PARE

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CHAPTER 14

The Two Boeing 737 Max Accidents and Consequences

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The two Boeing 737 Max accidents in less than one year have shaken the aviation world on a scale that has only two other precedents in the past decades, namely: (i) the demise in the 50's of the first jet airliner, the de Havilland Comet (Figure 14.1), due to acoustic fatigue problems unknown at the time, though it survived until recently in heavily modified form as the Nimrod maritime patrol aircraft; (ii) the intense media publicity due to the loss of life associated with structural failure of the tail of the Douglas DC-10 trijet (Figure 14.2) in the 70's, which did not prevent its continued development as the McDonnell Douglas MD-10. It is too early to predict the long-term consequences of the two B737 Max accidents that for all negative reasons have become the major undesirable events since the start of the PARE project, making them an inescapable candidate for a case study, as far as the patchy currently available information can support reasonable technical assessment.

Figure 14.1 - De Havilland Comet aeroplane.
(Source: http://bit.ly/2WyPbIe)

Figure 14.2 - McDonnell Douglas DC-10 aircraft.
(Source: http://bit.ly/2qcz7jg)

Chapter 14 – The Two Boeing 737 Max Accidents

14.1 Introduction

The Manoeuvring Characteristics Augmentation System (MCAS) that Boeing designed specifically for the 737 Max has been implicated in both accidents. Although the 737 Max was certified by the Federal Aviation Administration (FAA) as a modification of the earlier two generations (original B737 and B737NG – New Generation), the MCAS is a new addition to the aircraft systems. Thus three factors relating to the accidents (section 14.2) are: (subsection 14.2.1) the motivations that lead to the introduction of the MCAS in the third-generation B737 Max; (subsection 14.2.2) the list of issues on questionable design features that could have safety implications; (subsection 14.2.3) the limited information publicly available about the two accidents and the role the MCAS may have played.

The near-term consequences (section 14.3) can be viewed from three aspects: (subsection 14.3.1) the grounding of the Boeing 737 Max by Airworthiness authorities worldwide and the path towards ungrounding; (subsection 14.3.2) the changes to the MCAS performed by Boeing and the extent to which they meet current safety concerns; (subsection 14.3.3) the steps towards resumption of normal service when ungrounding is eventually certified by the various aviation safety authorities around the world.

Some near-term consequences may have longer-term effects (section 14.4) at least in three areas: (subsection 14.4.1) the loss of credibility of Boeing as an aircraft manufacturer and of the FAA as a certification authority, that may affect other aviation stakeholders, even if they had no influence in the accidents that rocked the public and the aviation community; (subsection 14.4.2) the multiple contributors to financial losses by Boeing and the extent to which some but not all these are temporary and can be recovered at a later stage, when airline operations re-start and new aircraft deliveries resume; (subsection 14.4.3) the effect on the current and future Boeing 737 Max order book in the context of the duopoly competition with the Airbus A320neo and derivatives, and the urgent need for a 737 replacement as a Middle of the Market Aircraft (MMA) or a direct Future SA (FSA) replacement or a family of new aircraft.

The ultimate aim of all current activities, by Boeing as OEM (Original Equipment Manufacturer), the FAA and other certification authorities worldwide and airline operators around the globe, is a safe return to services as soon as possible, at a date yet difficult to predict. The safety measures needed include: (14.5.1) reducing the probability of failure of the MCAS, making it fail-safe or alternative measures; (14.5.2) ensuring that the elevator runaway procedure is robust and sufficiently fast-acting without excessive control forces; (14.5.3) providing a pilot training package including failure scenarios and realistic and manageable control forces.

A tentative analysis is made of root causes and their consequences in future scenarios (14.6) within the uncertainties of currently available information that is patchy and dispersed but includes limited results of a Boeing internal enquiry (14.6.2). The root causes may be multiple like most aircraft accidents, combining questionable engineering and management choices driven by an unclear priority between safety, cost and expediency (14.6.1). While some corrective actions clearly resolve some of the six issues (14.2.2), others may require time and resources whose availability is less clear. The efforts to return the B737 Max safely to service may not be helped by market factors and other unrelated Boeing activities that may reduce incomes and consume available resources (14.6.3).

The introduction (14.1) outlines the scope of the analysis, and the conclusion (14.7) ventures into some conjectures on possible future developments.

14.2 Main Contributing Factors

The Boeing 737 Max was certified by the FAA for pilots without any transition simulator training from the preceding generation 737NG, requiring an MCAS to mask its different flying characteristics. The design of the MCAS incurred in a surprising number of basic flaws (subsection 14.2.2) in spite of Boeing experience and competence in the area. Based on the limited publicly available information on the accidents (subsection 14.2.3), the MCAS is widely suspected to be implicated in both instances.

14.2.1 The need for a MCAS in the B737 Max

The first generation Boeing 737 (Figure 14.3) already has automatic pitch trim that was carried over in the next generation 737 NG (Figure 14.4) and could be disabled by pilot action on the control column, reverting to manual control.

Figure 14.3 - Boeing 737 prototype at the Museum of Flight, in Seattle, USA. (Source: http://bit.ly/2BbtyUq)

Figure 14.4 – Boeing 737 NG. (Source: http://bit.ly/2B6WSeG)

The more recent Airbus A320 (Figure 14.5) has comparable systems, and the two competitors shared almost evenly a duopoly of the single-aisle (SA) airliner market, with perhaps a slight lead of the all-new more advanced first-generation challenger over the second generation of the incumbent benefiting from grandfather rights that required it to meet only past rather than current certification standards. The stable 'status quo' was disturbed by Bombardier developing the C-series (Figure 14.6) as an all-new aircraft in the 100-130 seat class competing in the low end of the A320/B737 market with efficiency gains mainly due to new engines.

Figure 14.5 – Airbus 320.
(Source: http://bit.ly/2OMbp7u)

Figure 14.6 - Airbus A220, previously known as Bombardier C-Series.
(Source: http://bit.ly/32ldBqQ)

Bombardier like its rival Embraer is about one-tenth the size of Airbus and Boeing, and brave or foolish enough to challenge them, although claiming that this was not the case. Embraer, perhaps more wisely, chose not to challenge head-on the 'giants' and remained within the upper reaches of the regional aircraft market. Boeing was aware of the limited development potential left in the B737, did not wish to try a compromised third-generation design and steadily worked towards an all-new clean sheet replacement towards the end of the decade; Boeing expected airlines to wait for its superior future product and saw no need to counter Bombardier scratching the bottom of its SA market. Airbus took the opposite position, realizing that adding to the development potential of the A320 the engine technology in the Bombardier C-series, it could produce in a short time and with modest budget an A320neo (Figure 14.7) that would prevent the newcomer from gaining its intended market share.

Figure 14.7 – Airbus marks its 1,000th A320neo family aircraft delivery.
(Source: http://bit.ly/2VG4oqk)

The Bombardier C-series was not helped by development delays and cost overruns that might have led to bankruptcy had the Canadian government not intervened. In the meantime Airbus determination to develop the A320neo without a launch customer was amply rewarded: the A320neo was a runaway success beyond the Airbus wildest expectations with more than a 1000 orders in a few months after the launch without customers, validating the Airbus faith in the concept: airlines could not ignore a 15% improvement in fuel consumption at a time of high fuel costs. The message was brought home to Boeing when American Airlines, an all

Boeing operator, made a record order for the A320neo. Boeing threatened to sue American Airlines for breach of its long-term soon-to-expire exclusive supply agreement but was told to develop a re-engined B737 if it wanted a share of the order. In a few days, Boeing decided it had no choice to keep a valuable customer other than to shelve its continuing work on an all-new B737 replacement in favour of the hasty development of a third-generation 737 Max compromised from the beginning by its origins half a century earlier.

