A VALUE PERSPECTIVE ON AEROSPACE INNOVATION

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Abstract

The basic hypothesis of this paper is that innovation is linked to value creation. Utterback's research on the dynamics of innovation reveal that opportunities exist for subsystem and process innovation. There is also the possibility that disruptive technologies such as those associated with piolotless aircraft could lead to innovative products. A value creation framework is introduced and past examples are considered in light of the framework. Several examples of opportunities for future innovation are suggested.

1 Introduction

Innovation is essential for the future of aerospace, as it is for any field. Innovation complements incremental improvement. Consider jet propulsion. High bypass ratio jet engines were an important innovation, offering both better fuel economy and reduced engine noise. Following their initial introduction, incremental improvements led to significant performance and economic gains, including the possibility of large two-engine jet transports. Both innovation and incremental improvement are important, and both deserve nurturing and support. However, this paper will focus on innovation.

A dictionary definition of innovation is "the act of introducing something new" or "a new device or process created by study and experimentation"[1]. "New" is the word most frequently associated with "innovation". Yet just because something is new does not mean it is valuable. And if an innovation isn't valuable, it will not have an impact. But what determines if something is valuable?

Slack [1] offered the following definition of value: *"Value is a measure of worth of a specific product or service by a customer, and is a function of (1) the product's usefulness in satisfying a customer need, (2) the relative importance of the need being satisfied, (3) the availability of the product relative to when it is needed and (4) the cost of ownership to the customer."* Words most often appearing in definitions of value are "customer" or "stakeholder". It is important to realize that that the customer or stakeholder decides what is valuable, not the inventor or the engineer.

This paper will link together two important concepts – innovation and value – with hypothesis that for innovations to be important, they must also lead to value creation. Let us first explore innovation, then turn to value concepts, and finally illustrate some past and perhaps future examples of valuable aerospace innovations. In keeping with the domain of ICAS, the focus of the paper will be on the aeronautical side of aerospace, although the underlying thinking is more broadly applicable.

2 Innovation

It is almost taken for granted that aerospace is synonymous with innovation. The first 100 years saw amazing innovations in aerospace. Today the public takes for granted safe and affordable air travel to virtually any city in the world, overnight package delivery of items

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[1] www.dictionary.com

bought on-line, up to the minute weather data, instant news from any point on the globe, and air defense from hostile enemies. Even human and robotic space exploration is almost taken for granted by the public. However, most people still consider it adventuresome, and rightly so. With so much accomplished, the question is often raised, "is this industry mature, or will there be future innovations".

Innovation can occur in both product and processes, and at any level from core technologies to the system of systems. Although most aerospace engineers associate innovation with the product, as will be highlighted below, there are many opportunities for process innovation in domains where the product architecture is stable. Process innovations can have far reaching influences. It is interesting to note that the 1997 issue of Newsweek on "Inventions of the 20th century" listed the Ford Production Systems at the top of the list. In aerospace, there have been innovations in basic technologies such as supercritical airfoils, or stealth, or friction stir welding. Or consider innovations in methods such as CFD, or multidisciplinary optimization, or design for manufacturing and assembly, or six sigma. Moving up in the system hierarchy, innovation has led to major new subsystems such as fly-by-wire flight controls, or all composite structures, or processes such as integrated product and process development. At the aircraft level, there may be new configurations such as the blended wing body, or new manufacturing systems such as approaches based on lean thinking. Finally, at the system of system level, there are further opportunities for innovation such as free flight, or globally integrated design teams or supply chains.

This year's Dryden Lecture by Professor Kroo of Stanford on "Innovations in Aerospace" [2] offered three general areas for innovation in the coming decades:

1. Exploiting computational advances for high-fidelity simulation and multidisciplinary design
2. Removing the constraint that aircraft must be designed around pilots or passengers.
3. Designing the system rather than the vehicle: collectives and systems of systems.

To these this author might add a couple more:

4. Supersonic flight with acceptable sonic boom
5. Build to demand production systems

There could be many more ideas added to this list such as personal air vehicles and so forth. But rather than creating a long list of possible innovation opportunities, let's review some findings from the literature of the enablers for innovation.

