion of silica. This particular eruption sequence was said to show concentrations from just under one-half to about two-thirds, depending on the type of eruption (an eruption sequence is not necessarily uniform in type or composition) [13]. The ash is very fine stuff. The silica melts in some parts of the turbine, and gives other parts a glass coating as a consequence.

What to call these physical observations? A "hazard constellation"?

There are almost no data points for the behavior of engines under exposure to volcanic ash. There are just the occasional damage reports, such as op. cit. It is known that higher concentrations will cause flame-out and seizing, but the effect on engines of lower concentrations had not been determined by anything much in the way of testing. For example, behavior on exposure to volcanic ash is not part of the certification requirements for engines. It looked as if, when you flew through this particular ash cloud for a couple of hours, then everything remained OK on a visual inspection of the engines (British Airways indeed did this, with permission of the UK Civil Aviation Authority), but I doubt anyone knew at that time what might happen if you flew through it for a week (which would represent an order-of-magnitude increase in exposure).

Consider the following scenario. Suppose flight through the ash cloud were permitted and some engine, somewhere, which had flown through the ash region, has a problem which might be related to volcanic ash. Call this the prime case. Note that visual inspection does not necessarily suffice to determine that a cause is volcanic-ash damage [12], so a disassembly would be appropriate. Standard safety regulatory action would be to take the engine type out of service until it has been determined what the exact nature of the problem is with the prime case, and if ash was implicated then all engines of that type that had flown in the ash region would have to be taken out of service while disassembly is accomplished. If ash abrasion was found to be a causal factor in the prime case, then the entire fleet would be grounded until all the engines can be disassembled and rebuilt. That could take months. If the engine happens to be one used intercontinentally, flying under ETOPS regulations, then there is a question what regulators do about ETOPS approval for that type, for those engines exposed to ash. ETOPS, or Extended-Range Twin-Engine Operations, is a regulatory regime under which participating twin-engine aircraft may fly further away from a nearest airport of landing than regulations would otherwise permit (the most common ETOPS range was 180 minutes of flight), allowing twin-engine aircraft to cross the Atlantic and Pacific Oceans for the first time in regular airline operations (ETOPS has since been extended to more than twins). ETOPS was predicated upon the demonstrated reliability of the engines as shown by the manufacturer, as well as appropriate and careful maintenance as demonstrated by the ETOPS-approved airline. The idea was that the risk of an engine failure was low, and, if it should happen, the chances of a failure of the remaining engine within the time it would then take to reach an airport to land, were very low indeed – assuming that the engine failures were independent! ETOPS operations are predicated on demonstrated lack of susceptibility to independent failures, and are not intended or appropriate for possible common-cause failure modes such as flying through volcanic ash clouds.

There is a significant economic risk here, not just safety risk. If one engine which has flown in the ash-cloud region has a problem, then all engines of that type which have flown in that region are grounded. That persists at least until the cause of the problem has been determined, which could take days, and if ash abrasion is a factor then all engines are grounded until rebuilt. That represents considerable loss of revenue to considerably many airlines, on the basis of one engine having some ash-related problem. Airlines who were dependent on transatlantic traffic to generate revenue, such as BA, suffered an immediate loss of revenue from the April 2010 flying prohibition. I know of no public estimate of the costs of having ETOPS rescinded on BA's entire 777 fleet, let alone many airlines' fleets, pending rebuild/overhaul of the engines. It would surely be enormous. And to this must be added the cost of the maintenance activity to return the engines to flight, which would also be very high.

The likelihood that one engine, somewhere on one wing, in Europe, would have a problem in the next couple of weeks following emission of the ash cloud, was, just on general experience, not small.

It is a hard risk-assessment issue. There arise safety risks and economic risks. The risks arise from

(a) the environment - the fact that the ash cloud is there;

(b) long established procedures for regulating aviation safety, which requires that possibly-affected systems be inspected upon evidence of a problem, which in this case would mean grounding because of the non-visible nature of some effects;

(c) the unknown but tangible likelihood that some problem will occur;

(d) the severe consequences of such a problem, given the established procedures for regulating aviation safety;

(e) the severe economic consequences of closing down airline travel in such a busy part of the world.

