Aircraft design innovation: creating an environment for creativity*

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Abstract: Innovation in aeronautics has been investigated by exploring the factors that promote innovation (e.g. adversity, observation and curiosity, contests, grand challenges, collaboration, analysis tools, and knowledge bases) and the factors that inhibit innovation (e.g. limitations of simulation tools, absence of a creative environment, fear of failure, unwarranted criticism, and poor definition of success). These factors are discussed in an anecdotal, retrospective manner, with numerous historical examples cited. Innovation relies heavily on underdeveloped methodologies and knowledge bases, generating immature technologies. The need to assess and manage the risks resulting from the incorporation of immature technologies in aircraft systems is an essential part of the innovation process. Risk management, in terms of risk assessment (using technology readiness levels) and risk characterization, is presented at an introductory level.

Keywords: innovation, creativity, risk, technology readiness level

1 INTRODUCTION

1.1 Historical perspective of innovation in aviation

The history of aviation shows aircraft undergoing rapid and radical technological change since the early 1900s, leading to dramatic improvements in performance, driven by the prevailing mantra of 'Faster, Higher, Farther'. Economic considerations in the post-World War II era introduced cost as a primary driving force, as least for civil applications. By the early 1990s (with the end of the Cold War), the call, even for military applications, was for 'Better, Faster, Cheaper' products. Concern for the environment has now seen 'Quieter, Cleaner, Greener' added to that call.

Tracing the number of completely new designs over this time, it is evident that the number increased rapidly over the first 60 years, and then, as the industry matured, fewer and fewer new designs emerged [**1**]. Derivative configurations with components and systems that evolved from previous designs became commonplace [**1**–**3**]. Dominant design configurations for various aircraft classes emerged in the 1950s and 1960s – for airliners, for example, this is typified by the B707. Murman *et al.* [**1**], using Utterback's model of industrial product design in reference [**4**], consider this – the emergence of dominant designs – as evidence that the industry has reached the '*specific phase* of industrial innovation', which they characterize as having opportunities for innovation in:

(a) incremental product technologies, to improve product productivity and quality;
(b) process technology;
(c) technological innovations that present superior product substitutes.

Murman *et al.* [**1**] infer that the current configurations, which represent highly optimized design solutions, are likely to represent future aircraft configurations.

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Predicting technological progress has always been a risky business. Certainly, there is considerable scope to get it wrong when looking at new scientific fields. It is reported that just 7 years prior to the success of the Wright brothers at Kitty Hawk in 1903, Lord Kelvin said, ‘I have not the smallest molecule of faith in aerial navigation . . . other than ballooning’ [**5**]. This is one of a number of quotes – dating from this time – from eminent people who got it completely wrong in their attempt to predict the future of aviation; other examples include [**5**, **6**]: ‘Aerial flight is one of that class of problems with which man will never be able to cope’ (Simon Newcomb, 1900); ‘It is complete nonsense to believe flying machines will ever work’ (Sir Stanley Mosley, 1905).

The ability of individuals to innovate and develop novel solutions for seemingly intractable problems will, no doubt, continue to surprise both the informed and the uninformed. Whatever configuration future aircraft take, opportunities for innovation – not least in the domain of emerging aeronautics applications (e.g. micro air vehicles and unmanned aircraft) – will be almost limitless.

1.2 Objectives

The central theme of the paper is innovation in aviation – this has been explored by setting three objectives, which were to examine the following inter-related issues:

(a) the factors that promote innovation (section 2);
(b) the factors that inhibit innovation (section 3);
(c) the risk management techniques of risk assessment and risk characterization (section 4).

2 INNOVATION PROMOTERS

It is interesting to consider what drives, promotes, or initiates innovation. There are clearly many different factors, which are not mutually exclusive. Six factors are discussed in this section, in a largely anecdotal, retrospective manner. The first four of the following factors are external to the innovator (providing the context in which the work was conducted) and the last two relate to mechanisms that facilitate innovation:

(a) adversity;
(b) observation and curiosity;
(c) races, contests, and inducement prizes;
(d) targets and grand challenges;
(e) collaboration and concurrent engineering;
(f) information technology, analysis tools, and knowledge base.

2.1 Adversity

There are many examples of engineering breakthroughs where designers responded to the enormous challenges that arose in times of conflict. When people are put into potentially life-threatening situations innovation thrives, resources are mobilized and there is a greater willingness to consider unconventional solutions and to take large risks.

‘Wars, both “hot” and “cold”, have been a major driving factor in a great deal of aerospace development, beginning prior to World War I and the beginning of the race for faster, higher, farther military aircraft’ [**3**]. World War I spurred numerous innovations in aircraft technologies. Using speed as a metric, the 116 km/h BE2c light aircraft (typical of the state of the art in 1914) can be compared to the 222 km/h SE5a fighter (flown in 1917). Production technology also developed rapidly. France, for example, had less than 140 aircraft at the start of the war, but produced 68 000 aircraft during the war years [**7**].

