PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

PARE

CHAPTER 14

The Two Boeing 737 Max Accidents and Consequences

Final Report

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Summary

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 '50s 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 '70s, 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 and slowly emerging information currently available can support reasonable technical assessment. The crisis associated with the two B737Max accidents pales in scale and consequences when compared with the effects of the COVID-19 pandemic which is causing the biggest disruption in aviation history. When aviation recovers from the spread of the pandemic, the competitive position of Boeing may have eroded further compared with its archrival Airbus.

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

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

Chapter 14 – The Two Boeing 737 Max Accidents and Consequences

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 somewhat 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 the 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 the FAA as a certification authority, that may affect other aviation stakeholders, even if they did not influence 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 Single Aisle (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 redundant or taking other fail-safe 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 resolve some of the 13 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 predictions of Boeing that the grounding of the 737 Max would last 3, then 6 and then 9 months, were dispelled when it became clear that recertification by the FAA would not occur in 2019, and would be delayed at least into the first half of 2020 (section 14.7). The emergence of the COVID-19 pandemic in the first half of 2020 created disruption with far greater impact than the two Boeing B737Max accidents. Part of the delay may be due to the reluctant and slow response of Boeing to provide a simulator training package that would satisfy an international team of pilots assembled by consensus of the airworthiness authorities worldwide (subsection 14.7.2). The Boeing approach of piecemeal palliative actions dragging over one year may, in the end, prove more costly in compensation and other losses than a fundamental redesign that would restore its credibility (subsection 14.7.3).

The change of leadership at Boeing, from Dennis Muilenburg to David Calhoun at the beginning of 2020 (section 14.8) marked a policy change from a focus on financial aspects like (subsection 14.8.1) using profits to buy back shares and pay sizeable dividends to (subsection 14.8.2) investment in engineering efforts to improve safety based on (subsection 14.8.3) closer cooperation with airworthiness authorities as regards the provision of technical information and pilot training materials.

The two B737 Max accidents lead the FAA to undertake a thorough review of the whole flight control system, uncovering further issues (section 14.9) not directly related to the MCAS, including: (subsection 14.9.1) rewiring the electrical connections to the tailplane to provide fail-safe operation in the case of short circuits or other electric disruptions; (subsection 14.9.2) amending the list of minimum operating equipment required to start a flight following an inconsistency found by an operator. The recertification of the B737Max has motivated a more strict and thorough approach that will also apply to all future aircraft, in particular with closer scrutiny of human factors and man-machine interface, and institutional Safety Management Systems that are critical aspects of flight safety (subsection 14.9.3).

The main modifications made by Boeing to the B737Max to seek (section 14.10) re-certification and return to service are: (subsection 14.10.1) redesign of the flight control system, including software changes to make the two flight control computers fully redundant; (subsection 14.10.2) a comprehensive simulator flight training package containing new information not only on the B737Max but also on its predecessor B737NG, to train pilots not only on normal flight modes but also putting particular emphasis on all possible non-normal flight conditions. The changes did not include (subsection 14.10.3) major hardware changes such as adding angle-of-attack sensors to provide fail-sate operations or servo assistance to reduce large manual control forces with electric pitch trim disengaged.

About one year into the grounding of the B737Max the sudden emergence of the COVID-19 pandemic caused a much greater disruption of the airliner market, and the effects on the Airbus-Boeing duopoly (section 14.11) can be seen in chronological order separated by (i) the B737Max grounding and (ii) the COVID-19 pandemic as the two major disruptive events: (subsection 14.11.1) the competition in the single and twin-aisle sector before the grounding of the B737Max; (subsection 14.11.2) the period before the COVID-19 pandemic including the successful takeover of the Bombardier C-series by Airbus and the breakdown of the rival Boeing-Embraer alliance; (subsection 14.11.3) the prospects after the partial or total recovery from the COVID-19 Pandemic are of further gains of Airbus relative to Boeing.

The conclusion (section 14.12) highlights the consequences of the Boeing 'expedient' of using "grandfather rights" to make the old B737 revamped as B737NG a temporary competitor to the all-new A320: (i) when forced to develop the third generation B737Max against the second generation A320NEO the latter gained a significant competitive advantage at the upper end of the single-aisle market with stretches beyond the potential of the former; (ii) to regain a more competitive position following the distraction of the middle of the market aircraft (MMA) and the loss of credibility of the B737Max, Boeing needs a future single-aisle (FSA), demanding technological advances and resources for development that may not be available.

Since this report is concluded when the B737Max is still grounded, a final note (section 14.13) addresses the three burning questions unanswered since the start of the B737Max crisis 18 months ago: (Subsection 14.13.1) when will be the undergrounding? By the FAA and other airworthiness authorities around the world separately or in a coordinated way;? (Subsection 14.13.2) When will the grounded aircraft return to service? At what rate? (Subsection 14.13.3) When will production stabilize again, at what rate and how long will take in the ramp-up?

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) despite Boeing experience and competence in the area. Based on the publicly available information on the accidents (subsection 14.2.3), that has gradually emerged over time the MCAS is widely suspected to be implicated in both accidents.

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 with the E-series. 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 valued 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 B737 NG but Boeing became acutely aware that development potential was near its limits, and accordingly planned the methodical 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. Despite 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 Thirteen issues: questionable design features

The design of the MCAS involved at least 13 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 as 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 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 was later reported that the FAA representation/derogation of authority at Boeing agreed that the MCAS was mentioned explicitly only in internal documents, with a more vague reference to pitch trim in external documentation. 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.

Issue 5 – Assumption of fast pilot reaction: Boeing assumed that, in case of MCAS failure, the pilots would within 4 seconds implement the elevator runaway procedure. This assumption could be optimistic on several grounds:

-since the MCAS was unknown to the pilots, and it was not mentioned in the flight manual, there was no instruction on how to identify an MCAS failure or to counter it;

-despite this the crew was supposed to realize within 4 seconds that there was a pitch anomaly from an unknown cause, and decide within that time the right response was to apply the elevator runway procedure;

-if the MCAS failure occurred in a critical flight condition involving other factors, leading to a higher workload or stress, the reaction time could be longer.

The pilots should know the checklist for elevator tuna way by memory, but there were omissions in that checklist.