I voiced all these considerations, using these terms, on 2010-04-20 [8] . Using my judgement as a system safety person, I favored at that point keeping aircraft out of the ash until it went away. I also don't recall any discussion of the economic risk represented by (c), (d) and (e). Most discussion focused on the direct costs of not generating revenue versus the safety risk.

There is a subtle, and often suppressed, issue here concerning the relation between safety risk and economic risk. Airlines often say that their number one priority is safety. But as businesses, they have regulatory obligations to their shareholders, of which staying in business where possible is one. Very little is said or written about the risk trade-offs between the obligation of safety towards users and the obligation of solvency and profit towards shareholders. The law sometimes recognises this trade-off explicitly. For example, English law requires that organisations reduce any safety risk to be "as low as reasonably practicable" (ALARP), rather than as low as possible. "Reasonably practicable" here means that the cost of reducing risk further is not "disproportionate" to the safety benefits obtained. The meaning of "disproportionate" is determined by the regulator (HSE), in its enforcement decisions, and the judgement of the courts. For further information see [**?**].

2.3 Considerations From Thursday 2010-04-22 (Seven Days After Closure)

The relief from condensation trails over Bielefeld did not last long. The ash cloud over Europe seemed to have abated somewhat in the early part of the week, and commercial air traffic returned to the air. The German DLR organisation (equivalent to the US NASA) sent up test flights of a Falcon 20E on Monday and Tuesday 19-20 April, to measure what was up there [**?**], and the report was available by Thursday 2010-04-22. It makes interesting reading. There are pictures in which you can see the ash layers below the aircraft.

It rained, very briefly, say spottily for 5 minutes, on Tuesday 20th and Wednesday 21st April in Bielefeld. My windows were then covered with a fine yellowish film of what I took to be ash (I have some skylight-type windows as well as vertical ones). The temperatures in Bielefeld were unusually low for that time of year, say 10° during the day in the sunshine (though with significant wind chill) and getting near zero at night. Indeed, it even snowed briefly in some places nearby on Wednesday 21st. The light was unusually white in the sunshine, an effect particularly pronounced in the evening. People used to smoggy atmospheres (Los Angeles, or the San Francisco Bay Area, where I lived in the 1970s-80s) are familiar with this phenomenon.

The debates after the DLR investigations seemed to concentrate on whether governments (rather, the regulatory agencies) were too cautious, not cautious enough, or just right, like Goldilocks's porridge. After various tests and detailed investigations, it was determined that the reaction, to close airspace where the highest concentrations were known to be, had been more cautious than the physical situation warranted [5].

Again, I expressed these points in almost these terms on the day in question [9].

2.4 Risk Management from a Regulatory Perspective

Consider the risk management. I thought that the reaction to this environmental phenomenon was exemplary:

First as noted above, flying gas turbines through volcanic ash can directly lead to catastrophic events (in the regulatory meaning of the term "catastrophic"; see below).

Second this phenomenon, that a major part of the world for commercial air traffic at all altitudes was affected, was and remains unprecedented, although it will likely happen again.

Third over the course of a few days, test flights taking measurements were organised and flown by the only organisations capable of producing believable results.

Fourth everyone became involved in assessing the phenomenon and reaction to it: manufacturers, regulators, and government.

Fifth the outcome was almost perfect for safety: no commercial air passengers were killed or severely injured; there were no train accidents injuring people who would have flown but were forced to take the train; ditto for ships. (As far as I know, there is no assessment of the number of deaths which occurred due to people making car journeys rather than flying.)

Safety is paramount to the regulators, by their charter, as well as to the manufacturers of the equipment involved, because of liability. National governments chose to prioritise safety, and that was achieved perfectly. There was, until many days into the incident, almost complete uncertainty as to the potential effects of this particular cloud. Ash had to be gathered, its characteristics analysed, and conclusions then drawn about its likely effects. This had not been done before. It turned out that the ash was not as abrasive as some has been.