The B737 Max (Figure 14.8) had little in common with the original B737 that first flew in 1967. A cabin with almost the double seating capacity, a much larger wing, more powerful engines, etc. ...Yet it was certified as modified aircraft. Boeing wanted pilots certified for the second generation B737NG to fly the third generation B737 Max without simulator training for the transition. And the FAA required that the flying characteristics should be the same.

Figure 14.8 – Boeing 737 Max.
(Source: https://www.boeing.com/commercial/737max/)

Perhaps the biggest handicap inherited from the original half-a-century old B737 design was a low wing beneath which was possible to fit a first-generation turbofan with a low by-pass ratio in a small diameter nacelle. The second-generation B737NG design was challenging in fitting a turbofan with higher by-pass ratio: the engine nacelle was no longer circular but had a flattened bottom close to the ground, and was also closer to the wing with a shortened pylon, resulting in the formation of shock waves in cruise flight. The resolution of aerodynamical and structural compromises did not prevent the commercial success of the B737NG but Boeing became acutely aware that development potential was near its limits, and accordingly planned the methodic development of an all-new replacement.

The requirement to develop the third generation B737 Max with high by-pass ratio turbofans posed almost impossible challenges on how to fit the large engine nacelle under the wing. The nose landing gear was extended to increase ground clearance but less could be made about the main landing gear retracting into the wing, short of a major structural redesign. The engine nacelle was pushed up and forward creating a strong pitch-up at high angles of attack and low speed. In spite of all this, the critical fan diameter in the B737 Max could not match the A320neo giving the latter a fuel-efficiency advantage that could not be clawed back by aerodynamic or structural measures. Ultimately competitiveness was ensured by reduced seat pitch and higher passenger capacity in a B737 Max cabin that is smaller than that of the A320neo; this is possible by the B737 'grandfather rights', which mean that it does not meet the more recent and stringent emergency evacuation standards that apply to the A320.

A problem remained: the 737 Max was required by the FAA to fly like a 737NG but had a more severe pitch-up at low speed and high angle-of-attack (AoA); the MCAS was developed by Boeing to automatically compensate this pitch-up and make the B737 Max respond like B737NG. The execution of the MCAS should fulfil that aim.

14.2.2 Six issues: questionable design features

The design of the MCAS involved at least 6 issues on questionable design features that could hardly be expected of a manufacturer with the competence and experience of Boeing, and should not escape scrutiny in a certification process with the high standards expected of the FAA:

Issue 1 – single sensor failure: the MCAS was triggered into action by a signal from a single AoA sensor exceeding a threshold indicating a pitch-up. Although the B737 Max has 2 AoA sensors (the Airbus aircraft have 3), Boeing chose to use only one per flight, alternatively from the left and right side. Thus a single AoA sensor failure signalling a false high AoA, without any warning, could activate the MCAS;

Issue 2 – safety a cost option: a cost option was available to use both AoA in all flights. In case of major disagreement, an indication in the cockpit would serve as a warning of sensor failure, with no possibility to identify which might be the correct or incorrect sensor. It is not clear why this valuable safety feature was made a cost option. This may have contributed to most airlines not taking the option since they could not see its usefulness because the existence of the MCAS was not disclosed (see issue 4) below;

Issue 3 – runaway elevator pitch-down: once an excessive AoA signal triggered the MCAS it would automatically apply a pre-set pitch-down, at regular intervals, without limit, until the AoA fell below the specified threshold. In the event of a failed AoA sensor, locked or frozen at an excessive high-value, the MCAS would apply a runaway pitch-down trim beyond the control power of pilots, who did not even know the MCAS existed;

Issue 4 – the omission of reference to MCAS in the flight manual: Boeing decided that since the MCAS system was 'transparent' to the pilots, they did not need to know about its existence, because the 737 Max would fly like a B737NG if the system operated properly. It is not known if this flawed Boeing decision was formally approved by the FAA or if the FAA was unaware because of a derogation of responsibility to the aircraft manufacturer… The argument of 'transparent' borders on contradiction because:

- The MCAS is vulnerable to runaway (item 3) due to a single sensor failure (item 1);
- In such a case the pilots could not know the cause of the runaway because of the existence of the MCAS was not disclosed;

- The pilots find a B737 Max pitch runaway when they expect B737NG like handling and were not trained for the difference.

All this looks more like “lack of transparency”. The pilots had to identify a pitch runaway without knowing about its cause.

Issue 5 – omissions in checklist: in the original B737 and B737NG the automatic pitch trim could be disengaged by the pilots moving the control column beyond a point leading to manual control. The MCAS in the B737 Max was designed to override this feature. It could be disengaged only if the pilots used some toggle switches together with the movement of the control column. This was mentioned in the pitch runaway checklist, although some airlines informed erroneously pilots that control column movement was sufficient to regain manual pitch control. This was not Boeing’s fault, but omissions in the pitch runaway checklist might be. When Boeing demonstrated in a simulator to airline pilots a redesigned MCAS they noticed that:

- To recover from an MCAS induced pitch-down, the control forces were so large that both pilots should pull their sticks together;
- Furthermore, to reduce the control forces, the initial stick movement should be the opposite.

These can be serious omissions in a critical situation requiring large control forces. Boeing always maintained that the way out of an MCAS failure was to apply the elevator runaway procedure and that the checklist should be known by memory by pilots. However, the checklist had the two omissions mentioned above.

Issue 6 – slow pitch response: after the two accidents, Boeing made software changes to the MCAS and re-submitted to FAA certification. The FAA pilots tested on the simulator the pitch trim runaway procedure that was presented by Boeing as the escape route from MCAS malfunction. They found in certain cases very slow response times of the order of seconds. This was traced down to some computer chips requiring hardware changes. The Boeing claim that these control issues are unrelated to the MCAS is to some extent questionable since the elevator runaway procedure was presented as the escape route to MCAS failure. Boeing agreed with the FAA that control system redesign is essential since such slow responses are not acceptable, in particular in an emergency situation. The requirement for hardware as well as software changes to the pitch control system introduced another step and delay in the re-certification process.

14.2.3 Sequence of occurrences in the accidents

Since the information available on the two B737 Max accidents was limited until the recent report on one of them, any judgement of contributing factors must be made with caution. Enough is known to implicate the MCAS in both accidents although there are different views on how responsibility should be assigned.

The B737 Max of Lion Air involved in the first accident already showed dubious readings of the AoA while on the ground prior to take-off, leading to speculation about some maintenance issue or other damage. After the take-off and about 15 minutes into the flight, the aircraft started an uncommanded dive into the ground. The crew may not have identified a runaway elevator condition and apparently did not apply the corresponding checklist. They failed to manually reverse the pitch-down that may have exceeded the control power available to the pilots.