2.1 Dynamics of Innovation

Professor James Utterback at MIT has studied cycles of innovation in industries making assembled products and reported some very informative results in his book *Mastering the Dynamics of Innovation* [3]. By plotting the number of companies versus years for any given industry, he found a common pattern. Consider Figure 1 that shows the number of major US aerospace firms. Prior to the late 1950s there were more firms entering aerospace than leaving, with exceptions in the post WWI and the stock market crash in 1929. Since the late 1950s, there have been more firms exiting the field than entering, mainly through mergers and acquisitions. The plateau from the mid 60s till the early 90s corresponds to the Cold War era when aerospace firms were kept in business by the US government for strategic reasons. Had market forces dominated, the industry would likely have consolidated earlier than the 90s.

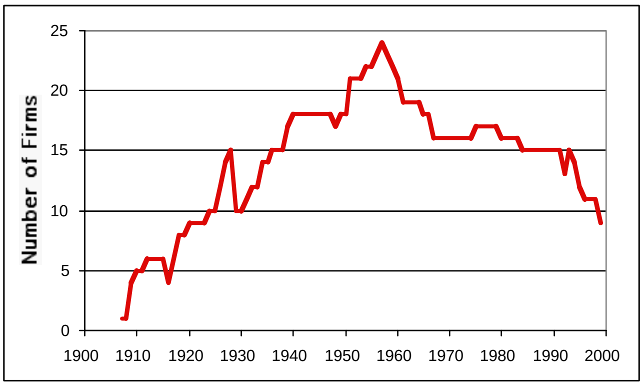

Figure 1 – Number of major US aerospace firms

The pattern shown in Figure 1 is typical of all industries. Utterback identifies the years of upward trend the “fluid period”. During these years the product architecture is not yet established and many firms enter with innovative concepts for new products. The years when the number of firms reaches a peak correspond to the emergence of a “dominate design” which establishes the basic product architecture. Once that occurs, the industry enters the “specific phase” and innovation shifts from product architecture to product features and to process innovation. The emphasis in the specific phase is to provide more capability to the customers at ever improving prices. This trend continues until some superior substitute emerges which replaces the product altogether, or at least a large portion of the market share. Or perhaps the external environment changes so dramatically that the product is no longer useful.

Taking aircraft as an example, this pattern is clearly represented. The current architecture of jet transports – swept wings, podded jet engines on struts, tricycle landing gears, monocoque aluminum structures – emerged. As has been so often noted, most new jet transports basically look like the 707. There have been incremental improvements and innovations in aerodynamics, propulsion, structures, controls, and so forth. And there has been innovation is subsystems such as fly-by-wire controls, avionics, composite structures, cargo handling. Meanwhile the number of commercial transport manufacturers has shrunk to two, and they compete fiercely on price and new products. The same basic picture applies to piloted military aircraft - fighters, bombers, transports, tankers, recon, etc. – with one significant exception. Stealth technology led to new architectures such as the B-2 and F-117A. Interestingly, as stealth technology improved and incorporated in modern products such as JSF and F-22, the architecture has not deviated substantially from the dominant design.

We learn from Utterback that once a dominant design emerges, innovation at the product architecture level becomes very difficult. The risk associated with radical changes is too great and the infrastructure becomes too set to warrant investment in radical new concepts. In anticipation of later sections this can be stated differently; the value to the stakeholders is not sufficient to drive the innovation at the architectural level. However there are plenty of opportunities for innovation in product features and in processes for designing and producing the product.

2.2 Disruptive Technologies

Given the above, it is interesting to explore the paths by which a superior substitute can emerge and displace the industry leaders who are wedded to the dominate design. There could be a number of scenarios, one of which has been articulated by Prof. Christensen of Harvard in his book *The Innovator’s Dilemma* [4], and illustrated in Figure 2.