Standard industry practice, for many years if not decades, had been to avoid all volcanic ash. At the beginning of the incident, this practice was followed, in the face of considerable uncertainty. Within a very few days, various organisations had determined that it was likely safe to fly, say, research aircraft. Data were gathered, knowledge about this ash was gained, uncertainty was reduced, then everyone went back to flying.

Safety was prioritised in the face of uncertainty. I think that to have been right. It is well to detail the uncertainty here. There was uncertainty about likelihoods and also about severities.

Likelihood of a volcanic ash encounter over most airspace in Western Europe was certain (the various meteorological offices knew it was there), so there is no uncertainty about existence. The uncertainty with this phenomenon lies with its severity (the effects of the ash cloud) alone.

Previous experience showed that the "worst case" is catastrophic, both for the people involved and (as it would be) for the government and agencies that would be said to have "allowed" an accident to happen. The classification can be derived from the experience of British Airways Flight 9 [**?**]. An explanation of the severity category “catastrophic” is appropriate. Although severe accidents with loss of many lives have not happened directly from volcanic ash effects, losing all of one’s engines is defined to be a "catastrophic" event in the airworthiness-certification regulations. The reason for this classification is that the “severity” of the event is defined to be multiple loss of life. After a loss of all engines, only environmental circumstances can affect whether one lands on-airport or off-airport. “Severity” is defined as the outcome in the least-favorable circumstances. The least favorable circumstances here would be an off-airport landing/ground impact and its likely deadly consequences. The event to BA Flight 9 is thus classified as “catastrophic”, even though finally no one was injured.

Since severity (defined as worst-case) over the sample (all volcanic-ash-encounter incidents) is catastrophic, and likelihood 1 (certainty), this says that there is certainty of catastrophe. This is obviously neither helpful nor correct. The approximation here for the severity is too crude.

One could attempt to define the range of outcomes more narrowly, to reduce the uncertainty if you like. What is the range of possible effects? Let us say, in order of severity,

- mildy increased maintenance costs on gas turbine engines
- heavily increased maintenance costs on engines
- flame-outs and the ensuing necessary tear-down of all engines of that type on all aircraft an accident resulting from near-simultaneous flame-outs of all engines on one airframe in flight.

(Note that some engines are rented, e.g., Rolls-Royce’s “power by the hour”. In this case the maintenance costs are born, not by the aircraft owner, but by the engine manufacturer. Still, someone has to pay the costs.) On general physical principles, we could presume that these effects are a function of

- the type of ash (known, and variable, in the current eruption)
- the density of the ash in the cloud
- the length of exposure of an aircraft to the ash

But we don’t know what function. Furthermore, over all flights, there is going to be a range of densities encountered and as well as a variety of lengths of exposure.

Erring definitively on the side of caution is an expected outcome of a rational approach, in a situation of great uncertainty, to a risk of which the value ranges from insignificant to catastrophic.

2.5 Further Developments in the Week After Flying Resumed

The observations in this section were largely made in [10], on April 28th, 2010.

The Economist had a briefing on the effects of the ash cloud from Eyjafjallajökull on the political economy of flight, which informed its lead commentary in the April 24th 2010 edition.

The article recounts that the "safe level" of ash was determined by the CAA (in Britain, but in fact the measure was coordinated across the continent) and started out at zero when flight restrictions were first imposed on Thursday April 15th. The "safe level" was changed on Wednesday April 21st to 2,000 micrograms per cubic meter.