The quest for greater speed, altitude, range, payload, and manoeuvrability during World War II produced dramatic improvements in aerodynamics, materials and structures, flight controls, and propulsion systems. In the *Greatest engineering achievements of the 20th century: airplane timeline* in reference [**8**] the following – of many achievements – were highlighted:

> The British develop airplane-detecting radar just in time for the battle of Britain. At the same time the Germans develop radiowave navigation techniques. The both sides develop airborne radar, useful for attacking aircraft at night. German engineers produce the first practical jet fighter, the twin-engine ME 262 . . . and the Boeing Company modifies its B-17 into the high-altitude Flying Fortress . . . . In Britain the instrument landing system (ILS) for landing in bad weather is put into use in 1944.

The almost constant tension between the US (and the NATO alliance) and the Soviet Union (and the Warsaw Pact countries) during the Cold War was a major factor behind the development of many strategically important weapons systems – for example: advanced missile system technologies (e.g. propulsion, guidance, and ordnance systems) were acquired by both sides.

2.2 Observation and curiosity

Nature may be viewed as a large and very effective laboratory (albeit one that works very slowly). Nature ‘experiments’ with physics, chemistry, mechanics, sensors and controls, and with many other scientific and engineering fields to produce evolutionary changes in successive generations of living organisms, enabling them to better cope with their environment.

The idea of imitating nature's processes or designs (known as biomimetics or bionics) for the purpose of making useful artefacts is not new. The natural world has long inspired people, and examples abound where an observation of the natural world has sparked someone's curiosity to develop something [**9**]. The fertile imagination of Leonardo da Vinci was frequently at work considering ideas drawn from his observations of the natural world – his sketches of gliders and man-powered flying machines, as in reference [**10**], are illustrations of this (Fig. 1). Today, the shape-changing ability of birds and bats (i.e. morphing) – which confers superior aerodynamics to that currently achievable with conventional aircraft designs – is the subject of much research into innovative flight controls.

2.3 Races, contests, and inducement prizes

The famous races of the 'golden years' of air racing (ca. 1913–1950) – for example: Schneider, Bendix, Goodyear, and Thompson Trophies – produced legends and folk heroes [**11**]. They also served to 'focus the attention of both companies and enthusiastic individuals on making great strides in high-performance internal combustion engines, drag reduction, improved structures and systems, etc., at a remarkable rate' [**3**]. Design features pioneered by Schneider Trophy designs (e.g. low drag shape and liquid-cooled engine) fed into many World War II aircraft designs (e.g. Supermarine Spitfire, P-51 Mustang) [**12**].

A related topic is inducement prize contests. In general, the term 'prize' is used in different contexts – for example, a prize may be awarded for excellence (e.g. Nobel Prize) or to the winner of a race (e.g. Schneider Trophy). Someone who won a patent race could be said to have won 'the prize'. Inducement prizes are incentives – usually financial – employed to stimulate innovation by setting goals (e.g. to cross the Atlantic). A study conducted under the auspices of the US National Academy of Engineering [**13**] concluded that, compared to traditional research grants and procurement contracts, inducement prize contests appear to have several comparative strengths, including:

(a) the ability to attract a broader spectrum of ideas and participants;
(b) the potential to leverage financial resources from sponsors;
(c) the capacity to educate, inspire, and mobilize the public with respect to particular scientific, technological, and societal objectives.

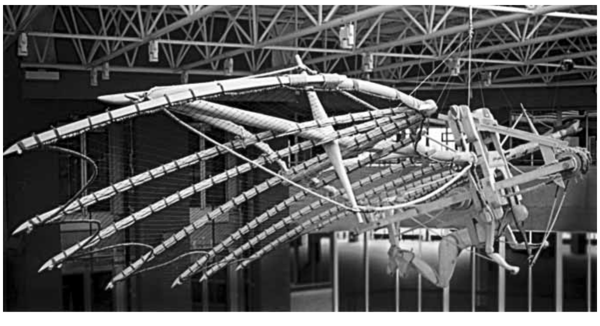

Fig. 1 Man-powered flying machine (model at the University of Limerick based on sketches of Leonardo da Vinci)

The recent (October 2004) – and resounding – success of the Ansari X prize is a vivid illustration that such contests do spur innovation. Established by Peter Diamandis (financed by Anousheh Ansari), the US $10 million prize was for the first privately funded team to fly to an altitude of 100 km twice within a fortnight [**14**]. The winners, Burt Rutan and his team at Scaled Composites (the project was funded by Paul Allen, co-founder of Microsoft), produced a superb design (Fig. 2) – at a fraction of the cost of state funded ventures – that featured innovative solutions in the fuel system (nitrous oxide/rubber), re-entry technique (wings 'folded up' like a shuttlecock), and structures (common nose section for the two vehicles) [**15**].