Boeing blames the crew for not applying the runaway elevator checklist they should know by heart. This assumes that the crew:

- Suspects a faulty AoA sensor although it has no warning of the situation;

- Identifies an elevator runaway condition without knowing about the existence of an MCAS that was implicated;

- Recognizes that manual control cannot cope with the runaway inputs of an unseen system.

Maybe this is to expect more of the pilots that fly the aircraft than from the engineers that designed the MCAS and the authorities that certified or derogated it.

The accident report lists multiple causes. Some relate to poor Boeing design of the MCAS and inadequate certification procedures of the FAA. In addition, the AoA sensors of that particular aircraft had a history of failures that the crew did not know about; the AoA might have a wrong calibration, and the workshop that did that work was closed. Finally, although the captain was an experienced pilot, the co-pilot was not, showing limited skills in earlier training. Perhaps aggravated by the stress of the situation with fault warnings, the communication was poor, and the co-pilot may not have fully understood when the captain handed over control to him.

Boeing was aware that the MCAS could be implicated in the Lion Air accident and:

- Issued a bulletin that did not explicitly mention the MCAS but reminded of the procedures following a suspected elevator runaway condition and advised that the bulletin be appended to the flight manual;

- The elevator runaway checklist had the omissions concerning control forces (issue 5 in subsection 14.2.2) that were identified later in demonstrations to airline pilots of the redesigned MCAS;

- The FAA reviewed with the European Union Aviation Safety Agency (EASA), as part of their cooperation, all past B737 Max incidents, and found no relation with the Lion Air accident, so made no flight ban, although it is not clear if the MCAS was considered as a possible contributor or if EASA knew or had been informed of its existence;

- Also following the Lion Air accidents, Boeing started an internal effort to redesign the MCAS to issue a modification within 2 months, but that date slipped as more changes were considered, possibly not only to MCAS but also to other systems.

Within 6 months of the Lion Air accident, a similar occurrence leads to a crash of an Ethiopian Airlines B737 Max about five minutes after take-off. The similarities were obvious: an uncommanded steep dive into the ground that the pilots could not counter with repeated pitch-ups. This time:

- The AoA only malfunctioned after take-off, leading to speculation about a bird strike or similar event, that cannot be confirmed;

- The pilots did recognize an elevator runaway condition and did follow the checklist using both the control column and toggle switches to regain manual control;

- Although the pilots did follow the elevator runaway checklist, they were unable to manually trim the aircraft and stop the dive: could this be due to the large control forces or slow control response (issues 5 and 6 of subsection 14.2.2)?

- Perhaps in a last desperate attempt to reverse the dive, and having failed to do so manually, the pilots used again the toggle switches to engage automatic pitch trim, unknowingly activating the MCAS that only made matters worse.

The excuse of Boeing that the pilots 'did not apply the checklist consistently' borders on the cynical. The pilots (i) did recognise the elevator runaway condition without information about the AoA sensor malfunction and without knowing of the existence of the MCAS and its effects; (ii) fully applied the runaway elevator checklist as it was known to them; (iii) could not have guessed the omissions in the checklist about control forces and directions; (iv) it is not known if the slow response to the pitch trim runaway condition found in subsequent FAA tests (issue 6 of subsection 14.2.2) occurred in this instance. It appears that the crew did all it could possibly have done but was betrayed by incomplete information and a hidden MCAS system. In both accidents, the crew repeatedly tried to counter the dive with mandated pitch-ups but failed to overcome the pitch-downs commanded by the MCAS that ultimately prevailed and caused a dive into the ground.

14.3 Near-term Consequences

The almost immediate consequence of the second B737 Max accident was a ban of operations, which the FAA was the last to implement on orders from the United States (U.S.) President (subsection 14.3.1). Boeing was already developing a number of software changes to the MCAS which it claimed would safeguard against further accidents (subsection 14.3.2). The return to normal service can be envisaged only when the aviation safety authorities around the world lift their bans (subsection 14.3.3).

14.3.1 Ban of operations from national authorities

The first to react to the similarities of the two B737 Max accidents were the Chinese airworthiness authorities: they questioned the FAA as the original certification authority, were not satisfied with the answers and within 24 hours banned all B737 Max flight operations. This swift action might have been seen as another episode in the U.S. – China trade war if Singapore and Australia had not placed similar bans soon after. The ban on B737 Max operations quickly spread worldwide, including Canada and starting in Europe with Ireland that hosts low-cost airlines that are major B737 Max operators. The ban was quickly followed by France and Germany, and then EASA. Given the efforts at cross-certification between EASA and the FAA, and their most successful cooperation, EASA may have been less inclined to question the FAA certification.

The FAA was the last airworthiness authority in the world to ban the B737 Max operations, claiming against all others that this was an unjustified action based on insufficient evidence. It was President Donald Trump who ordered the FAA to ban B737 Max operations. His motivation was that there had been no major jet airline accidents in the United States (as in most Western countries) for some years, and he wanted to avoid a new one. When finally banning B737 Max operations, the FAA argued it had received refined satellite data that clearly correlated the two accidents: similar altitude excursions resulting from MCAS enforced pitch-down opposed by crew commanded pitch-ups that ultimately could not cope, resulting in a terminal dive. A national ban of aircraft operations has two elements: (i) it forbids national airlines flying the aeroplane; (ii) it does not allow the aeroplane of any foreign airline to enter national airspace.

The B737 Max accidents damaged the credibility of the FAA almost as much as that of Boeing. If Boeing designed a flawed MCAS, how come the FAA did certify it? The FAA mandated the development of the MCAS so that pilots could transition from the second generation B737NG to the third generation B737 Max without any specific simulator training. And Boeing succeeded in making the B737 Max handle undistinguishably from the B737NG in pilot tests in the simulator, as long as the MCAS worked as intended. However, the questions about the unintended operation are unavoidable: (i) why a safety system was left vulnerable to a single sensor failure without warning?; (ii) how come that an automatic system can react to erroneous signals with runaway repeated commands beyond pilot control? Bearing in mind that the MCAS is not fail-safe, why were pilots not informed of its existence and trained at least in the simulator to identify and counter its failures? Boeing did not hide the existence of the system, at least in presentations about the differences between the B737NG and B737 Max and in the maintenance documentation of the B737 Max. But no mention of the MCAS was made in the flight manuals and most pilots were not aware that real flight characteristics of the B737 Max were different from those of the 737NG.

These questions apply equally to Boeing that developed the MCAS and to the FAA that certified it. Having mandated the development of the MCAS by Boeing, did the FAA check the outcome in detail? Did it not notice, the single point sensor failure, the runaway trim or the lack of documentation in the flight manual? Did the FAA explicitly approve all this or did it rely on a delegation of the supervisory authority to the manufacturer? In view of all these questions several Airworthiness authorities, including EASA, Canada and Australia, state that they will no longer accept an eventual FAA recertification of the B737 Max and will conduct their own independent investigations until they were convinced of the safety of the MCAS and perhaps other systems. The FAA holds regular meetings with other Airworthiness authorities on the Boeing 737 Max ban, reported to be sometimes hot with the FAA trying to restore its credibility in the face of scepticism of others.