The Economist published a leader in which it regarded it as "suspicious" that the "level was changed, in the face of an affluent cadre of displaced people, airlines feeling the pinch, a looming threat to some supply chains, and (in Britain) an election." I think, in the six days of the incident up to April 21, engine manufacturers had initiated projects to determine what they could about their engines, and the DLR had come up with data on the composition, density and distribution of the ash in the cloud. Given the evolution of knowledge and experience, I would suggest that the sequence of administrative events was both coherent and justified, with the following caveat. The newspaper suggests, correctly, that how the new level was determined "is not clear". The CAA apparently says it was set on the basis of data from equipment manufacturers, but no public data has been made available, and I agree with The Economist that "Regulations without a clear and open argument behind them are worrisome".

By Tuesday, 20nd April, the ash had confined itself to lower flight levels; upper airspace was freed for flight, and by Wednesday 21st April new guidance had been issued and implemented. I still think that shows an exemplary reaction to the situation.

The Finnish Air Force went on a training sortie on Thursday 15 April and suffered apparent damage to some engines [11]. News reports did not say how long they were up for, but one might guess it was on the order of an hour. The pictures showed glassification of deposits inside the engines, but it turns out that actual damage was much less than expected (when the pictures became public, some experts suggested the engines were not maintainable). However, the evaluation took eight days.

2.6 Making A Decision About Flying

The main observations in this section were first made in [10].

Suppose you are the CEO of an airline that wants to fly in closed airspace. Consider your financial risk. Air Berlin, for example, took in about €90 per passenger per flight from Paderborn to London Stansted, a route they flew at the time, if you booked shortly before flying, with a flight time of about an hour. They used standard workhorses, which for trips inside Europe are the twin-engine Airbus A320 series and Boeing 737 series, with seats for between 150 and 200 passengers. The engines put out, I think, about three times as much thrust each as the military engines, but they are higher by-pass (meaning cold air which is propelled around and not through the core of the jet engine). Simple arithmetic shows that the airline took in less than €20,000 for the Paderborn-Stansted flight. The cost of an engine rebuild or new engine (and, when one, then both!) lies well in the seven-figure range (I don't know how much – this is business-confidential information shared by an airline and its maintenance services and their suppliers), which is two orders of magnitude higher than the five-figure sum the airline was taking in. And until Monday 19th, after the research flights, no one really knew at what flight levels the ash was to be found. So, at a first guess, just to break even in monetary outlays, only one flight in a hundred can have such problems. Or, to put it another way, if just one plane on that route has problems, then you have to have another 24 days of problem-free flying that route (two flights a day in each direction) to break even.

This simple calculation doesn't take into account that, if one airplane has problems, you may well have to mandate the minute inspection of the engines of any other of your planes that flew part of that route around that time frame. And since airlines use a hub system, that means any planes which flew into or out of the hub into which the problem aircraft flew into or out of.

That doesn't look like a promising basis for deciding to fly.

Not only that, but suppose some other airline flying in and around your routes has an engine problem, which a tear-down indicates may be correlated with ash. Then the regulators could well mandate tear-downs of all similar engines (or maybe all engines) with similar exposure. So it doesn't even have to be your problem that initiates tear-downs of your engines.

Here is a further way you might then think. You are not making the decision to fly or not. Somebody else, a government regulator, is telling you you can't fly. Whatever your actual evaluation of the risk, you can now argue that the decision is being made by government, so government should be sharing with you the enormous cost of your

- forcibly, you will say - not being able to do business.

So, politically, one could expect discussions about bail-outs.

If you are a savvy CEO, you will also realise that uncertainty leads to an a priori decision about risk being very likely more cautious than the actual situation will have warranted. So you can wait for the actual data to accumulate, knowing that you will, in all likelihood, be able to argue "see, it was less dangerous than you said; we told you so".

2.7 Financial Risk Analysis

Let us try a simple financial risk analysis.

The hazard is an encounter with a volcanic ash cloud. This had, at the time, certainty. Let us classify the outcome categories per per flight which undergoes the hazard. I choose four. Let us call them Outcomes 1-4:

Outcome 1 No damage

Outcome 2 One or more engines need thorough inspection and cleaning

Outcome 3 One or more engines need major overhaul

Outcome 4 Engines stop in flight.