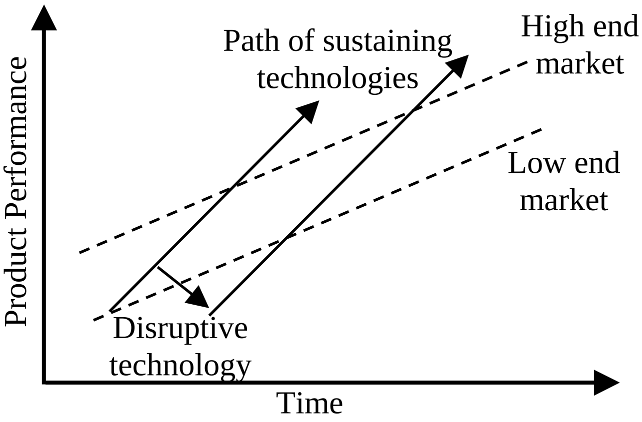

Figure 2 – Impact of disruptive technology [2]

Christensen argues that the normal progression of an established, or sustaining technology, is to move from the low end in any market to satisfying the high end of that market. Various economic and organizational factors tend to push companies into making products that are bigger, more capable, and more expensive. Companies can follow this path too far and put out a product that exceeds the high end of the market, as shown by the upper left arrow in Figure 2. A new “disruptive” technology emerges which is not yet capable of satisfying even the low end market, and the established companies fail to see its full potential. A new company develops this technology and begins to enter the low end of the market. In time, it improves the technology to the point that it gains a significant market share and can eventually displace the industry leaders. Christensen's work was based upon the disk drive industry, but this trend can be seen in the aerospace industry in products like regional jets or small launch vehicles. Although Figure 2 is not the only path for a disruptive technology to emerge, it does serve as one example of a way for a superior product architecture to displace a dominant design.

The above paragraphs serve to make the point that innovation takes more than just a new idea. For an innovation to take hold and have an impact, it has to be the "right idea at the right time". Often innovations from the past are held up as models for thinking of future innovations. These can be helpful as long as one understands the context in which the innovation occurred. The Apollo program is so often used as the stellar example of aerospace innovation. Yet the Apollo program was possible only because of the confluence of technology and geopolitics. Today's environment is completely different. This leads us into the next topic of understanding value.

3 Value Creation

Value is a familiar concept to consumers who make daily decisions about purchasing goods and services that provide them best value. As individuals, we are used to making choices based upon some combination of price, product attributes, and availability. However, for engineers, value is not a familiar concept. One reason for this may be that value does not have units, and therefore is difficult to quantify. Aeronautical engineers are comfortable working with range, weight, speed, mean time between failure, cost, schedule and other quantifiable parameters. Value is a somewhat fuzzy concept that can only be defined by the party who receives the value in exchange for some commitment of resources. But it is exactly this attribute that makes the concept of value so powerful. Value provides a way to approach the *combination of attributes* that must be considered to make a product or service successful. It can replace the outdated Cold War quests of *Higher, Faster, Farther* and post Cold War quests of *Better, Faster, Cheaper* with a single five letter word *Value* which has intuitive, albeit not quantified, meaning.

Recall Slack's definition of value for products or services given in Section 1. A short version of this might be "right thing at the right price and the right time". One might express this as a functional relationship:

$$Value = \frac{f_p(performance)}{f_c(\cos t) \bullet f_t(time)}.$$

Generally improved performance leads to greater value, as does lower cost or timely availability. Value can be useful for applying to comparative analysis - one can determine that one choice provides greater or lesser value than another choice. To work with many parameters at the same time, a balanced scorecard approach [6] is needed with a table of value attributes, each compared to a desired or target level.

Murman, et al [7] introduced a value creation framework and discussed its application to aerospace enterprises, including programs. Figure 3 shows the conceptually simple and potentially powerful framework.

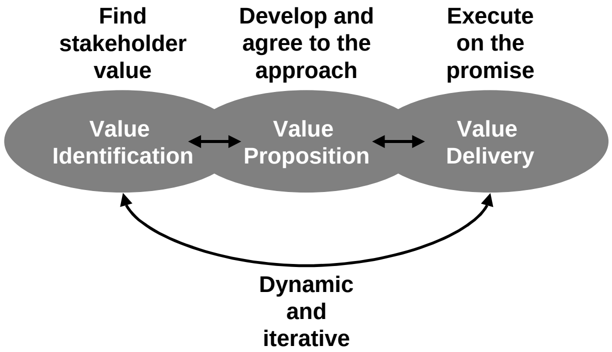

Figure 3 – Value creation framework [7]

The first step in value creation is to identify all the appropriate stakeholders and their value expectations. Let us consider a program such as an airplane, or a major subsystem, or an element of the infrastructure such as an airport or a collision avoidance system. The stakeholders are many and varied, as illustrated in Figure 4. Furthermore, their value expectations will be quite varied.

