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It's About Time: Toward Realistic Schedule Estimates

March 8, 2021

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Abstract

This paper is part of a research agenda outlined in Franck et al. (2016) directed toward improving the realism of defense acquisition schedules. Defense acquisition schedules have long been a difficult problem. In this particular effort, we consider primarily the case of the 737MAX, which has been a fortuitous example of the risks of scheduling-by-fiat. We analyze the 737MAX misadventure using Systems Dynamics and Root Cause Analysis methods.

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Introduction

Interest in project management estimation, cost, and scheduling remains strong in the academic world (and with practitioners), driven by the sometimes-spectacular cost and schedule overruns, with defense projects in particular. Unfortunately, projects continue to fail and overrun every established metric. Nevertheless, we continue to study in the hopes of a breakthrough—a cure—for all that ails the defense acquisition world.

No one believes it is possible to accurately estimate a schedule so there are no overruns. Sometimes, we get scheduling right, but often we get it wrong. After the fact, we can determine what went wrong and why; however, we have not yet been able to prevent failure. We believe we must do better to stay on schedule, and also to satisfy the need to deliver systems that work, with timely delivery. There are many hypotheses about why programs are not always successful. One (perhaps neglected) is that people, with complexity and imperfections, are one major constant in project management.

Humans tend to think about project management in the context of cause and effect (Dörner, 1996). We consider cost and associated variables during the project planning process. We do the same when developing a schedule. The planning process allows us to visualize how the development will unfold. Once we start executing, however, our ability to visualize the interplay of variables, from stakeholder demands to supply chain issues to requirements changes, is limited. We then react to events in a serial "cause and effect manner," solving the immediate problem, but often neglecting to consider feedback and second order effects of those decisions. Newton's Third Law of Motion states, "For every action, there is an equal and opposite reaction." In human activities from engineering to war, a corollary to that law adds the idea of a counteraction, or response to the *reaction*. This concept is well understood in military planning and is a basic concept in wargaming, but in planning for and managing projects we identify the cause-and-effect relationships, action-reaction, but don't consider the action-reaction-*counteraction* sequence. That is, games against "nature" can also be complex.

Scheduling is unique as studies by operational research experts, systems analysts, and even mathematicians attest (Boyd & Mundt, 1995; Herroelen & Leus, 2004, 2005; Rodrigues & Williams, 1998; Vandevoorde & Vanhoucke, 2006). In fact, we can explain schedule—the how and the what—using mathematics. We can also use the same mathematics and probability to develop schedules. What we haven't been able to do is apply mathematics and probability to get scheduling right. In this context, we believe system dynamics provides an opportunity to better understand scheduling and schedule execution, especially from the people perspective.

System dynamics was conceived and developed by Forrester in the 1960s (Forrester, 1971). In many ways, Forrester's approach was like that of Dörner (1996) in that both recognized not only the limitations in human ability, but also that social systems were far more complex and difficult to understand than any technology. Further, both saw the world in terms of systems. Although we may not always think of it, we treat a development project, commercial or military, as a system with both inputs and outputs, as well as constraints and mechanisms. Inputs represent those management, budget, policy, materials, and other variables that are transformed by the system into outputs. Constraints are those regulatory, legal, fiscal, and time variables that restrict the system. Mechanisms are the people and processes used by the system to transform to the outputs.

If a project plan is a mental model of a system development, it represents the project team's shared assumptions of how the development will proceed. It represents a system structure (Forrester, 1971). Forrester also recognized that the human mental model (including that of a system development) can fail because the human mind often draws the wrong conclusions about the consequences of that model. System dynamics thinking and a recognition of the criticality in considering the role and thinking of the human in project management, including scheduling. As such, it offers a method to better understand the execution of aerospace system developments.

The Boeing 737MAX: Background

The reader is entitled to ask why a commercial project, like the 737MAX, is a legitimate topic for defense acquisition research. We believe the answer has three parts. First, the Boeing airliner is an aerospace program with technical, program management, and scheduling issues. Second, the 737MAX program (particularly the aircraft accidents) has been highly publicized. Widespread discussion (some of it very good) has produced a fairly extensive understanding of the relevant facts, and also some excellent analyses (which make research in some depth both possible and potentially illuminating). Finally, the 737MAX is a superb example of what can happen when program duration is dictated by considerations outside the dynamics of the development program.[1]

The Boeing Corporation and Airbus SE, a duopoly, are the largest commercial and defense aircraft producers in the world. Boeing's first successful commercial jet was the Boeing 707 (first flight 1957). Airbus became a major commercial aircraft player with the A320 (the major Boeing 737 competitor) in 1987. In a very real sense, the Boeing 737MAX was a product of the Boeing-Airbus competition. Boeing has been continuously incorporated (albeit under different names) since 1916; Airbus since 1970.