14.3.2 Boeing modifications to the MCAS

Boeing started modifications to the MCAS in the time period between the two 737 Max accidents, and since the second accident and the worldwide grounding of the fleet this has become its highest priority, to submit the recertification file to the FAA and unground the aircraft. Under intense pressure over its apparent laxity in the certification of the original MCAS, and with the scrutiny of other Airworthiness authorities around the world, this time the FAA is unlikely to delegate anything and may go to greater scrutiny of the detail of the changes. Boeing delivered the list of software changes hoping for approval in a few months, but the FAA asserts it has no timeline for acceptance and will focus only on safety. The discovery of the situation of slow pitch control response (issue 6 of subsection 14.2.2) has led to the FAA to mandate and Boeing to agree to hardware changes delaying certification by several months till an uncertain date.

The Boeing first redesign of the MCAS consists only of software changes, and is claimed by Boeing to provide three layers of protection against similar accidents occurring:

1- First, the data from both AoA sensors are used in every flight, and if a significant discrepancy is detected, the MCAS is disconnected and the pilots warned;
2- Second, the MCAS can make only one pitch-down intervention unless the pilots require or authorize further actions;
3- Third, at all times the pilots have at least 1.2g of pitch-up control authority.

These changes correspond to how the MCAs should have been designed in the first place and are certainly an improvement, but may not answer all questions.

The redesigned MCAS remains not fail-safe since a single sensor failure deactivates the system. Errors of AoA sensors, due to freezing in icing conditions, or mechanical and electrical failures, are neither common nor extremely rare and have been involved in other accidents. Is it worthwhile to design a safety system that is disabled after a single sensor failure? Airbus uses 3 AoA sensors in order to be able to vote out one dissident sensor, which Boeing cannot do with 2 AoA sensors. Even 3 AoA sensors are not absolutely safe with recorded instances of two consistent frozen sensors outvoting the correct one. But if the A320 that does not have the B737 Max pitch-up issue uses 3 AoA sensors, should the B737 Max use 4 AoA in a fail-safe quadruplex system? Boeing appears to be reluctant to implement any hardware changes that would require a costly development, bring new certification requirements and delay ungrounding and resumption of operations.

However, Boeing will have to make other hardware changes after the software changes it submitted proved insufficient. This time the issue was not the MCAS itself but the pitch trim runaway procedure repeatedly put forward by Boeing as the answer to MCAS failures. The FAA pilots tested the procedure in the simulator and found rare cases of slow control response of the order of seconds. This may or may not be a new problem since in the original certification were found some safety situations that could only be resolved with pilot input. It was considered at the time that such situations were sufficiently rare not to require specific corrective action. Much tighter scrutiny has come into play since the two B737 Max accidents, and this time the slow pitch control response was traced down to a computer chip. Boeing agreed with the FAA that pitch control response times of the order of seconds are not acceptable in emergency situations, and will have to make hardware changes to the computer system. The need for hardware changes found more recently may also lead to more stringent requirements for recertification.

14.3.3 Return to Service and deliveries

More worrying is the Boeing initial position that following the MCAS changes 'computer training' or touchpad experience is sufficient and no simulator training of pilots is required, which Boeing will provide only at airlines request perhaps at extra cost, as a new business line; along similar lines, Boeing might be expecting the FAA to unground the B737 Max without including pilot simulator training in the minimum requirements and limiting itself to software and documentation changes. This rather light-hearted position calls into question again the Boeing commitment to safety, and if accepted by the FAA could further damage its credibility.

Pilots are likely to resist the notion that they need no training against the failure of a safety system disabled by one sensor malfunction and leading to a pitch-up at high AoA for a real aircraft (B737 Max) far removed from the flying characteristics they were trained for (B737 NG). Airlines may rightly take into consideration the concerns of their pilots, as guardians of passenger safety and their own. And several Airworthiness authorities around the world have clearly stated they may require pilot simulator training as part of the recertification process. Boeing and the FAA should realize that not including pilot simulator training in the minimum requirements could reopen the credibility gap they are trying to close. It is reported that there is a tendency towards convergence of the FAA and other Airworthiness authorities worldwide on the conditions for ungrounding the B737 Max and allowing the return to service, and this would include a pilot training package besides system software and hardware changes.

Boeing has set aside 100 million dollars as compensation for the deaths of 366 passengers in the two B737 Max accidents. Had just one of those accidents been in the U.S., the compensation bill could be much higher into billions. Had both accidents occurred in the U.S. with its tradition of litigation, criminal charges might have been levelled at Boeing and the FAA. Although safety is always the stated first priority, Boeing is also driven by the aim to unground the B737 Max as soon as possible and the FAA still tries to shake away the impression of lack of independence in its certification authority. As the International Air Transport Association (IATA) Director General noted, as his main concern about aviation safety: how can it be explained that the same aeroplane is safe to fly in one part of the world and not in another? If Boeing convinces the FAA to set minimum recertification requirements that other Airworthiness authorities around the world would not accept, it will further damage the reputation of both, and provide a sad image of certification spreading geographically at a pace determined by national criteria. Also, the situation where (i) some airlines can and other cannot fly the same aircraft, and (ii) the same aircraft can fly in some but not other parts of the world may leave passengers wondering whether they should be flying at all in that particular aircraft.

Even if all Airworthiness authorities around the world agree on a common recertification standard and the same date of lifting the current ban, it does not imply that the whole 737 Max fleet will come back into operation at the same pace. The 385 737 Max already delivered before the ban have been replaced by other aircraft, mostly leases, and will require inspection and software and hardware changes before returning to flight. It is no longer only software changes requiring a few hours as Boeing claimed at one time.

The B737 Max production at a rate of 52 per month was temporarily halted after the ban of operations and then reduced to 42 per month. Boeing has been parking the aircraft it produces and cannot deliver using a special FAA permission to ferry the aircraft away from the production site, to another with more available space for parking. The parked fleet totalling more than 250 B737 Max will require flight testing before handing over to airlines. All aircraft will require software upgrades to the MCAS which Boeing said can be performed in a few hours before the need for hardware changes was found. These changes will apply to (i) the 385 aircraft delivered to airlines and grounded, (ii) the more than 250 aircraft produced and parked but not delivered. The ungrounding of more than 600 aircraft would take place at a rate of 70 per month over at least 8 months according to the Boeing plan. However, it may take longer for airlines to reintroduce the 737 Max to the fleet depending on how many aircraft relative to the size of the airline and the time of the seasonal travel market when the activity is more or less intense.

14.4 Long-term Effects

The financial losses due to the grounding of the 737 Max (section 14.4.1) have mostly short-term effects while the large order book may be safe in the next few years (section 14.4.2). Resolving the current 737 Max issues as quickly as possible and returning the aircraft to operation is essential not only to stem short-term losses: Boeing needs to regain credibility and evolve away from the damaged 737 Max reputation towards all-new aircraft in the short-haul sector with a new SA, and perhaps the MMA as well (section 14.4.3).

14.4.1 Financial Losses and Recovery

Boeing has a 100 billion yearly turnover, of which 60 billion comes from airliner sales, generating a 9 billion profit. Its strong financial position is backed by a backlog of orders covering more than five years of production worth hundreds of billions. In the unlikely event, its internal financial resources prove insufficient, there should be no problem in obtaining credit. While Boeing may be able to absorb the losses associated with the grounding of the B737 Max, they can certainly affect profits and turn them into losses, due to multiple causes.