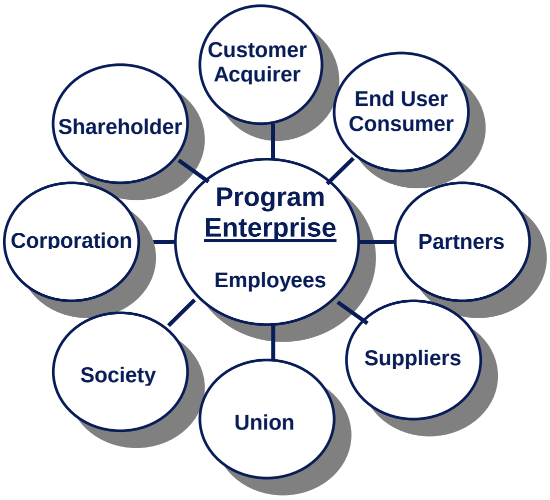

Figure 4 – Program enterprise stakeholders [7]

In this context, a suitable definition of value is: *"How various stakeholders find particular worth, utility, benefit, or reward in exchange for their respective contributions to the enterprise"*[7]. Slack's definition would apply to the customer/acquirer and the end user/consumer. But other stakeholders could be interested on return on investment, jobs, guaranteed business, clean environment, etc.

The next step is to formulate a value proposition that addresses each of the stakeholder value expectations. Generally it will not be possible to fully meet everyone's expectations and some negotiation will be needed to arrive at a workable value proposition. For this reason and others, iterations will be required between the first two phases. The value proposition might be manifest in forms such as a requirements document, a program plan, a strategic agreement, or even a speech or discussion. These agreements are important to establish to assure that the "right job" is being undertaken.

The final phase of the value creation model is to deliver the expected value, or "do the job right". The challenge of executing a program, particularly one involving innovation, cannot be underestimated. It is daunting indeed. There are plenty of best practices for program management, system engineering, lean manufacturing and the like that should be adopted before embarking on this phase, or even sooner. Again, there may be some iterations needed with the value proposition phase to assure that "the right job" can in fact be done right.

All of the above takes place within an external environment of constant change, and therefore the stakeholder value expectations and value proposition may need revisiting and updating. Technology, economic, political, competitive or other factors may shift enough that the value proposition is no longer viable, or the value cannot be delivered. Programs that cannot adjust to such changes may be doomed, as will be illustrated in the next section. Such factors are drivers for the development of robust design methods that anticipate change and build in flexibility at the product architecture stage. Good examples of these situations are the recent Iridium and Globalstar satellite communication systems [8].

With the contents of this section and the previous one as a reference, one can see that innovation in a field as complex as aerospace is not easy. There is a familiar saying that doing something new is "1% inspiration and 99% perspiration". Innovation is more than just a bright idea, but it certainly relies on that. Innovation is a combination of good ideas, good timing and good execution. A good understanding of value and value creation can aid the brainstormers pick the best ideas for follow. Let's now retrospectively look at some past innovations – both success and failures – and then look towards the future for the five innovation candidates introduced in Section 2.

4 Innovations in the Past

Before considering possibilities for future innovation in aerospace, it is instructive to use retrospective analysis and look at past examples to see to what extent the ideas of Sections 2 and 3 are manifest. The examples considered are not exhaustive or comprehensive. They are ones that the author is familiar with from some recent research, teaching, or just current events.