That rivalry has not been especially friendly. It has featured World Trade Organization complaints[2] and some hard-fought contests in various market segments. These have included aerial tankers (Boeing KC-46 vs. NG/Airbus A330 MRTT). However, the center of their competition has been narrow-body civil airliners—the contenders being the Airbus A320 and Boeing 737 families. Both have been major commercial successes and significant contributors to both companies' profits. Deliveries by year are shown in Figure 1. While the competition has been intense, both companies have been highly successful in the narrow-body market—so far.

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[1] This is what we term an "aspirational" schedule estimate, which we define more specifically later.

[2] This dispute has surfaced again recently, with U.S. threats to impose tariffs on EU goods because of a WTO finding of illegal subsidies for Airbus (Peker & Zumbrun, 2019). One previous chapter in this long-running story is recounted in Franck et al. (2011, pp. 8–9).

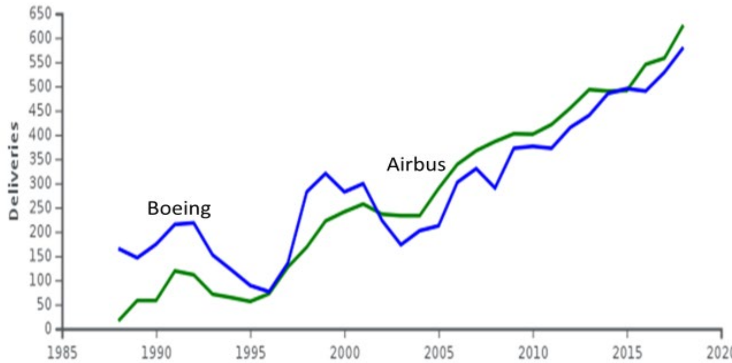


Figure 1. Boeing 737 and Airbus 320 deliveries by year (since A320 first flight)

By 2010, Boeing had reason to believe the Boeing 737 was becoming obsolescent, and was considering a new, clean-sheet replacement aircraft. The most promising enhancements then available were new turbofans, but they offered fuel efficiency improvements that were likely in single-digit percentages, certainly no more than 15% (Aviation Week, 2010). Boeing management reckoned that prospective customers would not be sufficiently interested in recapitalizing their fleets to purchase airplanes of this sort.

Thus, the near future for the narrow-body competition likely featured continued production of essentially the same aircraft (Boeing's 737NG) and the most recent versions of the Airbus 320 family. The next generation of narrow-body passenger airliners would appear around 2020.

At the time, that position was plausible, but proved to be wrong. New engines available (CFM International Leap 1B and the Pratt & Whitney PW 1000G) offered fuel efficiency increases of about 14%, and the customers were indeed interested in the fuel efficiencies the A320neo (new engine option) offered. At the Paris Air Show of 2011, Airbus presold 667 A320neos in one week. This, and related developments, convinced Boeing of a time-sensitive need to respond to the re-engined Airbus models. In response, Boeing promised in 2011 to deliver a narrow body fairly quickly (Gelles et al., 2019).

Boeing entered development of a new narrow-body product (named the 737MAX) at a double disadvantage. First, Airbus had started its program sooner. Second, the Airbus 320 (first flight in 1987) was a newer design than the Boeing 737 (1967). In particular, it had more vertical distance between the (wing) engine mounts and the tarmac. Figure 2A shows relative ramp clearances for the Airbus 320 and Boeing 737 engines; 2B shows the relocation needed to accommodate the new engine (LEAP 1B) for the 737MAX.

Basically, Boeing found itself in the position of having to produce a new narrow-body airliner that would be ready (soon enough) close to the A320neo launch with fuel efficiency improvements that were sizeable (good enough) to cause customers to remain with Boeing rather than moving to Airbus. Airbus was going to have the A320neo available by 2017, with 12–15% improvement in fuel efficiency (relative to the A320). Boeing's response was to promise *quick delivery* of a new model 737 with a new fuel-efficient engine.