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

Issue 6 – Identification of a pitch runaway: The flight manual identified pitch runaway as "a continuous uncommanded movement of the trim wheel". However, this is not the effect of activation of the MCAS that acts by short bursts of trim wheel rotation with intervals of several seconds. These short interventions of the MCAS can be easily confused with frequent movements of the trim wheel during flight phases such as climb after take-off. The pilots could not be expected to detect and act upon in 4 seconds on shard trim wheel movements at longer time intervals, due to a system whose existence they did not know of, not acting like the "continuous trim wheel movement" expected as a runaway pitch trim. As part of the B737Max recertification process, the flight manual was amended to define runaway pitch trim as 'a continuous trim wheel movement or movements inconsistent with the flight condition". Despite poor clues on how to identify a pitch runaway condition the pilots were supposed to apply the corresponding non-normal checklist that they should know by memory;

Issue 7 – omissions in the 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 8 – effectiveness of the electric pitch trim: The pilots could counter the pitch down imposed by the MCAS by commanding an opposing pitch-up using the electric pitch trim. However as long as the angle-of-attack exceeded the pre-set limit, the MCAS would apply a pitch down at regular intervals, and the electric pitch trim might not be able to compensate.

Issue 9 – Heavy pitch trim wheel: If the MCAS was disengaged using the toggle switches then the electric pitch trim was de-activated, and pitch trim had to be performed manually. The stick forces were high, and the pitch trim wheel could not be moved with one hand on the stick. Moving the trim wheel required two hands, and the effort increased with angle-of-attack and speed, until it became almost impossible to move, as stated in the intermediate report of the second accident.

Issue 10 – roller-coasted manoeuvre: The B737NG the pilots could reduce the effort to turn the trim wheel using a roller-coaster manoeuvre: pitching down to start a dive, them pitching up to use the transition to turn more easily the trim wheel. The roller-coaster manoeuvre could be repeated until the aircraft was fully trimmed; it is clear that the roller-coaster manoeuvre implies an altitude loss and cannot be used near the ground.

After the two B737Max accidents, in the revised flight manual for recertification, Boeing stopped short of recommending the roller-coaster manoeuvre. A possible reason is that the B737Max has more powerful engines further forward that the B737NG, generating a stronger pitching moment, making the roller-coaster manoeuvres more numerous and hazardous

Issue 11 – An increase of forces with speed: In the revised flight manual for recertification of the B737Max Boeing stops short of recommending the roller-coaster manoeuvre, and instead suggest that the two pilots turn the trim wheel together. This was found to be possible in-flight tests, although Boeing recommends reducing speeds. This raises two issues. If both pilots are needed to turn the trim wheel, presumably with one hand each, then each them has only one other hand free for other actions; assuming that this is sufficient in all flight conditions, making strong efforts with one hand in turning trim wheel and light and precise actions with the other hand elsewhere might not be easy; second reducing the speed to reduce the effort to pitch-up with the steering column or to turn the trim wheel may not be feasible if the aircraft enters a dive, which precisely what the MCAS does after erroneous high AoA signals. The report on the second B737Max accident states that the controls became unmovable after the aircraft entered a dive when the MCAS was reactivated by the pilots, after failing to reverse the dive with manual control.

Issue 12 – 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. The requirement for hardware as well as software changes to the pitch control system introduced another step and delay in the re-certification process.

Issue 13 – Standard safety assessment (SSA): The MCAS was designed for use at high-speed and subjected to the comprehensive safety assessment covering all combinations of failure modes. Later Boeing decided to use the MCAS at low speed and did not repeat the SSA, considering that the high-speed case was more critical. Also, Boeing may not have fully informed the FAA representative about the changes to the MCAS or its use in a wider speed envelope.

14.2.3 Sequence of occurrences in the accidents

Since the information on the two B737 has been made available gradually over time and is not always completely clear about surrounding circumstances, 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 before 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 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. Also, 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 9 to 11 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: The intermediate accident report made clear that the effort needed to reverse the dive was too large and increased as the aircraft accelerated beyond the never exceed speed in a dive;

-it is not clear if delays in pitch control (issue 9 of subsection 14.2.2) played a role since control forces (issues 9 to 11) were in any case beyond manual control;

- 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, thereby 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 knowledge 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 12 of subsection 14.2.2) occurred in this instance. But clearly, the control forces were too high for manual pitch trim. It appears that the crew did all it could 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 several 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 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? Given 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 independent investigations until they were convinced of the safety of the MCAS and perhaps other systems. The FAA decided to hold regular meetings with other airworthiness authorities on the Boeing 737 Max ban, reported being sometimes hot with the FAA trying to restore its credibility in the face of scepticism of others, in the beginning, leading to smoother cooperation afterwards.

14.3.2 Boeing modifications to the MCAS

Boeing started modifications to the MCAS in the 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 11 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 to be able to vote out one dissident sensor, which Boeing cannot do with 2 AoA sensors. Even 3 AoA sensors are not 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 the 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 emergencies 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 364 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 470 B737 Max before production was halted 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 470 aircraft produced and parked but not delivered. The ungrounding of more 855 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 future SA, and perhaps the MMA as well (section 14.4.3).

14.4.1 Financial Losses and Recovery

Boeing has roughly 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 the disruption to their flight plans and schedules. Second, with Boeing is still producing the B737 Max at a monthly rate reduced from 52 to 42 that may 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 had to halt production as the current issues dragged 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 the 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 2019.

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 the 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 MMA 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 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.

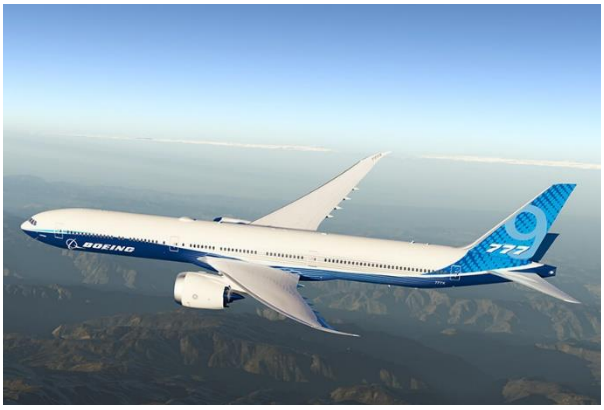

Figure 14.9 – The Boeing 777X.
(Source: http://bit.ly/2Mf5AOi)

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 the stick up together, after an initial pull-down Or the use of two hands to turn the steering wheel, point to large control forces bordering on the excessive. Even assuming that control system delays are eliminated, 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 manual control, in spite of high control forces, rather than provide emergency servo assistance. The loss of all forms of servo assistance when the MCAS is deactivated is also a questionable situation bearing in mind the large manual control forces involved. Some kind of dedicated servo assistance could counter or relieve excessive forces in Manuel flight, like both pilots having to pull the stick together or two hands needed to turn the trim wheel.

