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It's About Time: Toward Realistic Acquisition Schedule Estimates

Charles Pickar—is a member of the NPS faculty, where he teaches project management, defense acquisition, and systems engineering. Before joining NPS, he led the Applied Systems Engineering Program Area at the Johns Hopkins University Applied Physics Laboratory. He is a retired Army officer with extensive experience in the U.S. defense industry, including Director and VP levels at Lockheed Martin, Northrop Grumman, and SAIC. He is the current Chair of the Systems Education Technical Committee of the IEEE Systems Council. His research and published work focus on applying systems engineering and system dynamics analytical approaches to defense acquisition problems. [ckpickar@nps.edu]

Raymond Franck—retired from the faculty of the Graduate School of Business & Public Policy (GSBPP), Naval Postgraduate School (NPS) in 2012. He retired from the Air Force in 2000 in the grade of Brigadier General. His active duty career included a number of operational tours, staff positions, and head of the Department of Economics and Geography, United States Air Force Academy. His published work includes a number of journal articles and research reports on military innovation and defense acquisition management. [cfranck215@aol.com]

Abstract

This paper is part of a research agenda outlined in Franck, Hildebrandt, and Udis (2016) and 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 Dynamic and Root Cause Analysis methods.

Introduction

Interest in project management estimations, cost, and scheduling remains strong in the academic world, driven by the sometimes spectacular cost and schedule overruns in general, but defense projects in particular. Unfortunately, notwithstanding the effort, 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. However, we believe we must do better to not only stay on schedule, but to answer the overriding imperative in defense acquisition to deliver systems as fast as possible that work. There are many hypotheses about the why, but it could be we are ignoring the one constant factor in project management, the human being with all the complexity and imperfections.

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.

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. System dynamics provides the opportunity to consider scheduling and schedule execution from the people perspective.

System dynamics was conceived and developed by Forrester (1971) in the 1960s. In many ways, Forrester's (1971) approach was like that of Dörner (1996) in that both recognized not only the limitations in human's ability, but also recognized 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, whether 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) often fails 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 in general and scheduling in particular offer a tool to examine 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 is in 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) have been highly publicized. This public discussion has produced a fairly extensive airing 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 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

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

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, and 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 versus 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.

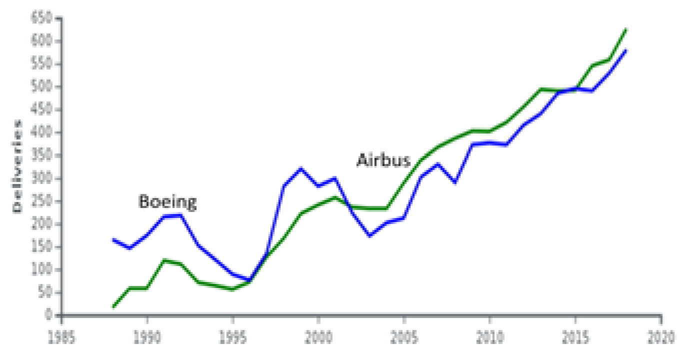

Figure 1. Boeing 737 and Airbus 320 Deliveries by Year (Since the A320's First Flight)

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

[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, Lewis, Matthews, and Udis (2011, pp. 8–9).

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 reengined Airbus models. In response, Boeing promised in 2011 to deliver a narrow body fairly quickly (Gelles, Kitroeff, Nicas, & Ruiz, 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. This is shown in Figure 2.

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.

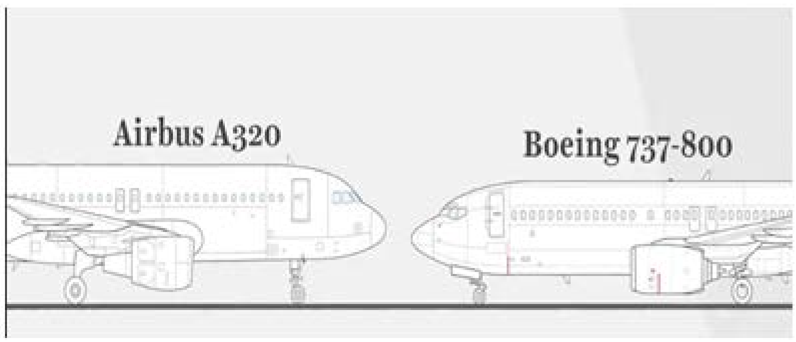

Figure 2. Engine Ground Clearance on A320 Family vs. Boeing 737 family
(bing.com/images)

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

- Competitive pressure from Airbus for single-aisle aircraft pressured 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 airline 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, seems to have been Boeing management's driving factor, rather than being driven by the time required for the necessary engineering.
- Use of the 737 airframe meant lower production costs, simpler Federal Aviation Administration (FAA) certification, and lower training costs (driven by pilot familiarity with the 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 B737 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 regimes. 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.