First, the airlines owning the 385 B737 Max already delivered and now grounded can claim compensation from Boeing: for lost flights and passenger revenue, for leasing replacement aircraft and for the disruption to their flight plans and schedules. Second, Boeing is still producing the B737 Max at a monthly rate reduced from 52 to 42 that may actually be a welcome relief to its overstretched supply chain. However, at a nominal value of 50 million each (without discounts), 42 aircraft a month represent a missing revenue of 2 billion; Boeing has permission to fly away aircraft to parking areas and is paying fines for late delivery. The missing revenue will be recovered when the ban is lifted and the aircraft are delivered to airlines, but not the fines. In the meantime, Boeing is allocating with the highest priority internal resources to solve the B737 Max issues and stem as soon as possible the losses.

Boeing quoted 4.9 billion over one quarter associated with B737 Max costs, resulting in an unprecedented loss of 2.9 billion over that quarter, wiping out 2 billion of profit from other programs. This was the biggest quarterly loss ever at Boeing. Boeing admits that it may have to halt production if the current issues drag into 2020 depending on the outcome of hardware changes. The software changes were submitted within three months with the expectation of re-certification within a similar period. The discovery of additional control issues requiring hardware changes sets the clock back to starting point, all depending on how long Boeing takes to perform the hardware changes and how long the FAA takes to validate them hopefully with a consensus of other Airworthiness authorities worldwide. The FAA has repeatedly stated it has no timeline for ungrounding the B737 Max and the emergence of new hardware issues vindicated that position. Boeing has publicly stated that, after submitting the second set of changes, the aircraft could be certificated before the end of the year.

On the other hand, Boeing intends to raise production to the 57 per month it planned before the ban as soon as the B737 Max is ungrounded. In order to quickly resume production, Boeing will have to mind not only its airline customers but also its industrial supply chain. The main airframe supplier, Spirit AeroSystems, is sheltered from the B737 Max troubles by a favourable contract previously signed with Boeing guaranteeing a monthly production rate of 52. Others in the supply chain may be dependent on the B737 Max production and not have the resources to survive a long interruption without Boeing support. The target of delivering 70 B737 Max per month after ungrounding is dependent not only on Boeing ability to do so but also on customer airlines agreeing on a suitably fast transition from the current 'substitution' schemes. For most airlines, the sooner they receive new more efficient aircraft the better, as long as feasible for transition plans.

14.4.2 Current and future order book

Airbus has a backlog of 6500 A320 orders corresponding to more than 8 years of production at the current rate of 60 aircraft per month. Boeing has a backlog of 4500 B737 orders corresponding to more than 7 years of production at a rate of 52 per month. Both Airbus and Boeing were struggling to increase their production rates from overstretched supply chains barely able to provide the required number of engines and other major and minor pieces of equipment; in some cases, the acquisition of suppliers was the way to increase production. The B737 Max ban does not change the fact that switching orders with the A320 is not a viable proposition in either direction. Airlines cannot afford to wait 5 years or more for a new more efficient aircraft and keep operating current older models and must stick to their precious earlier production slots.

In this situation where demand for airliners far exceeds supply, and waiting times exceed 5 years, the current order books of Boeing and Airbus are safe, and the B737 Max troubles are unlikely to lead to any cancellations. There have been some rumours of airlines talking to Airbus about shifting the order from the B737 Max to the A320: Airbus does not confirm this merely stating that it is in continuous contact with airlines. Airbus has been carefully silent about the B737 Max issues, being conscious that inflating safety concerns will harm the whole aeronautical industry. Instead, Airbus has been trying to expand its lead at the upper end of the SA market, with the A321LR and A330neo squeezing the potential MMA market from above and below.

While airlines are unlikely to shed their precious B737 Max production slots, the situation may change with regard to new orders, for which the long waiting time will be comparable for the B737 Max and A320neo. The negative publicity resulting from the two B737 Max accidents may explain why it has not received new orders since the grounding while Airbus sold more than 100 A320neo over the same period. Airbus planned to highlight its strength announcing its new A321XLR stretch at the Paris air show to collect 150 new orders. Contrary to all expectations, it was Boeing who stole the show with a larger order for 200 B737 Max from a single customer: a leasing company. Boeing was relieved that the order “could not have come at a better time”. The customer expressed its “confidence in the B737 Max” and later gave as a motivation a concern of “excessive dependence on the A320neo”. The financial details were not disclosed, as is usual practice, and there was no shortage of gossip on how big a discount the leasing company as a customer had obtained out of the Boeing need to bolster its credibility.

Even if the B727 Max current order book is safe, the damage to its reputation will not disappear soon. Lion Air says it will be the last airline to bring the B737 Max into service, only after all others have proved it safe, to erase its accident memory. The leader of a major airline has speculated that in order to bring passengers back into the B737 Max, Boeing might have to change its designation away from a tarnished name. In fact, most passengers are not aware of which aircraft they are flying, so the major consideration lies with airlines. If the B737 Max can be brought safely back to service without an excessive delay, then many of its current airline customers may even resume their planned follow-on orders, perhaps with some discounts to help. The main issue that Boeing has to face is that its losing position at the upper end of the SA market combined with the damaged reputation of the B737 Max make the transition to an all-new replacement and/or the MMA more urgent than ever.

14.4.3 The B737 Replacement and the MMA

Until the B737 Max is safely returned to service, resolving the related issues must remain the overriding priority for Boeing, claiming all resources needed to stem the associated losses as soon as possible. Once past this dramatic period, Boeing must focus on rebuilding its credibility and market share. The stability and size of the B737 Max order book give Boeing some years to build up a transition from the damaged reputation of its current product to all-new aircraft. Bearing in mind that the latter will take at least 5 years to come to market, there is no time to be lost in defining and implementing a new strategy. The dithering with and postponement of the MMA, or 737 replacement or whatever cannot go on as B737 Max sales trail at the upper end of the not-so-short-haul market and the tarnished reputation may not encourage new orders in the traditional-core-short-haul market.

The previous Boeing strategy was to develop an all-new MMA aimed at a higher efficiency that cannot be attained with modifications of existing aircraft like the A321XLR and A330neo. However, those aircraft can dry up some of the market for the MMA in the 5 years it takes to develop. The key to the MMA success could not be almost the same generation of engines but rather a new more automated 4.0 production infrastructure lowering costs and increasing flexibility. This strategic objective is also pursued by Airbus in a different approach of gradual modernization of production facilities, that is not turning out to be easy; it is open to debate what that implies for Boeing more radical global grassroots approach to modernization of production.

Following the Boeing rationale, the MMA would implement a more efficient and flexible production approach essential to reduce costs and overmatch the A321XLR / A330 neo in the middle of the market, wiping out the current weak spot of the B737 Max family, whose larger Max 9 and Max 10 models enjoy modest sales with reported sizeable discounts. The proven MMA production infrastructure would allow the rapid introduction of an all-new B737 replacement overwhelming the core short-haul market and tipping the current balance away from the A320neo in Boeing favour. One might imagine that Airbus would not be idle for so long and could prolong its current strategy of developing existing aircraft dovetailing with new designs benefiting from hindsight of Boeing known proposals and commitments. Under the same Boeing strategy, the MMA would cover up the development of the 737 replacement, without jeopardizing the sales of the current model.