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, ingenious, 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 two 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 ten issues

The Boeing remarks 'about unexperienced pilots' are an unfair excuse to hide its internal failures. Most though not all the pilots involved in the accidents were experienced and to be fair were betrayed by the failures of the 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 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 the 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 interests, 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.

Issues 9 to 11 of large control forces could have been overcome by a servo system, which would have involved further investment in time and money. Disabling a faulty electric pitch trim is necessary, but it is questionable leaving as a consequence large manual control forces. 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 11 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. It is difficult to substantiate the assumption that within four seconds the pilots would detect a pitch runaway without clues causes by a system unknown to them and implement a procedure with flaws requiring hardly manageable control forces

Thus, an analysis of the thirteen main issues (subsection 14.2.2) without any or much inside information, points towards several possible root causes. Aircraft accidents seldom have a single cause and often result from a combination of factors. Similarly, the 13 issues associated with the two 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 based on convenient assumptions. These conjectures based on the analysis of the 13 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 "undue 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 do reach the top immediately.

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 the error to obvious questions such as: why a safety system was designed to be vulnerable to 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. As a first step, he lost the position of Chairman of the Board but remained a member and retained the title of President and CEO (Chief Executive Officer). The changes were 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 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 allow changing the perceived status from a 'potential culprit in the crisis' to the outcome of the 'hero who saved the company' if the current challenges were 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 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 chose to retain a more traditional appearance of the flight controls, 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 the innovator (two crew cockpit, fly by wire) and Boeing adopting similar technologies without much delay without giving as much external evidence of change 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 they offer to provide simulator training packages; these are 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 external services 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 two 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, retesting, 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 as 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 after the two B737Max accidents and questions about FAA independence the certification of the B777X is likely to face closer scrutiny. 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 Grounding Extended from 9 to 15 Months

The Boeing publicly stated expectation that the B737X would be recertified by FAA at the end of 2019, after 9 months of grounding, were dispelled when it became clear the operation was unlikely to resume for another

6 months (section 14.7). The extension of grounding to 15 months can have serious implications for suppliers and airlines, and the consequences may extend for a longer period after return to service (subsection 14.7.1). A major factor in the additional delay may be the provision of a pilot training programme that meets the demands of airworthiness authorities (subsection 14.7.2). There is some contrast between the ideal clean sheet design (subsection 14.7.3) and the remedial actions that can be applied at a late re-certification stage with limits on time and cost.

14.7.1 Consequences of extended grounding

After losing the position of Chairman of the Board of Boeing on October 15, and while still retaining a seat at the board and the title of CEO, the change was intended to allow Dennis Muilenburg to concentrate on bringing the B737 Max back to service as early as possible.

He publicly stated that FAA certification was expected by the end of 2019, a claim viewed with scepticism by most observers. He also recognised that recertification of the B737 Max should be simultaneous for all airworthiness authorities around the world, a very desirable goal even less likely to be achieved in such a short time. The FAA Administrator called Dennis Muilenburg to tell him who set the schedule for certification and that Boeing could do more to bring that date closer. It became clear that the B737 Max would remain grounded probably for at least the first half of 2020.

The Boeing Board expressed lack of confidence in his ability to deal with the B737 Max and stripped him of all duties including CEO. Dennis Muilenburg received the news from David Calhoun, a veteran of the Boeing, who had replaced him as Chairman of the Board in October 2019 and took over as CEO as well in January 2020. David Calhoun has a strong engineering background and is a veteran of the Board, more than once in the past considered a candidate for CEO. Before the 737 Max crisis, the expected successor of Dennis Muilenburg as CEO of Boeing was the head of the commercial aircraft division, who was the first to be dismissed after the 2 accidents. Since David Calhoun is 62 and Boeing enforces compulsory retirement at 65, his task may be seen as bringing Boeing out of the Boeing 737 Max crisis and handing over a better situation to his successor. The change of leadership was minor news compared to the implications of grounding for another half year.

The airlines had already struggled to meet demand in the peak of 2019; despite resorting to leases and rescheduling there was no way to avoid massive cancellations of tickets. The prospect of a similar situation in 2020 is most unwelcome, as leasing companies are short of aircraft and crews. Faced with mounting compensation for airlines, for cancelled flights, leases and undelivered aircraft, Boeing may not be in the best position to support its supply chain as well. With production halted at the end of 2019 and unlikely to resume until the second half of 2020, some suppliers, in particular the smaller ones, will struggle to survive until production resumes, and may have to lay-off a large part of the workforce that may not return later.

Also, the return to service and stable production at pre-crisis rates of 52 aircraft per month will be gradual after recertification and is unlikely to be reached before 2021.

Boeing initially claimed a swift return to service after recertification since only software changes to MCAS would be needed. Later it become apparent that the replacement of some computers would imply hardware changes. As the grounding extended past 6 months with the aircraft parked for longer periods, the FAA made clear that return to service will require inspection after recertification; the priority must be bringing back to service the 385 aircraft already delivered to airlines so that compensation is no longer justified.

Then the 470 aircraft produced and parked must be delivered netting some revenue instead of fines for late delivery and mothballing or upkeep costs. In addition, resumption of after all production should deliver new aircraft against existing orders. It remains to be seen if there are no cancellations, new orders are placed, and production rates envisaged pre-crisis is ever reached. The COVID-19 pandemic in the first half of 2020 changed all the preceding assumptions (section 14.9).

14.7.2 Provision of Pilot Training Material

The failures and deficiencies of the MCAS have highlighted the issues of pitch trim and the relation with pilot training. Boeing has been overly reluctant to offer adequate pilot training packages to cover the failure of MCAS, and this has contributed to delays in recertification From the outset of the B737 Max program Boeing concluded that a major economic and sales advantage would be to require only computer-based training (CBT), with no simulator hours, when transitioning from the previous generation B737 NG to the new 737 Max. A case in point was Lion Air that would later have the first 737 Max accident. Lion Air wanted to add to CBT also 3 hours simulator training. The Boeing representative insisted this was unnecessary and wasteful and succeeded in the airline giving up. Thus, no Lion Air pilots had simulator training on the B737 Max, including those involved in the accident. Boeing had convinced most airlines to by-pass simulator training and pressured Lion Air to prevent it from becoming a precedent that other airlines might follow, thus damaging sales prospects. During development Boeing convinced the Authorised Representative (AR) of the FAA that the MCAS designation could be used internally but not externally, being in the latter case referred to as a pitch trim modification. Also, the MCAS was not mentioned in the flight manual, the pilots did not know about its existence, and even after the first B737 Max accident, it was not mentioned in the service bulletin that addressed the runaway pitch trim procedure.