To start with, the value creation framework of Section 3 emerged from and was used by Alexis Stanke in her master's thesis research in to best lifecycle value [9,10]. Four airplane programs were studied; B-777, F-16, F/A-18E/F and the SAAB JAS 39 Gripen. Although none of these would be considered break though innovations in the category of product architecture like the 707, each had more then incremental improvement of existing technology. Briefly:

- The B-777 used innovative design and manufacturing methods including CAD based digital definition and mock ups, and over 200 integrated product teams that included customers, suppliers and regulators in addition to engineering and manufacturing. Although fly-by-wire had been used before on commercial transports, the B-777 used the ARINC 629 data bus, arguably an innovation. There were also a number of incremental improvements in propulsion, aerodynamics and structures.
- The F-16 was the first production fly-by-wire aircraft. It broke the trend of being bigger and with more systems by emphasizing lightweight and agility. It has been the most successful fighter program in history with over 4000 units delivered to 19 countries. It's basic architecture has enable it to take over may roles from other aircraft, saving on maintenance and operational costs.
- The F/A-18E/F is a major upgrade to the C/D version, being 25% larger and more capable. From a technology standpoint, it is an incremental improvement. But from a program standpoint it is one of a handful of major programs that was completed on time, within cost and exceeding its performance objectives. A number of innovations included a fully integrated program information system that gave all stakeholders complete access to the same information and databases, program management that valued the contributions of people, and other features.
- The JAS-39 innovations include the first 4th generation digital avionics design with true multirole capability and design for low maintenance costs and rapid turn around times.

As mentioned earlier, none of these were paradigm shifting innovations of product architecture, but they certainly represent major innovations is process and significant innovations in avionics and fight control. Recalling Utterback's findings, they are in step with innovations for an industry in the fluid phase.

Perhaps the most radical innovation in the past 25 years from a technology vantage point is stealth and its influence on aircraft capability. Certainly the B-2 would be viewed as innovative from a product architecture and performance standpoint. However, it suffered from both cost and schedule factors. Since these factor into the value equation given earlier, one would have to say the B-2 was at best a qualified success from an innovation perspective. The F-117A was also a radical design with major improvement in performance. The program minimized cost and schedule by adopting existing technology and subsystems whenever possible. In that sense it provided good value to the customer and has seen considerable action in recent military campaigns. One would have to call the F-117A an innovation. As mentioned earlier, rather than spawning a family of arrow shaped aircraft, the stealth technology has been incorporated in more or less conventional configurations of the F-22 and JSF.

Another innovative aircraft concept currently under consideration is the Blended Wing Body (BWB). This configuration provides considerable reduction in form drag due to its reduced wetted area/volume ratio, and also major benefits in modular design and manufacturing. The configuration is suited for passenger and cargo transport, tanker, and bomber missions. From an engineering standpoint the BWB is certainly innovative. However it remains to be seen if the BWB will proceed to development and deployment. Referring to Utterback, it is competing with the dominant tube-and-wing design and its established design, manufacturing and certification knowledge base. And unlike Christensen's model of disruptive technology, it is entering at the high end market where the stakes and risk are larger. For the BWB to move forward, there needs to be investment in a demonstration model to reduce the risk. Likely this will come from the government as the existing commercial aircraft manufacturers are committed to other designs at this time.

To conclude this section, it is interesting to examine a couple of attempts that fell short of achieving real innovation. One is the supersonic transport (SST). As is well known, in the 1960s SSTs seemed like the next logical step after swept wing transonic transports. But that was not to be. Only the Anglo-French Concorde went into limited production and service. Although it was a technical success and an innovation in that sense, it was of limited business success. There were both environmental and economic reasons that its value proposition did not work out as expected. Basically the SST was of value to only a limited group of stakeholders – too few to elevate it to the ranks of major innovations.

Another innovative concept which missed achieving success was the Comanche stealth helicopter. This program is an example where the phases of the value creation framework were not successfully executed. After forming a value proposition in the 1980s, the program failed to deliver the expected value on schedule. As the Cold War ended, the original mission for the Comanche disappeared. And with commencement of the War on Terror and its asymmetrical force projection, the role for the Comanche dropped to lower priority than other needs and the program was cancelled.

Other "case studies" of success or failure of innovations from the past could be considered, but hopefully the above illustrate three points. One is that technical breakthroughs alone is not sufficient for innovation. There must also be value delivered to the stakeholders. The second is that innovation can occur at other levels than the product architecture, such as in avionics or low observables. With a dominant design to compete with, innovations in new configurations is a major challenge. The third point is that there can be innovations in process as well as product. These play an important role in keeping the aerospace industry healthy.