The B737 Max accidents and the resulting tarnished reputation may have turned that strategy upside down on its head. The development of an all-new 737 replacement dovetailing with the current B737 Max order book would provide a way out of the tarnished reputation of the current model: the airline customers would hold to the valuable production slots of the current aircraft and order the new design as a follow-on in the five-year plus timeframe when new slots are available. An all-new 737 replacement would not undermine the current model, but rather provide the exit route from its troubled recent past unworthy of earlier more glorious times. Thus the 737 replacement could become the declared first priority delegating the MMA to the status of a possible extended family option. Or the 737 replacement could be designed to span a wider payload range making a separate MMA a redundant or doubtful business case.

Recently Boeing has stopped all mention of the MCAS and is discussing with airlines plans for a FSA. The FSA cannot be the MMA that was advertised as a twin-aisle (TA). The choice of a TA smaller than the large twins (A350 and B777/B787) was questionable because of the higher drag for the same capacity. The unstated 'shelving' of the MMA and airline push for the FSA leaves little doubt where Boeing is heading.

14.5 Safety Measures to be implemented

The B737 Max accidents have shaken the aeronautical community and brought a level of unfavourable publicity unknown for decades, and at total variance with the trend of years without a major airline accident. The damaged credibility affects not only Boeing and the FAA but is also reflected in reduced trust in the whole aviation community. The FAA is scrutinizing the B737 Max beyond the MCAS. Other Airworthiness authorities will make their own independent assessments, Boeing may be more cautious with other aircraft developments like the 777X (Figure 14.9), Airbus can only worry about the damage to the aviation sector it has not contributed to, and the supply chain may be holding its breath for the storm to pass. Boeing has the competence, the resources and the determination to overcome the 737 Max problems, but it needs a successful return to service and all-new replacement to regain credibility – it can rise to the challenge as it did when launching the B747 (Figure 14.10) to overcome the challenge of the Douglas DC-8-60 series (Figure 14.11) that could not be matched by further development of the Boeing 707-320 (Figure 14.12); the 747 was an aircraft that needed a new factory and did not fit any existing airport; it could bankrupt the company and instead lifted it above its competitors.

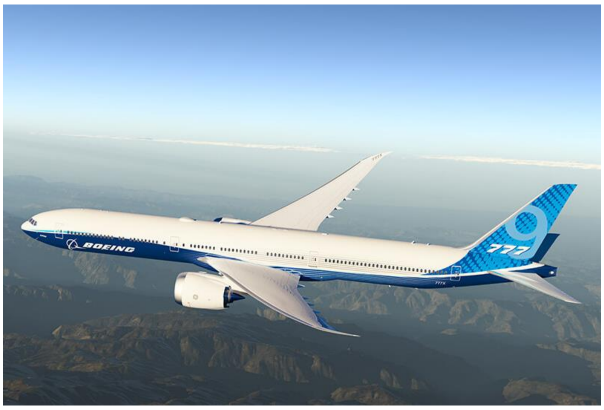

Figure 14.9 – The Boeing 777X.
(Source: http://bit.ly/2Mf5AOi)

Figure 14.10 – The Boeing 747-400F.
(Source: http://bit.ly/31dDYNL)

Figure 14.11 - The Douglas DC-8-60 series.
(Source: http://bit.ly/2nJEeX8)

Figure 14.12 – The Boeing 707-320.
(Source: http://bit.ly/2MgLLGi)

Airbus has its reputation for technical excellence unblemished, a strong SA market position to balance the Boeing advantage in the twin-aisle (TA) market, and will not miss a good challenge. The B737 Max accident must never happen again and the lessons must be learned by all, whether involved or not. Boeing maintains that its design methods "are safe but can be improved". After the second B737 Max accident, Boeing started two internal reviews: (i) one specifically about the B737 Max design; (ii) another about its design methods in general.

Beyond all the market, institutional and financial issues, and the key question no one can answer: "when will the B737 Max resume operations?", there is the safety issue: is the modified B737 Max safe enough to make sure no accident occurs again with any similarity to the preceding two? On the technical side, there are three issues: (subsection 14.5.1) should the MCAS be made fail-safe? (subsection 14.5.2) if not, at least the elevator runaway procedure must be robust and manageable by pilots beyond doubt? (subsection 14.5.3) is pilot simulator training in manual control of the high AoA pitch-up necessary in any case?

14.5.1 Should the MCAS be made fail-safe?

Failed AoA sensors have an undesirable long record of being implicated in aircraft incidents, often not as the only cause and mostly an initial trigger. Icing, ground damage during maintenance, bird strikes in flight, water ingress on the ground and freezing at altitude have all been invoked at various times and circumstances. Freezing of AoA sensors can be particularly perverse, with cases of two consistent false reading from frozen sensors outvoting the correct reading of another AoA sensor. Maybe it is time to have de-icing of AoA sensors and indication of physical damage.

Besides the general issue of reliability of AoA sensors, their use in the MCAS is not reassuring. Using two instead of one in every flight is an unquestionable improvement in allowing comparison: it is surprising it was not always this way from the outset and the 'cost option' was made 'free standard' only after the two accidents. But two frozen AoA sensors can agree on a wrong reading. And if two working AoA sensors disagree beyond a certain threshold, there is a warning, but the MCAS disengages. Should a flight-critical system disable itself after a single sensor failure? All the effort put into the development of the MCAS might be better matched by a triplex or quadruplex AoA system allowing one or two failures. Airbus uses 3 AoA sensors in its aircraft that do not have high AoA/MCAS issues of the B737 Max that uses only two!

Without being too prescriptive about the ultimate solution, whether it includes or not more AoA sensors, it is clear that the probability of failure of the MCAS must be very low, and safeguards exist in case failure does occur. Perhaps at EASA insistence, it is clear that there must be a safeguard after an AoA sensor failure. There is no expectation, even at EASA, that Boeing will fit more AoA sensors: the time and cost of modification are excessive. Instead, Boeing is looking at alternative sources of AoA information after an AoA sensor failure. However, the AoA vane was originally chosen as a sensor because other alternatives had a too-slow response. Thus, Boeing must be looking for new sources of fast and reliable AoA data. The issues of availability, accuracy and reliability of AoA data increases the focus on the elevator runaway protection.

14.5.2 Robustness of elevator runaway protection

Having a non-fail-safe MCAS places an increasing burden of safety on the pitch control at high AoA. The procedures must be clear, the physical effort of the pilots manageable and the control response time short enough. The omissions in the elevator runaway procedure highlight the first issue and hopefully, there are no more. The need for both pilots to pull up together, after an initial pull-down point to large control forces bordering on the excessive. Even assuming that control system delays are eliminated entirely, the scenario is far from an 'easy to fly' aircraft at high AoA and pilot training is crucial. In contrast to the unfortunate crews of the two accident aircraft, pilots must be aware of the normal operation and failure modes of the MCAS, learn to identify the latter and take corrective action, with acceptable control forces and short time delays. The issue of excessive time delays is being addressed by hardware changes to the computer system but it is less clear whether a specific action is needed to reduce control forces, provide more actuator assistance that could require another kind of hardware changes. Again, Boeing may exclude major changes and simply rely on the electric pitch trim to overcome high control forces, rather than increase servo assistance.