After the first B737 Max accident, the FAA did a study about the probability of recurrence over the lifetime of the aircraft. It assumed a fleet of 4800 aircraft operating over 20 years and that only in 1% of cases of MCAS failure the crew failed to apply successfully the runaway trim procedure: the result 14 accidents, an unacceptably high value. The assumption that the crew would overcome an MCAS failure in 99% of the cases looks optimistic bearing in mind that they did not know the existence of the system and the recovery procedure description had omissions and involved large control forces. The two B737 Max accidents in retrospect do not suggest a 99% success rate in overcoming MCAS failures. In any case, the prediction of 14 accidents due to MCAS failures over the lifetime of the B737 Max fleet was alarming enough, making a second B737 Max accident less than surprising. What is surprising is that nothing was done, and the study was reported much later in an external hearing after the accidents.

Even after the second accident, Boeing maintained that computer training was enough, with the option of providing training packages tailored to the requests of individual airlines. This was seen in internal reports as a new business opportunity to extend the activities of the Boeing services division and might offset some of the losses associated with the B737 Max crisis. Boeing hopes that the FAA would accept CBT only, and other airworthiness authorities around the world would follow, were wrong and only served to prolong the grounding since Boeing was eventually forced to provide a training package including simulator time. Under pressure from other airworthiness authorities around the world, the FAA assembled an international team of pilots with different levels of experience. The tests by both FAA and other pilots highlighted the large control forces required to apply the runaway pitch trim procedure: both pilots pulling on the stick to pitch up, and two hands to turn the pitch trim wheel. This raises the issue of fundamental design versus palliative measures.

14.7.3 Clean Sheet Design versus Remedial Measures

Assuming that the B737 Max was a redesign of the B737NG with more powerful engines further forward, a safe clean sheet design could include:

(i) A MCAS with limited authority, allowing a pilot override, using 4 AoA sensors to be fail-safe allowing two failures. This contrasts with 2 AoA sensors, leading to disengagement if they disagree, in the redesigned B737 Max MCAS that is not fail-safe. This would go farther than the 3 AoA sensors used by Airbus allowing one failure. The undesirable high AoA flight characteristics may justify 4 AoA in a double fail-safe configuration.

(ii) The large control forces in high AoA could be compensated by trim tabs (ii-1) or servo hydraulic assistance (ii-2). The trim tabs were used in large World War II bombers with manual control and high control forces. For example, a small trim tab up would push the elevator up for a pitch down. The control forces on the small trim tab are much smaller than on the control surface, as long as flow separation does not occur. The other alternative is a hydraulic servo system to power the pitch control with reduced pilot effort. Instead of duplicating the electric pitch actuation with hydraulic or other system another alternative after disengaging a faulty electric pitch trim, would be servo assistance to allow the pilots to turn the trim wheel and pull the stick with moderate effort with one hand

Both designs (i) and (ii) add complexity and cost, but not much at the design stage, with significant safety benefits they allow. The implementation of these changes to a certified aircraft would be a considerable effort in design, testing, certification, production and retrofitting but would restore confidence in a fail-safe system.

The remedial measures like software changes and training documentation may both provide the same level of safety and credibility. If their acceptance drags recertification over more than one year, there may be large commercial and collateral losses, beyond those of a serious engineering effort. Palliative measures that struggle to gain credibility may, in the end, cost more than correcting errors with a full redesign.

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 designs 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.

14.8 Change of Leadership and Work towards a Solution

The change of leadership at Boeing marked a new course, from the pursuit of profit leading to the technical and financial crisis (subsection 14.8.1) to the return to engineering quality as the best approach to safety (Subsection 14.8.2) based on close cooperation with airworthiness authorities (subsection 14.8.3).

14.8.1 The management of Profit, Dividends and Publicity

David Muilenburg lead Boeing in the period 2015-2020 following the policies established over more than a decade 2005-2015 by his predecessor James McNerney. The remark "no more moon shots" by Alan Mullary, head of the commercial aircraft division, stated the aversion to advanced technology and preference for plain profitable solutions. The CEO before McNerney Harry Stonecipher, who came from McDonnell Douglas and managed its incorporation into Boeing, once answered "yes" to the question: "you care only about money". The leadership of Harry Stonecipher was short 2003-2005 due to a personal affair with an employee, rather than any policy issues. The priorities of the leadership at Boeing for two decades were: (i) externally to increase profits, share values and dividends; (ii) internally to squeeze supplier prices, lower salaries and weaken labour unions. Boeing had profits of the order of 10 B$ on a revenue of 100 B$ based on its reputation for engineering excellence since its foundation in 1907. For the first time in a century, Boeing was led by finance not engineering, and for nearly two decades.

The profits of Boeing were mostly used to buy back shares and increase dividends. Boeing made bank loans to buy back its shares and pay higher dividends: (i) buying shares increases their prices so paying back the bank loan should not be a problem; (ii) larger dividends give more of the profit to the shareholders, and two-figure percentages likely exceed bank lending rates. These benefits might apply to top executives who may have preferential share options, besides bonuses and salaries. Not that the latter are unconsiderable: (i) the last yearly salary of James McNerney was 28 M$; (ii) Dennis Muilenburg did not take his 13 M$ bonus for the year 2019 of the B737max accidents. He left Boeing with a compensation of more than 60 M$, which was described as not a benefit since it was his net value before taking the position of Boeing CEQ.

During the leadership of the last three CEOs, Boeing invested less than one-fifth of its profits into research and development (R&D). Even in the year 2019 of the start of the B737 max crisis, Boeing borrowed 12.1 B$ but used only 2.2.B$ for R&D, in spite of having to address B737 max technical problems, B777X development and other programmes. The remaining 10 B$ in bank loans were used to buy back shares and pay dividends. In five years Being paid 78 B$ in dividends. All this financial manipulation did not prevent share price to drop from an all-time high of 446.62$ on 1.3 2019 before the B737max crisis to less than a third 128.28$ one year later on 24.4.2020. By that time, the B737max may have cost Boeing more than 20B$ and there was the possibility of a 60B$ government rescue package. Nearly two decades of pursuit of profit and dividends were most damaging for the underinvestment in engineering. The financial exploitation of Boeing's engineering past, in the end, damaged both its share value and engineering reputation.