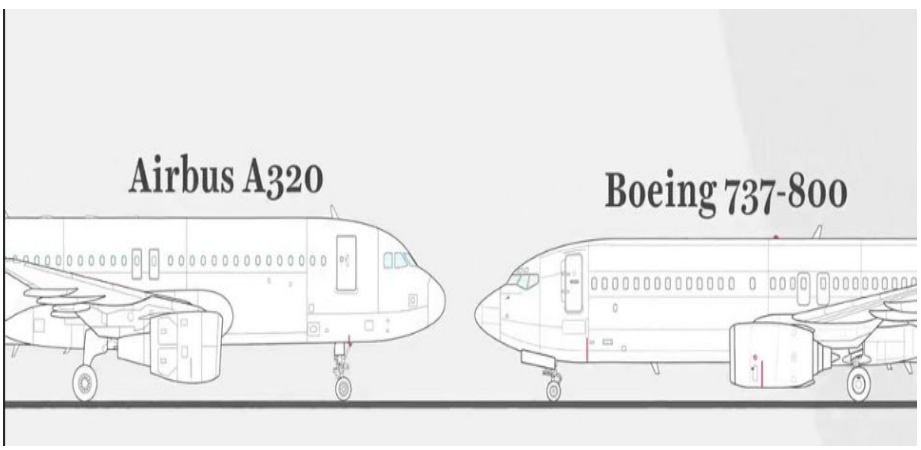
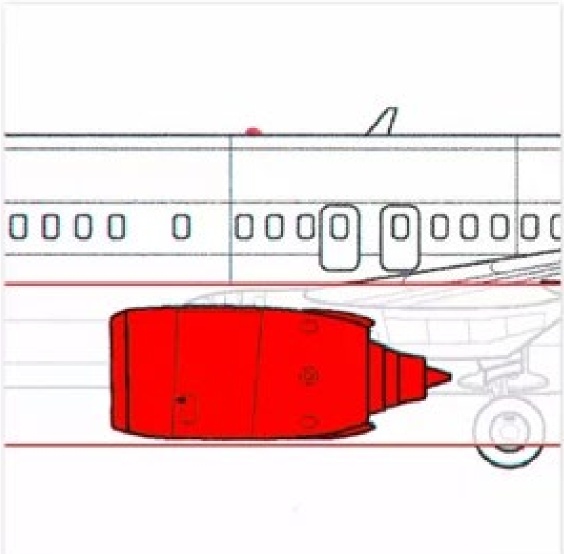


Figure 2A. Ramp clearance of Boeing 737NG vs. Airbus A320



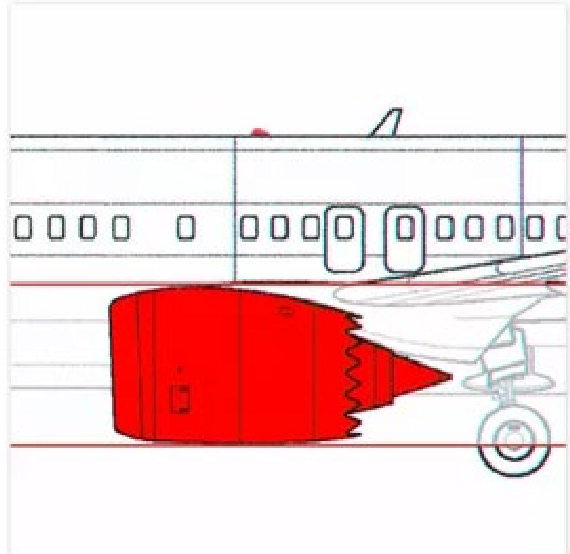


Figure 2B: Repositioning the 737 engine: 737NG on left, and 737MAX on right

In summary, the logic that appears to have driven the Boeing 737MAX strategy is as follows:

- Competitive pressure from Airbus for single-aisle aircraft forced Boeing to do something quickly in order to remain in that line of business.
- Fuel-efficient engines are necessary to sell passenger jets in the current global market. They were also necessary to tempt commercial customers to buy new aircraft.
- The schedule would be driven by the perceived need for an in-service time as close to the Airbus A320neo as possible.
- The schedule, over cost, and performance seem to have been Boeing management’s driving factors, rather than being driven by the time required for the necessary engineering.
- Use of 737 airframe meant lower production costs, simpler FAA certification, and lower training costs (driven by pilot familiarity with existing 737 fleet).
- Larger engines did not fit on the existing 737 wings, so design modifications were needed.
- Engine modifications changed the aerodynamics of the airplane.
- However, the airplane needed to match the pilot qualification requirements of in-service B 737 aircraft so that aircrew training did not significantly delay

introduction to commercial service. (This last constraint proved to be particularly consequential.)[3]