14.5.3 Pilot training package

Boeing succeeded in making the MCAS completely mask the pitch-up tendency at high AoA of the third-generation B737 Max to the extent that pilots in the simulator could not tell the difference from the second-generation B737NG or know which of the two they were flying. This success at 'transparency' leads Boeing to omit all information about the MCAS in the flight manual, inevitably mentioning the system in the maintenance documentation. The Oxford English Dictionary defined transparency, in a figurative sense not on physical light, as "open, candid, ingenuous, easily seen through, recognised or detected; manifest, obvious". By this definition, the MCAS system is the opposite of transparent to pilots, since they could not be aware of its existence. 'Transparency' would require that the pilots be made aware of a system so clever that they could not detect its presence.

The reverse side of the coin of 'transparency' or lack of it, is that when the MCAS system failed the pilots could not know the cause because they were unaware of the existence of the system. Also, if the MCAS fails or disables itself, the pilots trained for the B737NG find themselves flying a different machine; the 737 Max that is far less tractable at high AoA. A non-fail-safe MCAS gives a sense of security that vanishes at the first AoA sensor failure, and thus pilots must be trained to fly without it. The training package must take into account the probability of failure of the MCAS, the skill and force levels required for the successful implementation of the elevator runaway procedure, and a clear and transparent demonstration to pilots of the differences between (i) the B737 Max with MCAS operating like a 'fake' 737 NG and (ii) the real flying characteristics of the B737 Max when the MCAS is not available as a 'mask'.

14.6 Analysis of causes and consequences

While lying blame is not a contribution to safety, understanding the ultimate root cause of major accidents is essential to avoid recurrence and learn the hard-earned lessons. The tentative analysis of possible root causes and contributors (subsection 14.6.1) that ultimately lead to the 2 B737 Max accidents may be compared with the limited available information on the results of the Boeing internal enquiry (subsection 14.6.2). This may allow a hypothetical assessment of the evolution of the 'B737 Max crisis' and how it might be influenced by external factors (subsection 14.6.3).

14.6.1 Conditions that could lead to six issues

The Boeing remarks 'about unexperienced pilots' are an unfair excuse to hide its own internal failures. Most though not all the pilots involved in the accidents were experienced and to be fair were betrayed by the failures of system whose existence was unknown to them, would need to implement an emergency procedure with omissions, requiring large control forces in a critical high angle-of-attack regime for which they were never trained or had even been warned of. The ultimate root cause cannot be placed with the pilots that were actually the victims of a losing fight against a hidden fatal system.

The main root cause may lie in a phenomenon that is almost certainly not unique to Boeing, but rather a trend in the aerospace industry for at least two decades. Engineers in informal exchanges comment on the negative influence of other groups lacking in technological background and thus less aware of safety concerns and implications: (i) the finance department trying to reduce costs, cutting 'unnecessary' developments for the 'fun' of engineers; (ii) the sales 'department' looking for profit and suspicious of developments with less return on investment; (iii) the legal department considering sufficient to meet minimum requirements or satisfying the letter of the rules rather than the spirit of safety; (iv) the public relations department eager for innovations to show and less keen on 'invisible' improvements that consume resources.

There is indirect evidence that the development of the MCAS was affected by non-engineering priorities, for example as concerns the AoA sensors. It was decided that as a standard feature only one of the two available AoA sensors would be used per flight. A cost option was to use both in every flight, compare data and warn the pilots of the significant discrepancy. This cost option was made standard in the redesign of the MCAS after the two B737 max accidents, confirming that it is an important safety feature. It is hard to imagine that an engineer would turn a safety feature into a cost option. It is more likely that such a questionable idea might come from a sales priority overriding safety.

Although the engineers may have lost the safety argument against other interest, there is also evidence of plain design error. The issue 3 of runaway elevator pitch-downs beyond pilot control at regular intervals as long an erroneous sensor signal persists must be seen as an engineering oversight, unlikely to have other causes than hasty and ill-considered development. The MCAS was developed in response to an FAA certification requirement and fast response could override a careful closer analysis.

Issue 4 of large control forces could have been overcome by a servo system, which would have involved further investment in time and money. Maybe the electric pitch trim was deemed sufficient. Issue 5 of omissions in the elevator runaway procedure again suggests that work may have been done under time pressure rather with sufficient scrutiny and checks. Issue 6 of excessive time delays in the pitch control system points to problems found during certification and deemed sufficiently rare to require no action or assumed to be within the control abilities of the flight crew.

Thus an analysis of the six main issues (subsection 14.2.2) without any or much insider information, points towards several possible root causes. Aircraft accidents seldom have a single cause and often result from a combination of factors. Similarly, the 6 issues associated with the 2 B737 Max incidents point to a range of organizational issues: (i) safety concerns of engineers overridden by other interests; (ii) flawed engineering design perhaps due to haste and certainly not subject to proper checks; (iii) a tendency to let issues that are noticed remain unaddressed on the basis of convenient assumptions. These conjectures based on the analysis of the 6 main issues related to the MCAS may be compared with the limited publicly available information about the results of a Boeing internal enquiry (subsection 14.6.2).

14.6.2 Results of the Boeing internal enquiry

The internal review following the two B737 Max accidents recommended that the engineering function be separated from other groups. That each project has a lead engineer, reporting directly to the vice-president for engineering who reports directly to the president. This direct engineering line to the top existed in the past, but has been eroded over time, not only at Boeing but also elsewhere, so its restoration is a good Boeing example that others would do well to follow before they also fall into a Boeing style crisis.

The separation of the engineering function requires a major internal restructuring at Boeing. The current three major divisions (commercial aircraft, defence and space) include engineering together with other functions. The new structure would create four major divisions, with engineering, serving the other 3 divisions, but with no hierarchical dependence on them and with a separate direct line to top management.

The internal Boeing enquiry was led by a former vice-chief of staff, with a long career in the U.S. Navy and experience with nuclear submarines, thus well versed in safety measures. The four-person team was given almost unlimited freedom to interview anyone they wished inside or outside Boeing. They were not tasked to investigate the accidents but inevitably touched on related issues. They interviewed current and former staff at Boeing and in other organisations that had faced a comparable major crisis, to assess how they had faced the challenge. The restoration of engineering pre-eminence and line to the top together with greater accountability were only two at the new safety drivers.

The leader of the enquiry was appointed by the Board of Boeing as the Chairman of a new Airspace Safety Committee (ASC) that will oversee the organisation, including design, testing and certification. The ASC will consider "anonymous reports" on safety issues and should ensure that no "under pressure" is placed on technical staff. It is perhaps no coincidence that the highest level dismissal was at the lead of the commercial division that will no longer have authority over-engineering. The new head of the commercial business unit was formerly in charge of cutting supply chain costs, leading to complaints from suppliers that felt 'squeezed'. The new focus on accountability has reached level two, but may not reach the top anytime soon.