14.8.2 - Balancing safety, engineering, and finance

The external focus on profits and dividends had its counterpart in an internal focus on cutting costs. The suppliers were squeezed to cut costs by two figure percentages, leading Airbus to claim that it treats suppliers better than Boeing. The architect of the cut supply chain costs action was Kevin McAllister, who becomes head of the commercial aircraft division, that made more than half of Boeing revenue and profits before the B737Max crisis; he was expected to succeed Dennis Muilenburg, as CEO and was the first to be dismissed after. The management policy was also to reduce salaries and break the considerable power of labour unions, for example transferring work from the giant Everett factory in Washington State whose legislation protects workers, to other states that attract investment at the expense of worker's rights. The working atmosphere was described as 'toxic', not only for financial reasons; engineers had no access to management and technical issues and test pilot reports were ignored. The 6-year development time of the B737Max was not short bearing in mind it is a derivative aircraft and may have been more a result of weak R&D investment and focus. Reporting problems was considered a bad career move, and Mc Nerney crowed about his ability to cower subordinates

The reaction of Dennis Muilenburg to the two Boeing 737 Max was a public relations exercise that left most sceptical. He blamed "unexperienced pilots" For the accidents and claimed that the B737 Max was "safe but could be improved", where most independent observers saw the reverse. He publicised technical solutions that were partial palliatives and resisted the need for essential elements like a pilot simulator training package. He repeatedly claimed certification within 3 months, when the FAA repeatedly asserted "it had no timeline" and failed after 9 months to satisfy the safety requirements of the FAA, now more closely aligned with the other 10 main airworthiness authorities around the world. When Dennis Muilenburg was dismissed the Boeing board stated that it has lost confidence in him.

14.8.3 Engineering quality ensuring airworthiness

David Calhoun who brought the news to Dennis Muilenburg is a veteran engineer rather than a fast-rising manager. He immediately took major decisions in a quiet but determined way. He cancelled the Middle of the Market Aircraft (MMA) and put all the focus on the future single-aisle (FSA) as a direct replacement for the B737. He stated that Boeing would give the highest priority to a complete redesign of its flight control systems in close cooperation with the FAA, to ensure no certification issues would arise in the future. The main objective of the new flight control system is safety, including protection from flight excursions comparable to those used by Airbus. He stated that flight control system design will proceed ahead, or at most in parallel with the design of the FSA.

The emphasis on cooperation with the FAA is clear. In the first three months after taking over, David Calhoun did not announce any technical solution or claim any 'certification date' as Dennis Muilenburg repeatedly did to his disgrace. Clearly, Boeing is quietly and diligently working with the FAA behind the scenes and is going to let the airworthiness authorities report on their findings and conclusions.

It will be interesting to find out in the end what the certified technical solutions to make are:

(i) The MCAS or its replacement or evolution fail safe;
(ii) The pitch runaway procedure robust with moderate control forces;
(iii) A simulator training package that prepares pilots for all foreseeable situations.
(iv) This suggests that the homework is Being done instead of public claims.

David Calhoun has admitted that Boeing may not be able to pay any dividends for several years. This is a consequence of: (i) lack of liquidity due to using past profits to buy back shares and pay dividends; (ii) debt and R&D investment needed to remedy current problems. The architects of the Boeing 'financial boom' may have 'suffered' losses in the value of their shares but have kept the fat dividends and benefits.

In contrast, to signal his commitment David Calhoun renounced any payment for his work in 2020, for a crisis he had not led. Dennis Muilenburg had waived his bonus only in 2019 for a situation he presided over in deference to the 346 victims of the two B737Max accidents.

14.9 – Additional unrelated issues

The B737Max accidents damaged the credibility of Boeing as an aircraft manufacturer and of the FAA as a certification authority, leading as a reaction to a more thorough and stringent review of all aspects of the flight control system (subsection 14.9.3). This is turn highlighted additional issues remotely or totally unrelated to the MCAS for example: (subsection 14.9.1) the provision of an additional wiring path to the tailplane to provide redundancy and fail-safe operation in case of short-circuit or other electrical problem with the existing wiring loom; (subsection 14.9.2) identification of an inconsistency between an emergency procedure and the list of minimum equipment functioning for flight dispatch, requiring additional functions in the flight control system.

14.9.1 – Rewiring for short-circuit protection

In 2009 came into force the Electrical Wiring Interconnect System (EWIS) regulations to prevent short-circuits or other electrical hazards, by requiring at least two separate redundant wiring paths for the actuation of critical systems. The EWIS was not applied to the wiring to the stabilizer electric trim motor of the B737Max on the basis that it was an evolution of the B737 and B737NG that never had that kind of electric failure in their long operational history. The FAA nevertheless asked Boeing to check whether any electric wiring failure could cause an uncommented elevator failure. Boeing identified about a dozen places in the existing wiring looms where electrical separation could not be assured. Thus, a new wiring path had to be installed separately from that already existing to provide redundancy and fail-safe operation. The modification will be introduced in all future production aircraft and those already on the production line. The FAA also required that all existing 470 parked aircraft be modified before delivery to airlines. Concerning the 385 aircraft already delivered to airlines and currently grounded it has to be decided whether the modification is required prior to return to flight or can be postponed for a limited time.

14.9.2 – Revising the dispatch conditions

The B737Max, like the B737NG and the B737, has a Master Minimum Equipment List (MMEL) of the equipment that must be functioning correctly in order for a flight departure to be allowed. Although the MMELs of the B737, B737NG and B737Max are different, they all allow a flight to be dispatched with both Flight Control Computers (FCC) not operating, provided a triple set of rather stringent conditions are met: (i) limited duration of the flight; (ii) conditions throughout the flight for which autopilot is not essential; (iii) specific acceptance by the pilots of the additional workload that may be associated with the absence of autopilot assistance modes, such as manual landing without autothrottle. The 737Max differs from its predecessor 737NG in having a fly-by-wire spoiler system. When the elevator-Jam landing assist system is operating with spoilers extended the non-normal checklist instructs the pilots to use the autopilot to retract the spoilers, and then to continue to use the autopilot as needed. This contradicts the MMEL that allows flight departure with neither of the two FCC operating. This discrepancy was found by an operator Fly Dubai 18 months after B737Max entry into surface, and escaped Boeing design reviews and FAA certification scrutiny, even after the B737Max grounding. Adding to all the issues associated with the MCAS, having an operator finding an incompatibility in non-normal flight procedures, does not help the Boeing and FAA credibility.