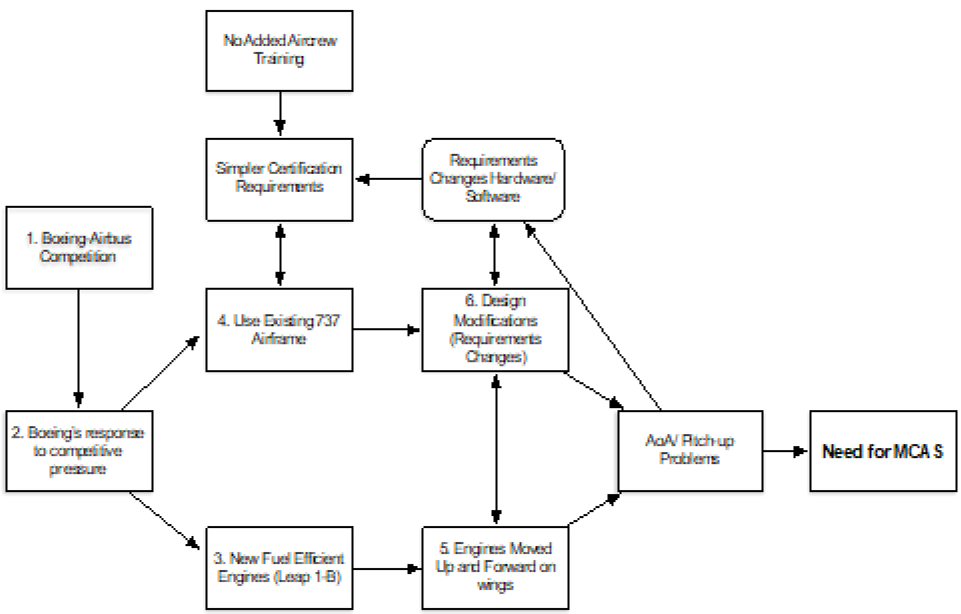

Figure 3. The 737 Upgrade "System"

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.

[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 of this succinctly and well.

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

EVENT	**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

Schedule Pressure: Speedy Execution

The schedule pressure had technical ramifications but also impacted the work environment. According to several open-source reports (e.g., Broderick, 2019; Gelles et al., 2019; Nicas, Kitroeff, Gelles, & Glanz, 2019), the 737MAX development program was something of a forced march, or in scheduling terminology, schedule pressure, defined here as employee perception to complete work within a time frame that is reduced from that originally planned.

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

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 anything but simple. The A320neo is mostly a re-engined A320. The new 737MAX required more complex modifications to reduce drag and a need to reposition the

[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.

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

engines. The new engines were almost 40% larger and weighed almost double those of the 737NG. The new plane was longer and had a wider wingspan. What Boeing couldn't change was the height without having to redesign the landing gear which would have threatened both the development schedule and quick FAA certification (Tkacik, 2019).

The testing program revealed the aircraft tended to pitch up its nose 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 4.

Acknowledging the challenges with the engine repositioning, one proposed solution involved modifications to the airframe itself (Langewiesche, 2019). However, given the schedule pressure, Boeing chose instead a software solution.[6] It was named the Maneuvering Characteristics Augmentation System (MCAS; Broderick, 2019; Gelles et al., 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).

However, later flight tests also revealed some difficulties at normal G forces and low airspeed. This led to increased realm of engagement parameters to include low speeds, high angles of attack (AoAs), and "normal" G-loadings. MCAS 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 MCAS2 "more aggressive and riskier" (Nicas et al., 2019).

From a software engineering perspective, Johnston and Harris (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 Pasztor and Tangel (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 release was a product of the marketing-driven strategy Boeing pursued—release 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).

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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 that is adopted for expository clarity.

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 four months (Johnston & Harris, 2019; Pasztor & Tangel, 2019). In at least one case, Boeing submitted a software fix to the FAA for certification seven 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).