The President of Boeing, Dennis Muilenburg, has faced tough questioning on several public occasions and not always provided fully satisfactory answers. There is no simple answer other than the admission of error to obvious questions such as: why a safety system was designed to be vulnerable to a single sensor failure and lead to a runaway condition? The answer that "the B737 Max is safe but can be improved" is a public relations exercise of not fully assuming responsibility in difficult circumstances. Dennis Muilenburg has resisted calls for resignation. He is no longer Chairman of the Board but remains a member, and retains the title of President and CEO (Chief Executive Officer). The changes are presented as allowing him to concentrate on resolving the 737 Max issues, and Muilenburg does not disagree with that choice.

The new chairman of Boeing, coming from the outside, has for first priority setting up the new safety organisation, ley by a competent, experienced individual with a strong reputation. The Board may have considered more drastic action to be undesirable since it could be interpreted as a tacit admission of more responsibility than Boeing is willing to accept. Staying on as President of Boeing, even deprived of some other duties, may give the opportunity to change the perceived status from a 'potential culprit in the crisis' to the outcome of the 'hero who saved the company' if the current challenges are eventually overcome. The Board of Boeing is not shy of dismissing a President: Harry C. Stonecipher had to resign not for any professional failure but rather for some personal involvement with a female subordinate. As external image prevails in both cases, there may be more tolerance to management failures than to personal drift. The internal reorganisation may take some time to be implemented and could help to pre-empt some of the criticism that Boeing could receive from enquiries led by Congressional

Committees, Government Departments and Agencies. Following hearings in congress, Boeing has already been accused of "putting profit before safety", which is a simplistic but perhaps not totally unfounded assessment of a complex situation.

A major new activity is a total overhaul of flight deck design covering not only technology and certification but also pilot training, which can differ between airlines. Boeing made the choice of retaining a more traditional appearance of the flight, understating automation features, and giving the pilots the feeling they are still in control in the age of complex systems. Airbus has adopted a more engineering-led approach, letting through the fundamental role played by automation, while trying to keep pilots informed of all options available as well as limits enforced. In reality, the level of automation is not very different between Airbus and Boeing aircraft, with Airbus playing the role of innovator (two crew cockpit, fly by wire) and Boeing adopting similar technologies without much delay without giving as much external evidence of change in order to retain the preference of pilots. Thus, in the future Boeing will extend its activities in design and certification to offer support in pilot training packages for airlines that is seen as a major profitable new business activity. The engineers have won, but the sales no less!

The Boeing position that pilots need only computer training on the MCAS may look less carefree if the offer to provide simulator training packages for flight new pilots is seen as a business promotion of services for airlines. In recent years, Boeing has expanded its activities beyond design, certification, production and spares supply to include an increasing variety of services. The service provision is the fastest growing business sector of Boeing, and although it has not reached yet the value of the traditional sectors, the potential may be there. Turning the 2 B737 Max accidents into a business of pilot training packages tailored to the individual needs of a considerable number of airlines might be a desirable outcome to recover the initial losses of the B737 Max crisis into a long-term very profitable new business line. The path to recovery may not be easy or rosy as there are both internal and external challenges to overcome (subsection 14.6.3).

14.6.3 Internal and External factors and evolution

Of direct concern to the future of the B737 Max are at least partially open issues:

- Are the software changes sufficient to make the probability of failure of the MCAS sufficiently low?
- Is the elevator runaway procedure sufficiently fast in response with acceptable control forces?
- Will the FAA accept the Boeing preference for software and hardware changes, revised documentation and computer training, but not simulator training for pilots?
- Will Boeing have to provide simulator training for pilots, which it says it will do at the request of airlines, but perhaps at extra cost?
- Will airworthiness authorities worldwide agree with an FAA ungrounding and there will be sufficient coordination to have a common standard that satisfies the independent analysis of each authority?
- If a non-simultaneous ungrounding of the B737 Max allows flights in some parts of the world and not others, how will passengers react?

- When ungrounding does occur, will airlines accept the B737 Max at a rate of 70 per month from direct production and storage, or will other considerations (refurbishing, leases of other aircraft, market and seasonal conditions) limit the achievable rate?

The potential for controversy remains, starting with safety issues that appear to remain open: risk of MCAS failure, reliability of elevator runaway procedure, large control forces and pilot simulator training. Besides direct issues, other aspects could affect the financial health of Boeing and its reputation and ability to weather the crisis:

- The estimated losses of 4.6 B $ may be exceeded if grounding extends into 2020 and production may have to be stopped, although compensation to airlines (and perhaps suppliers) will continue to drain resources;
- The sales of wide-body airliners are slowing, and the reduced production rates may limit the cash flow that could help compensate B737 Max related losses;
- Besides the commitment of resources to the solution of B737 Max problems as the highest priority, other current developments such as B777X face delays due to engine problems. The delays in the development of the B777X imply increased losses and Boeing may take extra care with testing to avoid the risk of an accident that would be most embarrassing in the current circumstances. As soon as the B737 Max crisis is over, and engineering resources that are made free and not needed for the B777X, there should be no delay in the start of the development of the B737 replacement and/or FSA;
- There are signs that, after several years of booming aircraft sales, there is a slowing down due to weaker worldwide economic growth and perhaps airline overcapacity and over-ordering;
- The continuing trade disputes, in particular between the U.S. and China, may exclude Boeing from one of the world's largest markets;
- Boeing has been quite aggressive in winning military aircraft orders, including supersonic trainers for the air force and unmanned refuelling aircraft for the navy and in competing in rotorcraft for the army. The Boeing bids were in all cases significantly lower than all other competitors and in some cases below customer expectations. Since Boeing has been drifting out of the military aircraft business for several years, this strong revival has been seen by some as securing contracts at a loss, to be recovered later in production and sales, with the gap filled by expected continuing profits in commercial aircraft. The reversal of the latter assumption may imply that Boeing may not have commercial aircraft profits to bridge the gap to lucrative military production.

This ensemble of circumstances does not make it any easier for Boeing to overcome the B737 Max crisis.

14.7 Conclusion

The short conclusion may be summarized in a single question and answer: how was it possible that, having a large cadre of very experienced and highly qualified engineers, the B737 Max came into service with an MCAS with multiple design and implementation flaws? Large organisations let financial, legal, publicity and profit issues override technical competence and safety concerns at their own risk. Accelerated development processes and stringent cost-cutting and excessive profit-seeking increase risks instead of promoting a thorough and safe design that is the key to long term success sustaining a good reputation. The B737 Max may still have more episodes to unfold, although Boeing recently reasserted the expectation of obtaining FAA recertification in December 2019 and starting ungrounding of airline aircraft and parked and new production without delay. The issues of maintaining the right balance of efficiency, safety, profit and expediency may remain as relevant in the future as they are now and have been since the start of the B737 Max crisis. That enduring lesson may last beyond any assessment like the present one, of a fast-moving chain of events that can render outdated and incomplete any account soon after it is signed-off.

Perhaps the best outcome that can be expected, in the interest of all concerned, is that the FAA and EASA succeed in their close consultations on the recertification and ungrounding of the B737 Max. Both have a vested interest in common certification standards that will apply in the future to both Boeing and Airbus aircraft. A common EASA-FAA position on recertification of the B737 Max could have enough credibility to be accepted by more than a dozen certification authorities worldwide. A common and orderly return to service of the B737 Max would best serve the reputation of aviation as the safest mode of transport. And, although Boeing is under pressure to cut losses and find a quick way out of the present crisis, an assured safe return to service is the best outcome for its future.