14.9.3 – Reconsideration of certification procedures

The preceding occurrences remind that the priorities in aerospace engineering should be

- safety first because there are people's lives at stake:
- engineering quality as the insurance of airworthiness;
- finance to make whole effort sustainable.

The Boeing 737 Max lesson is that persistent short-term focus on financial profit neglects quality engineering and undermines safety and may also lead to large financial losses and loss of confidence that may take longer to recover than money.

An investigation by the combined airworthiness authorities on the certification of the B737 Max points to some of the improvements expected. The airworthiness authorities have much more limited resources than the aircraft manufacturer and must delegate technical details while providing overall supervision. Also, there is little point in duplicating the supervisory function, which is led by the airworthiness authority of the country of the aircraft manufacturer. However, closer information exchange and cross-checking among airworthiness authorities is desirable in particular in the four regions hosting the main aircraft manufacturers (USA, Europe, Brazil and Canada).

An area of certification that needs to be improved is human factors: most of the recent accidents and incidents are neither a fault of the pilots nor a failure of the systems but rather a mismatch or misunderstanding between partial technical failures and misaligned pilot reactions. The B737 Max was a case in point when Boeing assumed that following an MCAS failure the pilots would recognise the need to apply the elevator runaway procedure and implement it in four seconds. This sounds rather optimistic even in an ideal situation of zero workload let alone in the midst of an emergency with several other concurrent issues to mind about. A better understanding of human factors is essential to design a symbiotic relation with automated systems and their protective measures and failures.

Besides a much stronger focus on human factors, both the FAA and EASA are preparing new rules concerning safety management systems (SMS). The SMS are recommended by ICAO, are mandatory for airlines in the US, and have been adopted voluntarily by major industrial actors like Bell and General Electric as useful tools to keep an oversight of complex development and detect issues before they become problems. Both the FAA and EASA are developing rules mandating aircraft manufactures to implement an SMS. This supplements the transactional information for certification about details with an overall safety picture. In the case of the B737Max, the FAA admits that the disconnected, partial, and incomplete information it received did not give an overall picture of the flight control system and related issues.

14.10 – Modifications for return to service

The main modifications made to the B737Max to regain certification are: (subsection 14.10.1) a thorough revision of the flight control system with full redundancy of the two Flight Control Computers (FCCs); (subsection 14.10.2) provision of a much more comprehensive flight simulator training package, with much more emphasis on an improved non-normal checklist (NNCs). Although some issues remain (subsection 14.10.3) there is for the first-time reasonable expectation of a possible return to service towards the end of 2020.

14.10.1 – Redundant flight control

The B737Max flight control system has been thoroughly revised using mostly existing hardware, thus stopping short of a larger effort if for example additional AoA tensors were used to provide fail-safe operations. The data from the two AoA sensors is used by both flight control computers in a fully redundant way including a comparison to detect discrepancies. The case of consistent but erroneous AoA information, for example, both AoA sensors frozen, is no longer as critical since the MCAS can command only one pitch-down, not a runaway sequence. A further MCAS pitch-down must be allowed by the pilots than retain a 1.2g authority at all times. Excessive time delays in the system have been eliminated through changes in computer hardware. The remaining issues include that following a single AoA sensor failure, it is not clear how reliable angle-of-attack data can be obtained, as an alternative to disengaging the MCAS.

14.10.2 – Simulator training package

In the past, up to the resignation/dismissal of Denis Muilenburg, the Boeing policy was to avoid overwhelming pilots with data, to the point of choosing to omit the existence of the MCAS from the flight manual, possibly leaving some pilot questions unanswered. The takeover by David Calhoun at the beginning of 2020 signalled a radical change of policy towards indulging the pilots with data in a 190-pages report detailing the features of the flight control system not only of the B737Max but also of the B737NG. Some of the information had not been available before, and much of it was accessible only to instructors, and never passed to pilots. The new approach put much more emphasis on non-normal checklists (NNCs) with more clear revised instructions of 7 NNGs, namely (i) speed trim fail; (ii) horizontal stabilizer out of trim, (iii) runaway stabilizer, (iv) stabilizer trim inoperative, (v) airspeed unreliable, (vv) altitude disagree and (vii) AoA disagree. As an example, to the previous definition of elevator runaway as "continuous uncommanded movement" of the trim wheel, that does not cover erroneous MCAS activation, is added "or uncommanded motion inappropriate to the flight condition". The pilots are also warned of large control forces following the disengagement of electric pitch trim and advised to reduce airspeed if necessary. Issues remain like the need to use two hands to turn the trim wheel and whether the effort can be reduced by decreasing speed in a dive.

14.10.3 – Remaining issues and assumptions

Although some issues remain like fail-safe MCAS design and large control forces, Boeing was quietly confident that the changes to the flight control system (subsection 14.10.1) and much more comprehensive pilot training package (subsection 14.10.2) would pave the way for ungrounding the B737Max in 2020. The expectations of a return to service were delayed by additional issues with wiring (subsection 14.9.1) and the Master Minimum Equipment List (subsection 14.9.2). Boeing performed 9 hours of testing in three flights from June 29 to July 1, 2020, covering a wide range of airspeeds up to 500kt altitudes up to 37000ft and demanding manoeuvres including steep dives and climbs and banked turns. The path to recertification includes flight simulations for the Joint Operations Evaluation Board (JOEB) consisting of pilots nominated by airworthiness authorities around the world, and possibly with different skill levels. The travel restrictions due to the COVID-19 pandemic may delay the JOEB report that the FAA will consider together with other airworthiness authorities. Together with technical evidence supplied by Boeing, the FAA could unground the B737Max, perhaps after a further public consultation period. The predictions of Denis Muilenburg after grounding that the B737Max would be flying in 3, 6 or 9 months were not credible and proved wrong; the diligent work under David Calhoun, without public announcements, aimed at recertification after 15 months in mid-2020, may bear fruit towards the end of 2020, after 21 months of grounding.

14.11 – Effect on the Boeing-Airbus duopoly

The effect of the B737Max on the Boeing-Airbus duopoly can be analysed in three periods separated major crisis: (i) the two B737Max accidents and grounding that pale by comparison with (ii) the impact of the COVID-19 pandemic. The three periods are thus: (subsection 14.11.1) competition between the A320 and B737 families before the grounding of the B737Max; (subsection 14.11.2) and an intermediate period during which the Airbus-Bombardier dear was consolidated and the Boeing-Embraer arrangement collapsed; (subsection 14.11.3) the overwhelming and hardly predictable effects of COVID-19 as the biggest crisis in aviation history.