It appears the modifications to this aircraft originally designed in the late 1960s to make it a competitor in the 2010s were greater than originally anticipated. Relocated, more powerful engines significantly changed the aircraft handling characteristics in some flight regimens. Any new requirements resulting from the changes probably should have driven new requirements, which would have increased the schedule an unacceptable amount of time. This management reaction to competitive pressure seems a classic case of what we call an aspirational schedule. Figure 3 shows a system view of the 737-upgrade. The arrows show the interrelationship of the system variables, as well as the feedback those variables can cause.

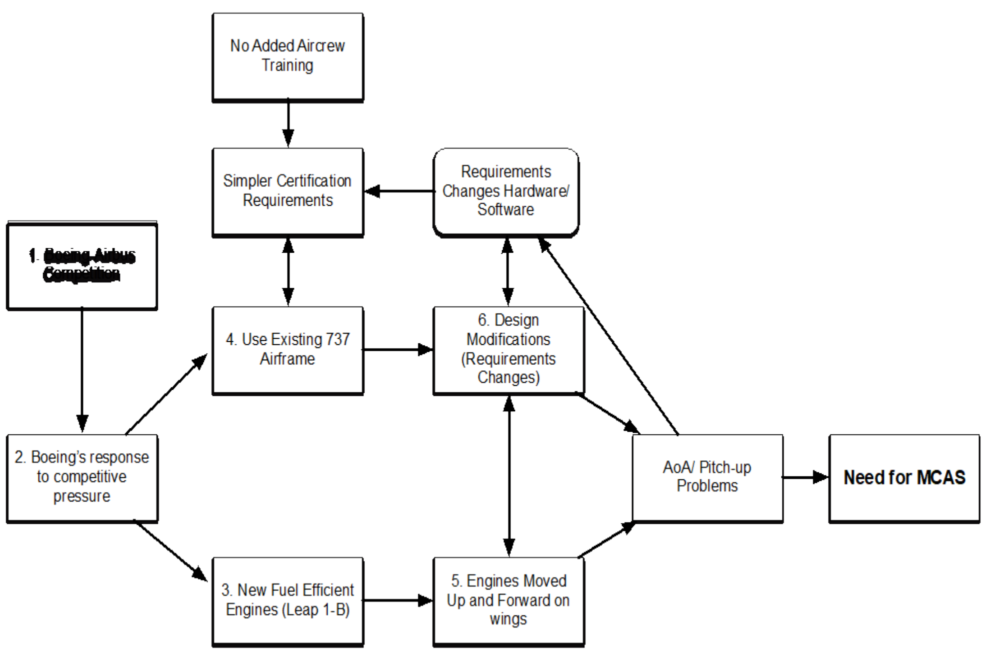


Figure 2. The 737 upgrade "system"

[3] This would mean that the 737NG and 737MAX would carry the same “type rating” and pilots could be qualified to fly both. Campbell (2019) explains all this succinctly and well.

The Race to the Swift

Completing development of the Boeing aircraft to the Airbus timeline was a schedule challenge as shown in Table 1. The major program objective was to deliver a more fuel-efficient narrow-body airliner quickly and at a relatively low cost before the market was saturated by Airbus.

The new engine was larger in diameter than those on current 737s.[4] This difficulty was overcome by modifying the nose landing gear and positioning the new engine forward and upward relative to the wing. The overall effect was to keep the same ground clearance while taxiing. However, moving the engines changed the flight characteristics of the aircraft.

Table 1. Major Milestones (actual) for the Airbus A320neo and Boeing 737MAX

VENT	A320 neo	737MAX
Program Announced	December 2010	August 2011
First Aircraft Produced	July 2014	December 2015
First Flight	September 2014	January 2016
First Customer Delivery	January 2016	May 2017

[4] The 737 was well designed for a low-bypass turbofan, like the JT8 (48" in diameter). A high-bypass turbofan like the CFM-56 (60") necessitated an oval cowling to preserve ground clearance. An advanced high-bypass turbofan like the LEAP 1-B (69") also necessitated repositioning the engine for the 737MAX family.

Schedule Pressure: Speedy Execution

The schedule pressure had technical ramifications, but also impacted the work environment. According to several published reports (e.g., Broderick, 2019; Gelles et al., 2019; Nicas et al., 2019), the 737MAX development program proceeded on something of a forced march. Boeing employees perceived a compelling need to finish the development program within the company's time frame.