Using prizes to promote technological improvements is not a new idea. At the beginning of the 20th century, a series of prizes were offered in France: for the first person to fly around the Eiffel Tower; to fly a motor-powered aircraft a distance of 25 m; to fly an aircraft 100 m; and to fly a 1-km circle. The London *Daily Mail* set challenges to fly across the English Channel and the Atlantic Ocean. The most famous of the 'grand prizes', the US $25 000 Orteig Prize, was claimed by Charles Lindbergh when, in 1927, he flew from New York to Paris. (Raymond Orteig's actions – in establishing the Orteig Prize in 1919 – had repercussions 77 years later when, after reading about Lindbergh's exploits, Peter Diamandis established the X Prize [**14**]). Also in 1927, the Guggenheim family established a competition with a difference: for the safest aircraft. The contest – won by the Curtiss Tanager – succeeded in advancing aircraft safety features, but it also spurred the development of high-lift devices [**12**, **17**–**19**].

In more recent times, human-powered flight owes much to the competitions established by Henry Kremer and the Royal Aeronautical Society. The

Fig. 2 Takeoff for SpaceShipOne and WhiteKnight in June 2004 (courtesy of Richard Seaman [**16**])

first contest, which was to fly around a one-mile figure eight course, was won by Paul MacCready in 1977 with the *Gossamer Condor* [**12**, **17**].

2.4 Targets and grand challenges

For many aerospace engineers working in the US in the 1960s, the grand challenge of President Kennedy to send a man to the moon provided a clear focus for research and innovation; it certainly set the research agenda for more than a decade in the US. It also captured the public imagination, and, as recently stated (January 2005) by James Albaugh (Executive Vice President, The Boeing Company (2006)), it infused a generation of engineers 'with a passion that still stirs our hearts today' [**20**].

A current example of defined targets establishing a direction for research and innovation is the European Commission's (EC) Strategic Research Agenda (SRA). The Advisory Council for Aeronautics Research in Europe (ACARE) published its SRA in 2002 [**21**] to serve as 'an overall guide for planning European research'. It supported the top-level objectives of the 'Vision 2020' report [**22**], which, among other issues, identified the following targets for new aircraft, to be achieved by 2020:

(a) to reduce fuel consumption and CO_2 emissions by 50 per cent;
(b) to reduce NO_2 emissions by 80 per cent;
(c) to reduce perceived external noise by 50 per cent.

The viability of attaining these targets has been the subject of much debate. If the first target is assessed against historical improvements (Fig. 3) then it is evident that this is an enormous challenge. The rate of improvement in fuel efficiency has dropped since the early days of jet travel. As the industry matures, a greater effort is needed to make significant improvements (the 'low hanging fruit' gets picked first). The 'law of diminishing returns' – in which further improvements become harder and harder to achieve with time – applies to mature (dominant) products, as limits set by the laws of physics or by practical constraints are approached.

In the case of the dominant civil aircraft configuration, Adam Brown [**23**] (Vice President, Strategic Planning, Airbus Industries (1997)) indicated that the aspect ratio of the A3XX (now A380) was restricted – impairing its potential aerodynamic efficiency – because of the need to comply with the International Civil Aviation Organization (ICAO) Standard F for airport design. Birch [**24**] reports that significant reductions in jet engine specific fuel consumption were achieved over the past 40 years through improvements in thermal efficiency, but that technological progress is likely to slow as materials limitations and physical constraints in cooling technologies are approached.

An extrapolation, based on past achievements, suggests that the SRA goals will not be achieved by evolutionary design improvements and that radically new concepts will be required to produce the necessary step changes in performance.

Clearly, it is too early to judge the success of the EC's approach in setting these targets. However, it does appear that the SRA's ideas have permeated into the research objectives of a significant number of European aeronautics research projects: from the newly proposed – and massive – Clean Sky JTI (valued at approximately €1.5 billion) [**25**] to the many Framework research projects (valued at ca. €2–50 million each) [**26**] and down to the hundreds of student projects (run on cash-strapped university budgets). By this measure, the SRA has already been successful in aligning research objectives across a broad spectrum of aeronautics projects.