14.11.1 – Competition before grounding

The B737 (Figure 14.3) was the most successful twin-engine single-aisle aircraft of the first generation, in spite of coming into service after its European competitors, the Sud Aviation Caravelle, British Aircraft Corporation One-Eleven (Figures 14.13 and 14.14), The Boeing 737/737NG (Figures 14.1 and 14.4) also eventually prevailed over its only remaining America rival, the Douglas DC-9/McDonnell Douglas MD-80 (Figures 14.15 and 14.16), after declining sales lead to the acquisition of McDonnel Douglas by Boeing.

Figure 14.13 – The Sud-Aviation Caravelle (Source: https://bit.ly/3jQ37rA)

Figure 14.14 – The British Aircraft Corporation One-Eleven. (Source: https://bit.ly/3jZlj2i)

Figure 14.15 – The Douglas DC-9

(Source: https://bit.ly/32781ug)

Figure 14.16 – McDonnell Douglas MD-80.

(Source: https://bit.ly/3m1h1t2)

In spite of the modest success of the Airbus A300/A310 (Figures 14.17 and 14.18), Boeing was still diffident of European government aeroplanes; when the A320 proved to be technically a significant advance over the B737. The Boeing expedient to use grandfather rights to seat more passengers in a second-generation B737NG was effective in matching the sales of the more advanced A320 but left it with an underdog. The sales success of the second generation A320neo did not give Boeing the time to develop an all-new B737 replacement, forcing a compromised third-generation B737Max.

Figure 14.17 – The Airbus A300

(Source: https://bit.ly/2Zfn4QK)

Figure 14.18 – The Airbus A310.

(Source: https://bit.ly/2GGwYEl)

The lack of development potential of the Boeing B737Max was highlighted by the development by Airbus of the extended A321/LR/XLR (Figure 14.15) that Boeing could not match. The introduction of a new generation of engines, the GE/Snecma Leap and geared fan PW 1200, gave single-aisle aircraft a transatlantic range, that could not be expected with the earlier less efficient CFM56 and V2500. The A321LR/XLR (Figure 14.19). was able to fly the medium-range routes with higher efficiency than long-range twin-aisle wide-bodies. Thus, the A321 became a dominant sales force, stealing sales both from wide bodies for thin medium-range routes and from narrowbodies with a more versatile payload-range combination. The A321 accounted for most of the difference between the Airbus backlog of 6 500 A320neo versus the Boeing backlog of 4 500 B737Max. The Boeing advantage in widebodies with the B777/B787 (Figures 14.20 and 14.21) over the Airbus A350/A330 neo Figures 14.22 and 14.23 was eroded by the A321LR/XLR that also put the A320 family at advantage with regard to the B737 family. The A321LR/XLR became the best-selling of all airliners.

Figure 14.19 – The Airbus A321 LR
(Source: https://bit.ly/3jQeQ9A)

Figure 14.20 – The Boeing 777
(Source: https://bit.ly/2FgfJcJ)

Figure 14.21 – The Boeing 787
(Source: https://bbc.in/2F8uEG6)

Figure 14.22 – The Airbus A330 Neo
(Source: https://bit.ly/2GAuJCF)

Figure 14.23– The Airbus A350
(Source: https://bit.ly/2ZhWMNK)

14.12.2 – Between grounding and COVID-19

The grounding of the B737Max after two related accidents was a major blow to the finances and reputation of Boeing and also harmed the credibility of the FAA. The boom in the aviation sector, with large order books and long waiting times, shielded Boeing from cancellations, since airlines had to stick to their precious delivery slots. Of greater consequence was the success of the Airbus-Bombardier deal and failure of the competing Boeing-Embraer arrangement, both triggered by Boeing miscalculations. When the Bombardier C-series won a large order in the US against a Boeing backed Embraer E-series competitor, Boeing resorted to a legal filing leading a large import duty on the C-series assembled in Canada. This controversial trade ruling was subsequently reversed, but by then its consequences were iron-clad. Bombardier offered for a nominal fee its C-series program to Airbus, allowing finial assembly at the Airbus factory in Mobile, Alabama and avoiding U.S. import taxes altogether. The clumsy actions of Boeing led Bombardier into the arms of Airbus, and it would have been worse for the duopoly if Bombardier technology had gone to China to help certify their troubled airliner programs. The Bombardier-Airbus deal was a win-win for both. Airbus gained a modern and efficient C-series rebranded A220, to revitalize the modest sales of the A319 at the low end of the single-aisle market; the C-series/A220 gained the support of the vast Airbus network and had the negotiating clout to obtain better conditions from suppliers with the backing of an Airbus ten times larger than Bombardier.

Boeing tried to correct the initial mistake with the only option left, a deal with Embraer, that at best could not match the Bombardier-Airbus deal. The Embraer E-series is smaller than the Bombardier C-series; the E-series does not fit as well at the bottom of the B737 family as the C-series/A220 fits at the bottom of the A320 family. Airbus incorporated the C-series for a nominal fee, whereas Boeing should pay 4.2 B$ for the E-series and the engineering workforce behind it. With Boeing seeking a 60 B$ bail-out from the U.S. Government, it could not possibly pay 4.2 B$ to buy a foreign company. The collapse of the Boeing-Embraer deal was a loss-loss for both: Embraer was left with the E-series competing against a C-series backed by Airbus an order magnitude larger, a situation it had avoided in the past. In the single-aisle market Boeing was left behind in all three sectors with: (i) a grounded B737Max in the middle versus a flying A320neo; (ii) a growing gap at the upper end between B737-9/10 and the A321/LR/XLR; (iii) a small B737 Max derivative versus the new A220 and old A319.

14.12.3 – Post-covid-19 recovery scenarios

In March 2020, when the Covid-19 pandemic reached the U.S. Boeing was already in dire financial straits: (i) it had ended 2019 with a debt of 27 B$; (ii) the commercial aircraft division alone was consuming 4.3 B$ per month; (iii) al loan of 15 B$ had been depleted in less than three months. It becomes clear that left on its own, Boeing would be bankrupt in a few months; not that would ever be allowed to happen to the U.S. largest exporter and second-largest defence contractor. The U.S. Government bail-out was to be expected and a sum of 60 B$ was mentioned. This was the time the U.S. Congress was approving the CARES (Coronavirus Aid Relief Economic Stability) act. The Boeing 60 B$ bill raised some eyebrows in Congress even in the CARES context and might have raised more if it had been submitted on its own. Boeing argued that the 60 B$ also covered the supply chain, not disclosing how much was keeping for itself. The CARES allocation of 60 B$ to Boeing insured its survival in the coming months, probably long enough to recertify the B737Max towards the end of 2020. Although the coronavirus pandemic is an unmitigated disaster for the whole of the aviation sector, it arrived at the right time to help justify a Boeing 60 B$ bail-out that was needed before.