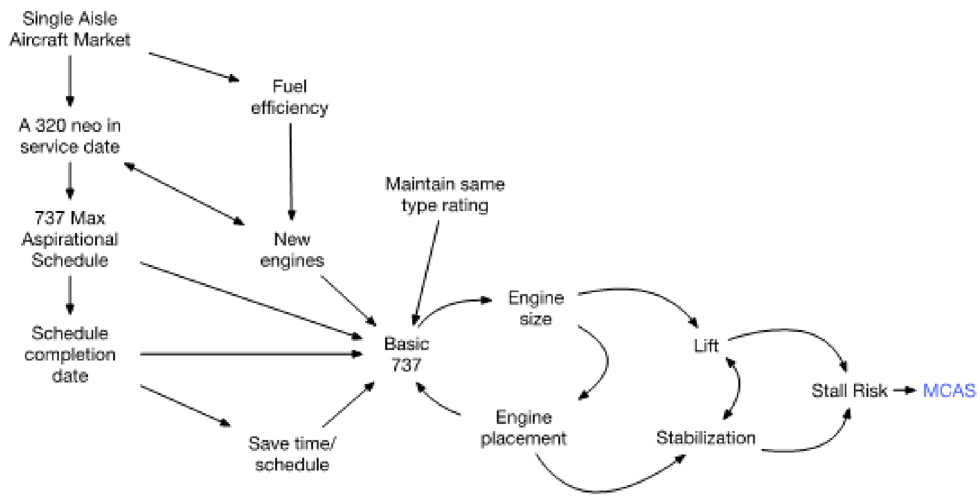

Figure 4. How the B737 Max Came to Be

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 (Langewiesche, 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 or miscommunications. Those out of the loop were not limited to pilots. For example, relevant FAA officials were not informed (Gates, 2019); discussion of the MCAS system was deleted from the 737MAX pilot manual (Tangel, Pasztor, & Maremont, 2019); and furthermore, the more aggressive version, MCAS2, was not well shared with interested parties—including airworthiness certification authorities (Tangel et al., 2019).

Our summary of the 737 Max story is shown in Figure 5. The key drivers were time perceptions based on the market rather than engineering estimates. It is worth noting that the getting to “MCAS decisions” include both technical and communications issues

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

(especially not fully informing the pilots). Figure 5 shows our assessment of the dynamics of the development.