In search of faster progress, an approach described as "compartmentalized" came into being.[5] (This, of course, raises the question of whether this approach contributed to the MCAS problems that arose later.) Some concluded in retrospect that the development schedule had been "stretched to the breaking point" (e.g., Campbell, 2019).

[5] This is analogous to problem decomposition in the Operations Research literature, and also bears resemblance to "concurrency" in the acquisition literature.

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The Problematic MCAS

> "Scientists and engineers seem able to predict only a fraction of the difficulty they are likely to face in a specific project. Much of it simply crops up unexpectedly." (McNaugher, 1987, p. 66)

In fact, even programs intended to be simple can have complications, and the 737MAX was apparently more complicated than originally believed. The A320neo is mostly a re-engined A320. The new 737MAX required more complex modifications to reduce drag and a need to reposition the engines. The new engines (LEAP 1B) were almost 40% larger and weighed almost double those of the 737NG (CFM-56). The new plane was longer and had a wider wingspan. What Boeing couldn't change was the height above airport ramps without having to redesign the landing gear, which would have threatened both the development schedule and quick FAA certification (Tkacik, 2019).

A later part of the testing program revealed the aircraft tended to pitch up, because the Center of Gravity (CG) and the Center of Lift (CL) were too close together due to the new engine location (Coughlin, 2020). The change in engine position is shown in Figure 2B (shown previously).

Acknowledging the challenges with engine repositioning, one proposed solution involved modifications to the airframe itself (Langewiesche, 2019). However, given the schedule imperative, Boeing chose instead a software solution.[6] It was named the Maneuvering Characteristics Augmentation System (MCAS; Broderick, 2019; Gelles, 2019). The first version of MCAS (MCAS1)[7] was intended to input automatic, corrective control inputs to situations involving relatively high airspeeds (and G forces)—in the form of 0.6 degrees of pitch-down trim applied in 10 seconds, with maximum trim change limited to 5 degrees (Gates, 2019).

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[6] There were, however, other reasons to favor a software solution.

[7] We term the earlier version as MCAS1 and the later (more aggressive version) as MCAS2. This is our own terminology and adopted for expository clarity.

However, later flight tests also revealed some pitch-up handling difficulties at normal G forces and low airspeed. This led to increased realm of MCAS engagement parameters to include low speeds, high angles of attack (AoAs), and "normal" G-loadings. Pitch changes were increased to 2.5 degrees (Campbell, 2019). Moreover, the resulting MCAS2 could engage any number of times (Gates, 2019; Langewiesche, 2019). The overall effect was to make the new iteration of MCAS (MCAS2) "more aggressive and riskier" (Nicas et al., 2019).

From a software engineering perspective, Johnston et al. (2019) suggest there were four key errors in the development and fielding of MCAS: poor documentation, a rushed release, delayed software updates, and humans out of the loop. The poor documentation refers to not only the lack of documentation on MCAS, but that the documentation was printed instead of digital. MCAS1 was regarded (correctly we think) as an "innocuous" feature that could or would seldom emerge as a problem. And, should it occur (in either version), treating the incident as a runaway-trim malfunction would solve the problem. Thus, the flight crews involved in the Lion and Ethiopian accidents had little, if any, knowledge of MCAS2 operation or potential consequences should an AoA indicator malfunction. According to Pastzor (2019), "One senior Boeing official said the company had decided against disclosing details about the system that it felt would inundate the average pilot with too much information—and significantly more technical data—than he or she needed or could realistically digest."

The rushed development was a result of the Boeing marketing strategy—timely release of a product so as not to lose business (Johnston & Harris, 2019). Statements attributed to Boeing employees assigned to the project included "intense pressure cooker," "fast turnaround" environment," and work at "double the normal rate." One technician reported that he had received "sloppy blueprints" with a promise of future fixes. However, that remedy was still incomplete in early 2019 (Gelles et al., 2019).

The delayed software updates were affected by some things Boeing could not control; the U.S. government shutdown in 2017 caused updates to be delayed by at least 4 months (Johnston & Harris, 2019; Pasztor, 2019). For example, Boeing submitted a software fix to the FAA for certification 7 weeks before the Ethiopian

Airlines crash. It is impossible to know whether a less rushed, more robust software design process would have made a difference (Johnston & Harris, 2019).