14.12 – Conclusion

Viewed with hindsight Boeing has been the victim of its expedient of countering a new technologically superior A320 with an outdated B737NG competing through unequal grandfather rights. The trick would no longer work in the next generation when Boeing was forced to put the third generation B737Max against the second-generation Airbus A320neo. The profit-before-quality and sales-before-engineering culture at Boeing only made matters worse with flawed development of a B737Max starting at disadvantage. The coronavirus pandemic has massive negative consequences in the airliner market, and its evolution is hardly predictable, yet in almost every conceivable scenario Boeing is likely to lose further ground to Airbus:

- the long-range twin-aisle wide-body market, in which Boeing is stronger than Airbus, is likely to take longest to recover since international travel restrictions remain uncoordinated;
- for the medium-range routes, with reduced market demand, the A321LR/XLR offers superior economics relative to widebodies and has feeble competition from the B737-9/10 if the latter is pursued; the reduction of the A320 backlog from 6500 to 5000, and B737Max backlog from 4500 to 3000, is accompanied by a comparable decrease of 30% (or more) in production rate, keeping the Airbus advantage at the middle of the SA market, even assuming that the B737Max problems fade away;
- the A220 leaves Airbus at a stronger position at the bottom of the SA market, and with more development potential;
- the lack of orders, cancellations, and delayed deliveries at least until 2022-2023, affect both Airbus and Boeing, but Boeing has the bonus of bringing more than 800 grounded B737Max into service;
- keeping the supply chain in operation is a challenge to both Airbus and Boeing they can face, with many common suppliers and a possibly increasing Airbus market share.

The current COVID-19 pandemic is so damaging both to Airbus and Boeing that it may hide the fact that Airbus is a position of growing advantage in almost any recovery scenario. In order to keep its market share, Boeing desperately needs a Future Single Aisle (FSA) aircraft, but the odds are against:

- The 10-15 B$ development cost cannot be financed in the current depressed financial situations unless another bailout is coming;
- the technology has not yet matured enough to justify a major improvement over current aircraft;
- Airbus has a much better development potential and untarnished reputation with the A320/A220 to win new order over the B737Max whose sales were already stagnant before the COVID-19 pandemic;
- major advances could be expected in the 2030-2035 timeframe when Airbus should have a 30% more efficient A320 successor, again raising the bar for Boeing;
- the ability of Boeing to recover should not be underestimated, but Airbus has the lead and the means to at least keep it, and perhaps enlarge it.

14.13 – Final Note

Since at the time of conclusion of this report the B737Max is still grounded, this final note addresses' the main open issues, waiting for an answer since the beginning of the B737Max crisis: (Subsection 14.13.1) When will the B737 Max return to flight? (Subsection 14.13.2) How long will it take to bring into service the 385 grounded aircraft plus the 450 aircraft built but not delivered? (Subsection 14.13.3) When will normal production of the B737Max resume and at what rate?

14.13.1 – When will the B737Max be ungrounded?

At present Boeing has delivered to the FAA the documentation about changes to the Boeing737Max and the FAA has published for comment the steps required to bring the aircraft back into service. Thus, the ungrounding of the B737Max by the FAA is possible before the end of 2020.

On the other hand, the ungrounding cannot take place before the approval of the report of pilots with different levels of experience, nominated by several airworthiness authorities around the world, that will evaluate the flight simulator training package proposed by Boeing.

If the FAA ungrounds the B737Max unilaterally, other airworthiness authorities around the world may make their own independent assessments, leading to phased returns to service at different times in different countries. To paraphrase the ICAO Director-General, it may be difficult to explain why the same aircraft is already safe to fly in one part of the world and not yet in another. A simultaneous ungrounding by the airworthiness authorities around the world is desirable and it remains to be seen if that will be the case.

14.13.2 – How long will it take to bring into service the grounded fleet?

The grounded fleet totals about 855 aircraft, consisting of 385 aircraft to airlines before the grounding plus about 470 aircraft produced since the grounding and that could not be delivered to airlines.

When Dennis Muilenburg was still CEO and before the COVID-19 pandemic, Boeing claimed it could bring up to 70 aircraft per month back into service, taking at least one year for the grounded fleet of 855 aircraft. In the most optimistic scenario of ungrounding at the end of 2020, all grounded aircraft would be flying by the end of 2021.

Multiple challenges are suggesting that ungrounding the B737Max will take beyond 2021. First, the recertification process has added more changes and work to be done on the aircraft and pilots will need simulator training. Second, airlines may not be in condition amid or following the COVID-19 pandemic to take all aircraft and may delay or cancel orders. Still, it is in the airlines' interest to operate the B737Max rather than the older models like the B737NG, to reduce costs and emissions.

14.13.3 – When will normal production resume and at what rate?

At the time of grounding the B737Max, the production rate was 52 per month, with Boeing pressing the supply chain to raise to 57 per month. Following the grounding In March 2019, production was decreased to 40 per month, on the expectation of ungrounding until the end of the year. When grounding extended into 2020 Boeing stopped production to avoid a greater accumulation of undelivered aircraft. Then Boeing realised it had to keep the supply chain active and resume production at the lowest rate that is economically sustainable and is estimated by external observers at 11-12 per month.

The official Boeing target is to stabilise production at 31 per month (versus 52 per month before the grounding) at an unspecified time in the future after a slow ramp-up. It is likely that bringing back into service the 855 grounded aircraft will have priority over new production, so no ramp-up can be expected before 2022 at least. Boeing has been losing about 5 B$ per quarter in 2020 and expects to come back into profit in 2021.

The state of the supply chain is a particular concern on three grounds since suppliers: (i) have been forced to cut prices, with profits of less than 10%; (ii) were also pressed to share development costs and risks; (iii) were expected to invest in increased capacity production in the 'boom' before the COVID pandemic. Thus, some suppliers are indebted by past investments with modest unit prices on production rates much lower than expected. With most airlines unwilling to make new orders for perhaps the next 2-3 years, production rates may linger at the survival mode of lowest that is economically sustainable for some time until a ramp-up starts. All these scenarios depend on overcoming the remaining recertification issues and the evolution of the COVID-19 pandemic.