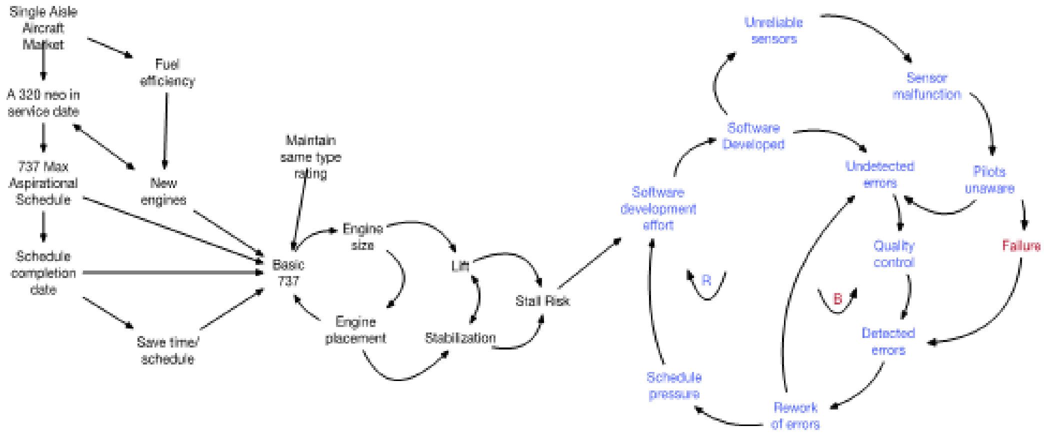

Figure 5. The Dynamics of the MCAS Development

The 737MAX Crashes

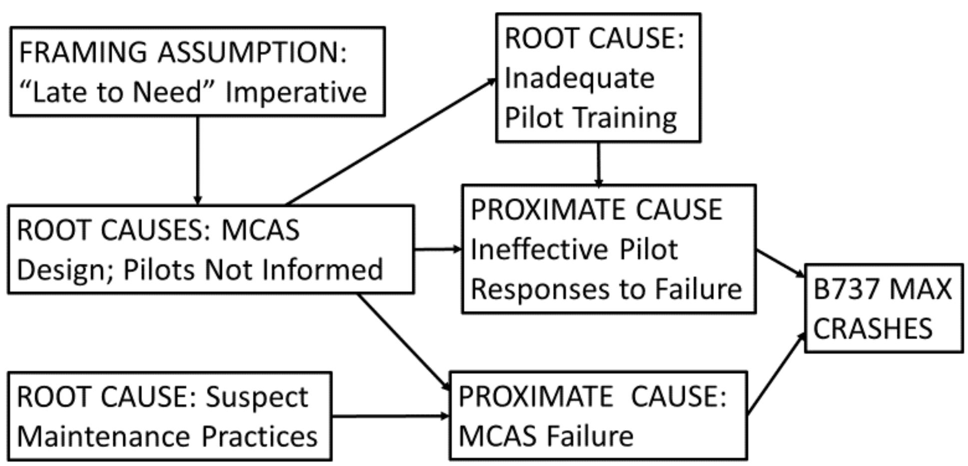

Figure 6. Hypothesized Causes of 737MAX Mishaps
(Langewiesche, 2019; Pasztor & Tangel, 2019; authors’ interpretations)

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, by various agencies (e.g., Joint Authorities Technical Review [JATR], 2019; House Committee on Transportation and Infrastructure, 2020; National Transportation Safety Board [NTSB], 2019) are very informative.

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

Overall Comments on This Case

1. What trades were made?
    - o Schedule got major (close to exclusive) emphasis—with attendant design constraints. Strict (at least fairly strict) adherence to the original schedule was pervasively enforced.
2. Consequences of the trades (results of schedule emphasis)?
    - o A new narrow-body type was conclusively ruled out; schedule constraint dictated a 737 variant with a new but already developed model.
    - o In development: a lack of overall program review and oversight.
    - o 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).
    - o Time pressures throughout 737MAX development effort
    - o Some steps skipped
    - o Some steps done concurrently
    - o Most notable specific example of unknown work (ex-ante): bigger engine on an old airframe design resulted in pitch-up problems—noted at low speeds and high angles of attack.
    - o 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?
    - o Schedule emphasis due primarily to the commercial success of the A320neo, which put Boeing at a major strategic disadvantage in the narrow-body airliner market.
    - o Recovery strategy focused on a quickly developed 737 variant.
4. What is the evidence or rework? Primarily responding to the pitch-up problem:
    - o MCAS (part of the 737MAX software suite) was changed to deal with aircraft handling issues in high-speed flight.
    - o 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 (both quality and quantity) available in publicly available sources.

Much, very good information regarding these questions is available in published reports and analyses.

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 and Boeing without a 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 that is indeed the case, then 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. The 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 had Boeing not made the strategic miscalculation noted previously and 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 (reengining) 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 design team might well have made other miscalculations for which the consequences have been nonexistent or less serious.

Finally, and most relevant to our current purpose, is 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 a commercial aircraft manufacturer and defense contractor. We posit the aerospace-defense world practices two inherently different kinds of system development scheduling. There are two kinds of scheduling. The first is based on a structured planning (e.g., Critical Path Method [CPM] or Program Evaluation and Review Technique [PERT]). The second kind of scheduling is that described in this paper—aspirational scheduling. We define an aspirational schedule as one defined by a political or business desire, aim, or goal rather than accepted scheduling techniques.

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. In and of itself, the idea of

[9] This seems unlikely at first glance but is understandable. For example, Franck, Lewis, and Udis (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 now being a joint venture with Boeing (which holds an 80% interest).

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, are acknowledgement of 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 current Assistant Secretary of the Air Force for Acquisition Will Roper. He advocates rapid development and production of a series of fighter aircraft—such as those the Air Force procured starting in the 1950s. His rationale includes a more agile response to peer competitors enabled by new generations of design simulation software (Freedberg, 2019). This is to take place in a less risk-averse acquisition culture with these technologies and development of new combat aircraft types in five years or less (Insinna, 2019). The centerpiece of Roper's vision is new combat aircraft developed and fielded relatively quickly. 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 (FTC) investigation (Censer, 2019; Clark, 2019; Erwin, 2018; FTC, 2018).

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Acquisition Research Program
Graduate School of Defense Management
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net