2.5 Collaboration and concurrent engineering

James (Jim) McNerney (Chairman and Chief Executive Officer, The Boeing Company (2006)), in a recent speech [**27**] at St Louis University, described innovation (in aviation) as 'a team sport, not a solo sport'. He said, 'It depends on a culture of technical sharing and openness to others. It takes people working together across different groups and organizational lines to make it happen'. The simple action of people talking through ideas in 'brain-storming sessions' brings out innovative solutions. Here, the collective whole is clearly greater than the sum of the parts. Bringing together specialists from different engineering disciplines – for example: structures, aerodynamics, propulsion, systems, control, manufacturing, etc. – in design-build teams, is a well

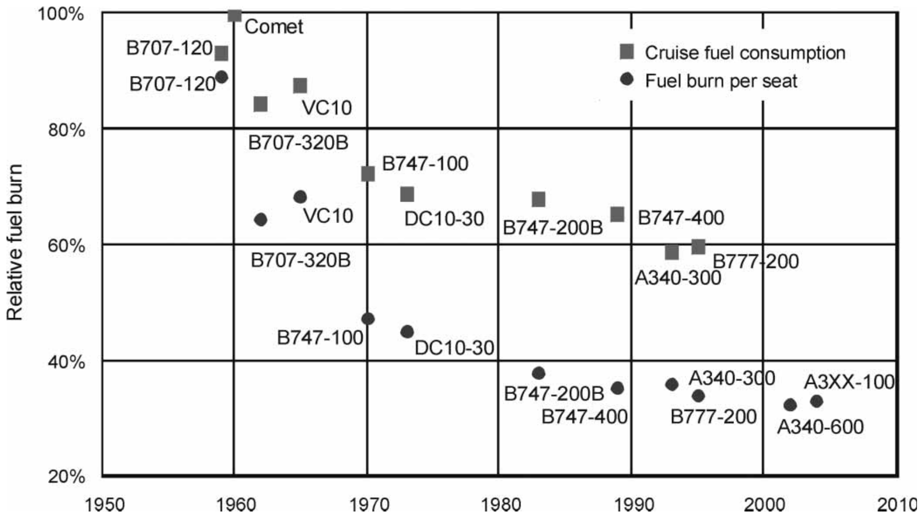

Fig. 3 Historical improvements in fuel efficiency (redrawn after Birch [**24**])

established engineering model that promotes innovation (and eliminate mistakes). Bringing together people with different cultural, ethnic, or educational backgrounds can also create a setting in which novel viewpoints may be expressed.

Rothwell [**28**] traces the evolution of the post-World War II industrial (not aviation specific) product innovation process and notes that the 'speed of development' became an increasingly important factor in the 1980s. He identifies *integration* and *parallel development* as two significant attributes in organizations that exhibited high levels of innovation (e.g. Japanese automotive and electronics companies). Suppliers and sub-contactors were integrated early into the product development, as were the internal departments (e.g. design, procurement, manufacture, and after-sales support). Project development – where possible – occurred in parallel, not in series.

Rothwell [**28**] identifies concurrent engineering as 'the core of innovation' in a parallel development process. There are many definitions of concurrent engineering (CE). For the European Space Agency (ESA) it is 'a systematic approach to integrated product development that emphasises the response to customer expectations. It embodies team values of co-operation, trust and sharing in such a manner that decision making is by consensus, involving all perspectives in parallel, from the beginning of the product life-cycle' [**29**]. ESA maintains that 'CE provides a collaborative, co-operative, collective, and simultaneous engineering working environment'. Their concurrent design facility is described as 'a state-of-the-art facility equipped with a network of computers, multimedia devices, and software tools', which is 'primarily used to assess the technical and financial feasibility of future space missions and new spacecraft concepts' [**29**].

2.6 Information technology, analysis tools, and knowledge base

The role of modern information technology (IT) tools in facilitating the coordination of the parallel activities is a crucial element of concurrent engineering [**28**, **30**]. The revolution in computing power (quantified by Moore's Law*), which was responsible for many of the IT advances, also produced a dramatic improvement in the capabilities of engineering simulation tools (e.g. finite element analysis (FEA), computer aided design (CAD), and computational fluid dynamics (CFD)). Kroo [**2**] views the anticipated further improvement in computing power and 'high fidelity simulation' as one of the three key technology areas that is likely to drive future aeronautics innovation.