The fourth issue, the "human out of the loop" problem, resulted from the MCAS2 being activated by a single AoA sensor (Nicas et al., 2019). Choosing to rely on one indicator when two were readily available could only be regarded as a "bewildering mistake" in retrospect (Langeiwesche, 2019).[8] A related mistake was allowing the more powerful MCAS2 to be activated an unlimited number of times. As Langewiesche (2019) noted, "No one I spoke to from Boeing, Airbus or the NTSB could explain the reasoning here."

It is clear in hindsight that Boeing's haste led to mistakes and miscommunications. Those out of the loop were not limited to pilots. For example, relevant FAA officials were not informed (Gates, 2019) and discussion of the MCAS system was deleted from the 737MAX pilot manual (Tangel et al., 2019). Furthermore, the more aggressive version, MCAS2, was not well shared with interested parties, including airworthiness certification authorities (Tangel, 2019). Our summary of the 737 Max story is shown in Figure 4.

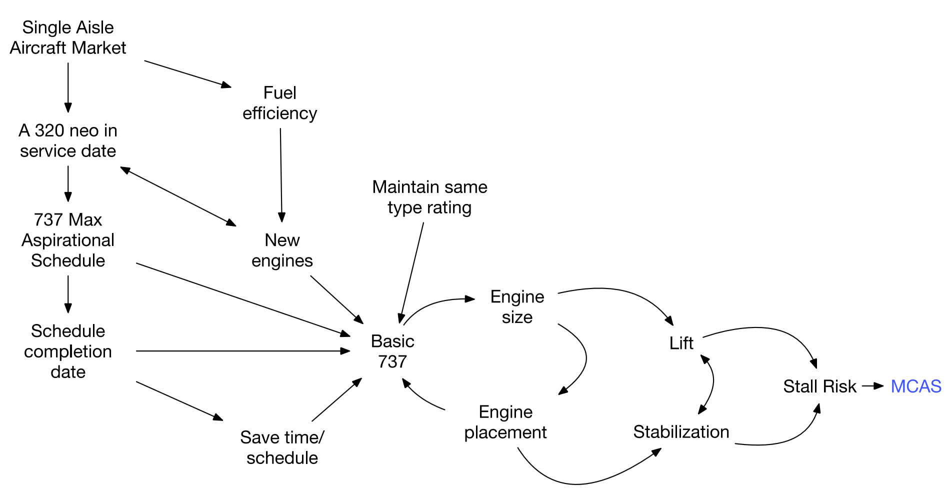

Figure 3. How the B737Max came to be

[8] We regard Langewiesche (2019) as the best single source on the B737 fatal accidents, particularly as to what happened and why.

The key drivers were time perceptions based on the market rather than engineering estimates. It's worth noting that getting to "MCAS decisions" include both technical and communications issues (especially not fully informing the pilots). Figure 5 shows our view of the dynamics of the development.

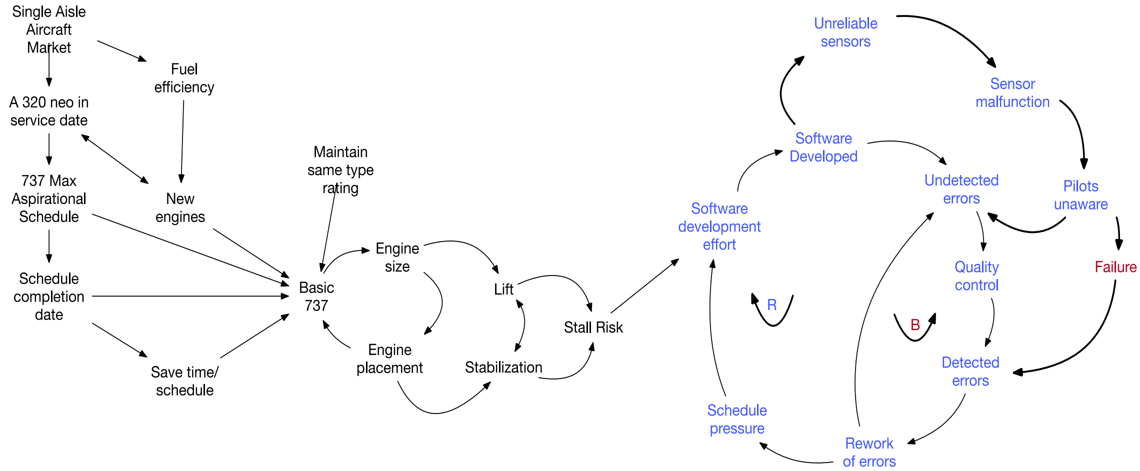

Figure 5. The dynamics of the MCAS development

The 737MAX Crashes

The circumstances of the Lion and Ethiopian Air accidents with the 737MAX have been discussed extensively. For those interested in learning more about the events surrounding the crashes, we recommend Langewiesche (2019) and Tangel, et al. (2019) as good starting points. In addition, reports by various agencies are very informative (e.g., JTAR, 2019; House Committee on Transportation and Infrastructure, 2020; and NTSB, 2019).