5 Innovations in the Future

There are many opportunities for innovation in aerospace in the coming years, as long as one accepts that innovation can occur at all levels of the system and in both product and process arenas. Let us briefly consider these five candidates introduced in Section 2, referring to Kroo [2] and other references for more details.

1. *Exploiting computational advances for high-fidelity simulation and multidisciplinary design*. Kroo covers a number of design applications that have already opened up as a result of current algorithm and computing capability for coupled aerodynamic, structure, and control numerical simulations. However, the reach goes well beyond modeling in these domains. Adding in solid modeling, design for manufacturing and assembly and other simulations, the engineer of the future will be able to *fully* simulate the entire design, manufacturing and operation of a vehicle early in the product development cycle. Indeed, the 7E7 program is using the term "digital rollout". The implications for these lean engineering [11] capabilities are truly revolutionary.
2. *Removing the constraint that aircraft must be designed around pilots or passengers.* The prospects for unpiloted aircraft improve each year with progress in control, autonomy, sensors and computing. Already in use for military missions, civil applications await. Small package delivery, long haul cargo transport, and even personal air vehicles are potentially possible. Referring to Section 2.2, this is a prime candidate for a disruptive technology to enter the low end of the market and displace an existing product, not necessarily an aeronautical one. There are major system level issues that need addressing, including

safety and security. And the value creation aspects need to be addressed if any of these are to become true innovations.

3. *Designing the system rather than the vehicle: collectives and systems of systems.* This is an interesting area that the author has recently explored with Kroo, Liebeck along with students and colleagues at MIT. Looking into only one aspect of this problem domain, the opportunities for exploiting formation flight for long haul cargo aircraft were investigated [12]. Although formation flight is as "old as the birds", recent developments in the same technologies as related to UAVs have made station keeping for long durations possible without high pilot workload. And with gas prices on the rise, the fuel savings are significant. This is another candidate for the framework outlined in Section 2.2.
4. *Supersonic flight with acceptable sonic boom.* As mentioned earlier, supersonic flight has been a quest of aeronautical engineers for decades. Although the business and technical cases do not seem to close for large SSTs, it appears that they may well close for small SSTs, or sSSTs [13]. Two markets have been identified: business jets and scheduled shuttle service for the North Atlantic. The latter market does not rely on removing sonic boom restrictions over land, but if those were removed there are additional markets for scheduled shuttle service. The business jet market requires removing the over land sonic boom restrictions. With current sonic boom shaping technology and lower weight aircraft for sSST compared to earlier SST configurations, it is quite possible that sonic booms from sSSTs could be acceptable to the public. That could lead to one of the key stakeholder groups of Figure 4 being satisfied, and the possibility of satisfying the elements of the value creation model. Further work needs to be done on emissions and economics, but this is an area well worth pursuing.
5. *Build to demand production systems.* Despite a steady growth in both worldwide passenger and cargo demand, the commercial aircraft business remains highly cyclic. The orders for commercial aircraft roughly correlate with the derivative of the demand curve rather than its absolute value. So a small change in the rate of passenger growth translates to a large reduction of orders. And blips like 9/11 are devastating to the industry. One of the factors that drives this is the long lead time for commercial transport orders. Shortening the time to produce aircraft could have a stabilizing effect on the industry and enable more innovation. How much shortening of the lead time is possible is unclear, but a breakthrough in this area would be a major innovation, just as was realized by Henry Ford.

These five scratch the surface of the innovations that might be possible in the future. Major subsystems have not been considered, nor have propulsion concepts that will be needed as oil supplies dwindle in this century. Nor has much attention been given in this paper to innovations at the systems of systems level. Wherever they arise, the basis hypothesis of this paper is that innovations must be associated with value creation.

6 Conclusions

This paper has explored innovations in aerospace from the perspective of value creation. The hypothesis is that unless value is being created for multiple stakeholders, new ideas do not lead to true innovations. Considering the dynamics of innovation, it is noted that innovations at the product architecture level are difficult when a dominant design exists. However, there are many opportunities at the subsystem level and also for process innovation. Furthermore, disruptive technologies such as pilotless aircraft can lead to innovations in new market areas. A number of examples are considered to illustrate past and future opportunities for innovation.

Acknowledgements

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