New developments rely on increased knowledge within the specializations (aerodynamics, structures, material and surface science, control systems, digital communication, human factors, etc.) and on the ability of the developers to integrate the increasingly complex systems into a viable product. These products – and the environment in which they operate (i.e. airports, air traffic control, regulatory authorities, etc.) – are characterized by complex and interlinked

A popular formulation of Moore's Law – attributed to Gordon Moore, co-founder of Intel – is that the number of transistors on integrated circuits (a rough measure of computer processing power) doubles every 18 months* [12**].

knowledge bases. Mowery and Rosenberg [**31**] discuss this point:

> Central to an understanding of the innovation process in the commercial aircraft industry is the high degree of systemic complexity embodied in the final product. The finished commercial aircraft comprises a wide range of components for propulsion, navigation, and so on, that are individually extremely complex. The interaction of these individually complex systems is crucial to the performance of an aircraft design, yet extremely difficult to predict from design and engineering data, even with presently available computer-aided design (CAD) techniques. . . . This pervasive technological uncertainty has been and remains an important influence upon producer structure and conduct in the industry. Such uncertainty also introduces an additional dimension to the innovation process 'learning by using'.

The role of the 'users' (e.g. production staff) in the development process is embodied in the 'design–build' team approach that manufacturers have adopted. The complementary know-how resident in teams of people is the critical raw material needed for innovation in complex systems. In particular, key manufacturing skills have acted as development enablers.

Notwithstanding the fact that new scientific breakthroughs from other fields have yielded valuable knowledge for the development of new aircraft, Acha *et al.* [**32**] conclude that '. . . this is an industry in which new findings in technology per se have often led science'. The authors, citing Vincenti [**33**], use the development of flush riveting to illustrate the point:

> Some knowledge did have to be generated for detail design, but the pivotal developments were in production, and it was there that the greater part of the innovative activity took place'. (Vincenti, p. 542) Unlike patterns of diffusion from an initial creative source described with respect to other types of innovation, production-centred innovation appears to occur simultaneously and pervasively across the entire industry [**32**].

3 INNOVATION INHIBITORS

There are also many factors that discourage or inhibit innovation – besides the absence of innovation promoters (discussed in section 2) – and these would include:

(a) limitations of computer simulation tools;
(b) absence of a creative environment;
(c) fear of failure;
(d) unwarranted or unsubstantiated criticism;
(e) poor definition of success.

3.1 Limitations of computer simulation tools

Computer-based simulation and optimization – of aerodynamic, structural, flight control, or manufacturing processes, for example – is an essential part of modern engineering. It has, in many cases, replaced what McMasters and Cummings [**3**] refer to as 'physical techniques (e.g. drafting and the use of mock-ups, wind-tunnel testing, and experimentation)'. Although modern engineering software has been responsible for the dramatic reduction in the required time to complete design cycles it has also distanced engineers from the underlying scientific principles, mathematical formulae, and empirical databases at the centre of the engineering process. This can have undesirable repercussions. A novice, for example, may rush into a detailed numerical analysis of a stress concentration or flow field, producing a very detailed study, without due consideration of alternative possibilities or solutions. A second issue concerns the production of a numerically correct answer that is inconsistent with the boundary conditions of the specific problem – a scenario that brings to mind the attitude of John Maynard Keynes: 'I'd rather be vaguely right than precisely wrong'.

McMasters and Cummings [**3**] question whether being able to 'go pretty much from daydream to simulation to some sort of flight-test validation of predictions with the computer and its massive database as the core element of the process' has actually made the design process better. They write, 'Have we not actually started merely to codify our biases and assumptions and thus essentially stifle creativity and new configuration explorations by relying on the computer to perform most of the routine mechanical work?' With this observation, they suggest that the full benefits of computer-based synthesis and optimization have yet to be realized and envisage an opportunity to 'use computers to revolutionize the design process, as a complement to, rather than just a copy or extension of, the thought processes of human designers'.

3.2 Absence of a creative environment

It is self-evident that the physical environment in which people work impacts creativity (someone's best ideas may come while walking on a beach). The issue of the work environment impacting creativity was mentioned by Burt Rutan [**34**] in an interview:

> We spent an awful lot of money on how to analyse, but we do not spend much money on creating an environment for creativity. Much of what people do, called design, is really better called analysis. So [aircraft] design is something different. . . . . You need to be

able to visualise load paths and visualise the flow over an airplane and just what it needs to do.

3.3 Fear of failure

Innovation and risk are inseparable. The concern is that a moderately successful concept (say in the eyes of management or a research funding agency) is more attractive than the pursuit of an innovative and potentially higher risk alternative.

James Albaugh [**20**], addressing the Royal Aeronautical Society (2005), described the industry as risk-averse, where 'long-term visions succumb to short-term profits' and where 'large companies purchase small companies for their innovation rather than innovate on their own'. He challenged the industry to 'embrace the risk in discovery' and to 'move away from how we have done things for the past 40 years, where we have merely evolved what has made us successful in the past'.