Figure 6 is our synthesis of the information available, including accident reports, analyses and recommendations from regulatory agencies (e.g., FAA). It is our version of a Root Cause Analysis of the mishaps.

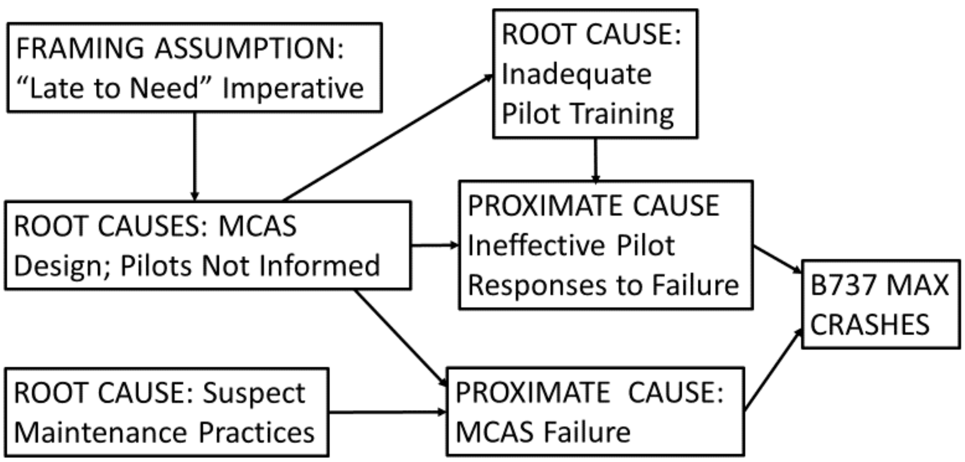

Figure 6. Hypothesized Causes of 737MAX Mishaps. Sources include Langewiesche, 2019; Pasztor, 2019; authors' interpretations

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Overall Comments on this Case

1. What trades were made?

    - Schedule got major (close to exclusive) emphasis—with attendant design constraints. Strict (at least fairly strict) adherence to original schedule was pervasively enforced.

2. Consequences of the trades (results of schedule emphasis)?

    - A new narrow-body type was conclusively ruled out; schedule constraint dictated a 737 variant with a new, but already developed model.
    - In development there was a lack of overall program review and oversight.
    - In at least some cases, multiple concurrent tasks were completed with insufficient regard for overall aircraft safety. (Nothing apparently went wrong with “performance” or apparently with cost.)
    - There were time pressures throughout the 737MAX development effort.
    - Some steps were skipped.
    - Some steps were done concurrently.
    - Most notable specific example of unknown work (ex-ante) is that a bigger engine on old airframe design resulted in pitch-up problems noted at low speeds and high angles of attack.
    - Although not intended, the program pace detracted from the operating safety of the airplane delivered for commercial service.

3. How and why were the trades made?

    - Schedule emphasis due primarily to commercial success of A320neo, which put Boeing at a major strategic disadvantage in the narrow-body airliner market.
    - Recovery strategy focused on a quickly developed 737 variant.

4. What is the evidence or rework? Primarily responding to the pitch-up problem:

    - MCAS (Maneuvering Characteristics Augmentation System, part of 737MAX software suite) was changed to deal with aircraft handling issues in high-speed flight.
    - Further rework arose with the need to resolve pitch-up problems at low speed with high power settings. A solution (MCAS2) appeared late in the game (within the corporate-dictated schedule) Good information on this issue is available in publicly available sources.

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Some Further Observations

An interesting, but so far somewhat neglected, question was how Boeing was caught wrong-footed in 2011 with the Airbus 320neo under way (with no planned response until 2020). One report (Broderick, 2019) has it that the A320neo family was originally intended as a defensive response to the potential threat from Bombardier's Canadian Regional Jets.[9] If so, this does much to explain Boeing's initial surprise.