All of these have actually happened to aircraft at some point:

- Outcome 1 to the majority of airline flights
- Outcome 2 to a couple of Ryanair planes [BBC20100510] and to the Finnish F-18s op. cit.,
- Outcome 3 to the NASA DC-8 in 2000 op. cit. (apparently at a cost of some $3.2m)
- Outcome 4 to Capt. Eric Moody on the famous BA Flight 9, a Boeing 747 in 1982 op.cit.

One can almost directly read off the severity from these outcomes. Let us consider units to be equivalently pounds or euros or dollars.

Severity of Outcome 1 0

Severity of Outcome 2 104 to 105

Severity of Outcome 3 106 to 107

Severity of Outcome 4 If a catastrophe is caused (i.e. the airplane does not succeed in making a dead-stick landing on an airport) then 108 -109

Curiously, these four categories fit crudely but so neatly into powers of 10, covering the range. Writing the probability of Outcome 1 as $prob(1)$, etc., the risk is

$$probability(hazard).expectation(hazard - outcome) =$$

$$1.expectation(hazard - outcome) =$$

$$prob(1).severity(1) + prob(2).severity(2) + prob(3).severity(3) + prob(4).severity(4)$$

This is only a crude estimate. If some engine is found to be damaged, then all engines on all airplanes flying into or from those airports that engine flew into and around those routes that engine took will have to be inspected as well, and that might run into the hundreds. This calculation does not take account of these multiplicative effects.

Using $severity(1) = 0$, the risk per flight then lies between (using the lower factors of ten associated with the severity)

$$0.prob(1) + 104.prob(2) + 106.prob(3) + 108.prob(4) =$$

$$104.prob(2) + 106.prob(3) + 108.prob(4)$$

and (using the higher factors of ten associated with the severity), ten times this amount, namely

$$105.prob(2) + 107.prob(3) + 109.prob(4)$$

Consider an average intraeuropean flight, say Paderborn-London Stansted in a Boeing 737NG, let's say 150 people on board, paying €100 per seat (Air Berlin flew that route at that time for about €90 per seat, and much of that was airport tax). Revenue for the flight is €15,000 (much less, maybe about half, when airport tax is removed).

A cleaning event won't set you back much, but you had better be sure, if you wish to break even, that you have at most one chance in 100 flights of an overhaul event (Outcome 3), and only one chance in 10,000 flights of an engine-out event (Outcome 4).

Given what was known on April 16th about outcomes (for example, that the Finnish engines might be trash), I suspect that much of what was heard in the way of complaints from airline chiefs was manoeuvring for government handouts to "compensate" them for being forced to do what a risk analysis such as this indicates they would have done anyway.

2.8 Exercises

1. Estimate prob(1), prob(2), prob(3) and prob(4) from the standpoint of knowledge on 2010-04-15, when airspace was closed. Give your reasons for your estimates. List the uncertainties which attend your estimates. Derive the financial risk.

2. Estimate prob(1).... prob(4) from the standpoint of knowledge on 2010-04-22, after the DLR flights and analysis of the ash. Give your reasons for your estimates. List the uncertainties which attend your estimates. Derive the financial risk.

3. Estimate prob(1).... prob(4) after the Finnish analysis showed damage to be benign. Give your reasons for your estimates. List the uncertainties which attend your estimates. Derive the financial risk.

4. List all possible trigger events for Outcomes 1-4.

5. Derive an estimate of probabilities for all those trigger events. Redo the risk calculations in Exercises 1-3 using these trigger events and their estimates. How do the new estimates compare with the old?

6. Suppose at the outset the regulators had said "go fly if you want, but inspect all engines every two hours of in-ash-cloud flying". Based on the revenue derived from a flight, as above, and your estimates of probability and cost, would you have taken up that offer as an airline CEO? Give your reasoning. If you would

not have taken up the offer, what difference in your estimates would have induced you to do so? Would those different estimates have been plausible (even if not yours) at the time?

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