3.4 Unwarranted or unsubstantiated criticism

Managers and academics can, unwittingly, kill innovation through unwarranted or unsubstantiated criticism. There are, possibly, many examples of professors who are guilty of such actions: one well-known case concerns Ted Smith. It is reported that a Yale University management professor, on reading Smith's paper – in which he proposed an overnight parcel delivery service – noted, 'The concept is interesting and well-formed, but in order to earn better than a C, the idea must be feasible' [**6**]. Fortunately, Smith was undeterred: he later started FedEx.

3.5 Poor definition of success

There are many ways to grade student projects or evaluate research concepts. Success – which would result in a good grade or continued research funding – could be decided by asking, 'Does it (i.e. the concept) work?' Or, in a more precise manner, it may be asked, 'Is it fit for purpose?' Better still, it could be asked, 'Have the performance targets been met?' Clearly, the better the definition of what constitutes success, the fairer the assessment process. By establishing measurable performance parameters the subjectiveness of the evaluation is removed.

A difficulty, however, arises when innovative concepts are involved. Consider, for example, the objective of designing and demonstrating – by flight test – a highly manoeuvrable unmanned aerial vehicle (UAV) and two radically different solutions emerge. Concept A is an evolutionary development of known technologies, with low risk and a demonstrated improvement in the key performance parameters. Concept B includes radically new ideas (which are potentially risky) and modest performance. On the surface it appears that Concept A is superior to Concept B (in an academic environment Concept A would get the better grade; in a research environment it would get funded). But, what if Concept B had the potential – with further research – to outperform Concept A (Fig. 4)? In this case Concept B is deserving of more marks or money. To promote innovation and the development of novel – and potentially high risk concepts – the assessment technique should include a metric that takes into account both demonstrated and potential performance.

4 RISK MANAGEMENT

4.1 Introduction

Creativity leads to innovation, which in turn leads to the development of immature technologies. The need to understand and manage the risks inherent in immature technologies is thus an essential part of the innovation process. Conventional thinking processes and techniques are likely to produce designs that are, more or less, evolutions of past designs. However, 'stepping outside the box' (i.e. considering unconventional solutions) can produce designs that are radical in concept, bearing little or no resemblance to that which came before. These concepts can produce step changes in performance, but are potentially of higher risk.

Various techniques have been developed to manage risks in engineering projects [**35–38**]. These risks may be viewed as the probability that cost or timescale or performance targets are not met. Two key issues: risk assessment and risk characterization are discussed, in an introductory manner, in this section.

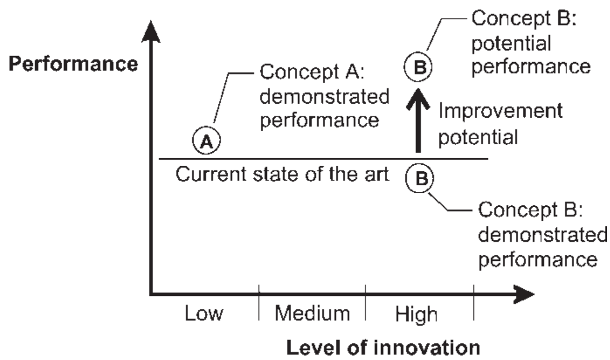

Fig. 4 Performance and innovation in design solutions

4.2 Risk assessment

Technology readiness levels* (TRLs) have become the *de facto* standard technique used to assess the maturity of new technologies as a means of evaluating their readiness for incorporation in new aircraft systems. The US Department of Defense (DoD) TRL definitions are given in Table 1. Valerdi and Kohl [**38**] observe that ‘government acquisition managers generally seek technologies [for inclusion in projects] at TRL 6 or higher’, but that the ‘DoD likes to invest in technologies that are at TRL 4’. Obviously, the lower the maturity of the emerging technology, the greater the effort required to raise that technology to a readiness level suitable for its inclusion into an acquisition programme.

Notwithstanding the fact that TRL allocation is a well-understood process, with clear guidelines and tools (e.g. US Air Force’s Excel-based TRL ‘calculator’ [**41**]), the fundamental assumption that is usually made is that the risk (to the success of the project by the inclusion of the new technology) is inversely proportional to the TRL. With this assumption, the ‘indicative’ level of risk reduces with increasing TRL and this corresponds to an increase in the level of project confidence (Fig. 5). This approach provides a broad framework for risk management; however, as pointed out by Valerdi and Kohl [**38**] it has its limitations. In their view it fails to account for the obsolescing of technologies. This introduces another form of project risk – the risk of backing a mature (e.g. TRL 9) technology, when there is a new technology that could ‘leapfrog’ the mature technology, rendering it obsolete.