Even so, why did Boeing not feel a similar need to likewise defend itself? For Boeing, like Airbus, the narrow-body airliner family is its leading source of profit. How did Boeing look at the same market environment (with the same contestability concerns) and reach a very different conclusion, especially when the B737 design was closer to the end of a long run than was the A320? Bottom line might well be that the fundamental root cause of the current 737MAX difficulties was a strategic miscalculation a decade in the past.

As noted, this miscalculation led to a difficult problem for Boeing in two parts: (1) coaxing additional competitive life from a half-century-old design, and (2) doing so in a manner responsive to the threat posed by the Airbus A320neo. This first part was due primarily to an old design originally intended for low-bypass turbofans. The second part would have been less difficult if Boeing had not made the strategic miscalculation noted previously and had started its 737-replacement program sooner.

In short, Boeing launched a program which (like all new programs) had both competitive and technical aspects. In this case, a timely response to the A320neo dictated the form (re-engining) of its narrow-body program at a pace driven by the A320neo family. The MCAS consequences were partly a matter of bad luck, but the

[9] This seems unlikely at first glance but is understandable. For example, Franck et al. (2012) contains an analysis of various potential competitors to the Boeing-Airbus narrow-body duopoly, of which Bombardier and Embraer regional jets were reckoned the most serious. This hypothesis is supported, *inter alia*, by Airbus acquiring the Canadian Regional Jet production facilities, and Embraer's regional jets pursued as a joint venture with Boeing (which would have had an 80% interest).

design team might well have made other miscalculations for which the adverse consequences have been nonexistent or less serious.

Finally, and most relevant to our current purpose, is that the 737MAX case is an object lesson concerning the hazards of aspirational schedules, especially if they’re taken too seriously.

A Final Word—Aspirational Schedules

While this study examined a commercial aircraft project, the similarities of complex system development are strikingly like the broader aerospace and defense (A&D) sector. Indeed, Boeing is both commercial aircraft manufacturer and defense contractor. We hypothesize that A&D programs respond to two inherently different kinds of system development scheduling. Standard scheduling methods (and estimates) are generally based on a structured planning (e.g., Critical Path Method [CPM] or Program Review Evaluation Technique [PERT]).[10] Another type of scheduling is that described in this paper—aspirational scheduling. We define an aspirational schedule as one originating from a political, competitive, or business desire, aim, or goal—rather than experience-based scheduling estimates.

Aspirational schedules are driven by political and commercial processes and decisions. It is an example of making engineering development fit a strategy, rather than allowing the engineering discipline to define the time needed.[11] In and of itself, the idea of political or commercial events driving developments is not new. Developments from the Manhattan Project to the Lockheed U-2 to Polaris are examples of political requirements driving development. What may be lacking in this latest move to aspirational schedules, however, is acknowledging the challenges of aspirational scheduling and an acceptance of the necessity for reasoned trades in a development.

Aspirational schedules now appear to be highly fashionable, and they also have attracted powerful institutional advocates. One recent example is the Air Force's Digital Century Series initiative. Its chief advocate is former Assistant Secretary of the Air Force for Acquisition Will Roper. He advocates rapid development and production of a series of fighter aircraft, such as the Air Force procured starting in the 1950s.[12] His

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[10] The PMBOK Guide (2017) has good discussions of these sorts of methods.

[11] In a perfect world, program planning would consider both parts of the problem and formulate a well-considered program schedules that considers both.

[12] This refers to the Century Series of U.S. Air Force fighters that originated in the 1950s: F-100 (Super Sabre), F-101 (Voodoo), F-102 (Delta Dagger), F-104 (Starfighter), F-105 (Thunder Chief), and F-106 (Delta Dart).

rationale includes a more agile response to peer competitors, enabled by new generations of design simulation software (Freedburg, 2019). This is to take place in a less risk-averse acquisition culture. With these technologies and development of new combat aircraft types in 5 years or less (Insinna, 2019), this looks a lot like a large-scale adoption of aspirational schedules.

A second example (emerging) is the Ground-Based Strategic Deterrent (Minuteman ICBM replacement). The program has been declared "late to need," and is proceeding apace despite potential complications with an ongoing Federal Trade Commission investigation (Censer, 2019; Clark, 2019; Erwin, 2018; FTC, 2018).

Later the fighter designations were merged with the Navy's. For example, the Air Force Phantom II was first designated as the F-110 but served as various models of the F-4 (basically a Navy designation).

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