4.3 Risk characterization

The assignment of a TRL to a new technology is a valuable tool for assessing the level of maturity of that technology. The permissible level of risk that a project can tolerate, however, by the inclusion of a new technology, also depends on the consequences of the failure of the particular system, in which the new technology is included. By assuming that TRLs translate to the probability of failure – or more precisely, to the probability that the system does not meet the defined cost, timescale, or performance targets – and by independently rating the consequences of system failure, a useful project management tool, in the form of a matrix, may be constructed (Fig. 6). Low risk items that have a negligible consequence (e.g. negligible safety or performance impact) when they fail to perform as anticipated are of little concern; however, high risk items which result in catastrophic consequences, obviously get a lot of attention. Crossland *et al.* [**36**] report that a matrix similar to that shown in Fig. 6 (without the TRL equivalence) was used during the development of the Trent 800 engine. Rolls-Royce identified between 1600 and 2000 risks, which were all placed on a register, and that approximately 400 were characterized as ‘top risks’ requiring a mitigation plan [**36**].

*TRLs were pioneered by NASA in the late 1980s and 1990s to assess the maturity of evolving technologies (described by Mankins [**39**]). The approach was adopted by the US Air Force and the use of TRLs rapidly spread to aircraft manufacturers and their suppliers (civil and military). The US General Accounting Office (GAO) has now endorsed the use of TRLs for all major development programs [**40**].*

Table 1 Technology readiness levels (US Department of Defense)

TRL	Definition†
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Component and/or breadboard validation in laboratory environment
5	Component and/or breadboard validation in relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and qualified through test and demonstration
9	Actual system proven through successful mission operations

†See DOD Deskbook 5000.2-R [**42**] for expanded TRL definitions.

5 CONCLUDING REMARKS

This paper is essentially a collection of thoughts and ideas regarding factors that promote and inhibit creativity and innovation. By way of conclusion, two-interlinked themes: (a) the irrational and uncertain nature of innovation; and (b) the inevitability of risk are discussed.

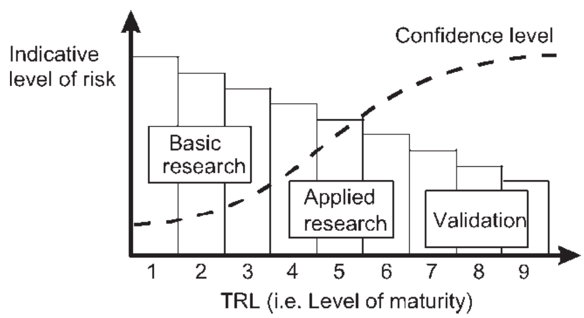

Fig. 5 Risk associated with technology maturity

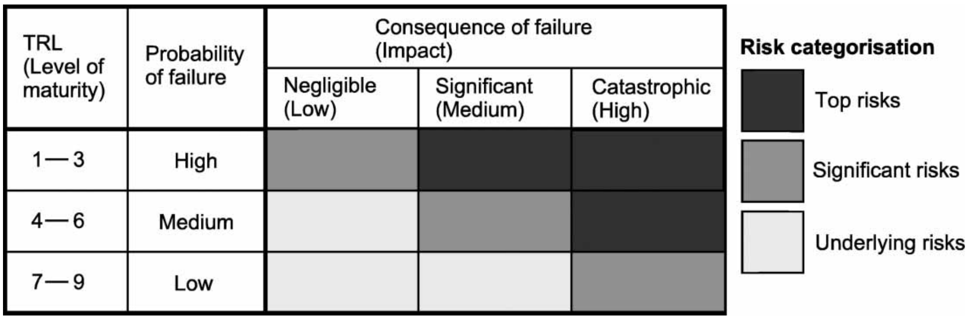

Fig. 6 Risk characterisation matrix: probability of and consequence of system failure

5.1 Innovation: irrational and uncertain

Scranton [**43**] – in his excellent study of the process that produced one of the true marvels of 20th century engineering: the jet engine – maintains that success was not the result of 'skillful management of technology and organization'. He explains:

> Examined closely, it stands rather as a shining example of non-linear, irrational, uncertain, multi-lateral, and profoundly passionate technological and business practice, yielding success not through planning but through dogged determination, a certain indifference to failure (which secrecy aided), and massive expenditures of public funds.

The development of the early jet engines (in post-war America) is described as a 'messy, contingent, and intense process', driven by passion, Cold War fears, and 'the challenges of mastery (in engineering and in organizational terms)'. The development involved multiple technological areas, in which 'no one understood enough ... about turbulent combustion, alloy metals, heat fatigue, or fluid dynamics to approach scientific certainty or reliable knowledge'. Designs did not always rely on theoretical science, but 'on empirical knowledge' that came from the systematic cycles of design, build, and test. Scranton reports that 'engineers often did not know why something worked, just that it worked' [**43**].

5.2 Innovation: equates to risk

Innovation is not always logical as novelty relies heavily on underdeveloped methodologies and knowledge bases. It employs technologies that are at the boundaries of scientific understanding. This, inevitably, introduces a risk that the technology will not yield the envisaged performance or that it will introduce an undesirable side effect. These risks must be identified and managed – not used as a rationale to ditch promising technologies.

Albaugh [**20**] advocates that the aerospace industry must think in terms of 'revolutionizing how we do our business, from the development of technology to how we build our products' and that 'we must foster the innovation that comes from a risk culture'. He concludes that if 'we want to transform the aerospace industry, we can not be content with an evolutionary approach. We have to choose between being incrementalists, content to simply upgrade airplanes, or becoming innovators creating the next quantum leap that will mark the dawn of a whole new era in aerospace'.

The inherent creativity of engineers and their ability to conceive the irrational – and thereafter to apply established engineering methods in a systematic manner (design, analysis, test, and review) – and above all, their compulsion to succeed, is at the heart of innovation. This compulsion may be heightened by factors such as adversity (as in war) and the desire to win (a contest); it may also be dampened by a lack of resources or the absence of a creative environment or by a pervasive, risk-averse culture.

REFERENCES

1 **Murman, E. M., Walton, M.,** and **Rebentisch, E.** *Challenges in the better, faster, cheaper era of aeronautical design, engineering and manufacturing*. The Lean Aerospace Initiative Report, Series RPOO-02, Center for Technology, Policy, and Industrial Development, Massachusetts Institute of Technology, MA, September 2000.
2 **Kroo, I.** Innovations in Aeronautics. AIAA Dryden Lecture, 42nd AIAA Aerospace Sciences Meeting, 5–8 January 2004, Reno, NV, AIAA paper 2004-0001, pp. 1–11.
3 **McMasters, J. H.** and **Cummings, R. M.** Airplane design – past, present, and future. *J. Aircr.*, 2002, **39** 10–17.
4 **Utterback, J.** *Mastering the dynamics of innovation*, 1996 (Harvard Business School Press, Boston, MA). Cited by Murman *et al.* (2000).
5 **English, D.** *The air up there: more great quotations of flight*, 2003 (McGraw-Hill, New York).
6 **English, D.** *Slipping the surly bonds: great quotations of flight*, 1998 (McGraw-Hill, New York).
7 **First World War.com.** The war in the air – summary of the air war. Updated 9 August 2003, available from http://www.firstworldwar.com/airwar/summary.htm, accessed 1 June 2006.

8 **Greatest engineering achievements of the 20th century: airplane timeline.** Available from http://www.greatachievements.org/Default.aspx?id=3728, accessed 16 June 2006.
9 **Bar-Cohen, Y.** (Ed.) *Biomimetics – biologically inspired technologies*, 2005 (CRC Press, London).
10 **Leonardo da Vinci National Museum of Science and Technology.** Milan, available from http://www.museoscienza.org/english/leonardo/galleria.html, accessed 22 June 2006.
11 **Society of Air Racing Historians.** Available from http://www.airrace.com/, accessed 1 June 2006.
12 **Wikipedia.** Available from http://en.wikipedia.org/, accessed 16 June 2006.
13 **National Academy of Engineering.** *Concerning federally funded sponsored inducement prizes in engineering and science*. Steering committee report, 30 April 1999, available from National Academies Press at http://darwin.nap.edu/books/.
14 **X Prize Foundation.** Available from http://www.xprizefoundation.com/, accessed 15 June 2006.
15 **Scaled Composites.** Available from http://www.scaled.com/, accessed 15 June 2006.
16 **Seaman, R.** Available from www.richard-seaman.com, accessed October 2003.
17 **Davis, L.** and **Davis, J.** How effective are incentives to innovation? Evidence from three 20th centuries contests. DRUID Summer Conference, Elsinore, Denmark, 14–16 June 2004.
18 **Harrison, J. P.** *Mastering the sky*, 2000 (Da Capo Press, Cambridge, MA).
19 **Centennial of flight.** Available from http://www.centennialofflight. gov/, accessed 10 June 2006.
20 **Albaugh, J.** Embracing risk: a vision for aerospace in the 21st century, Frank Whittle Lecture, Royal Aeronautical Society, London, 19 January 2005, available from http:www.boeing.com/news/speeches/.
21 **Strategic Research Agenda (SRA).** Advisory Council for Aeronautics Research in Europe (ACARE), November 2002, available from http://www.acare4europe.com/html/strategic0.shtml.
22 **Commission of the European Communities.** *European aeronautics: a vision for 2020*. Report of the Group of Personalities, January 2001.
23 **Brown, A.** Very large civil transport. In *Future aeronautical and space systems, Prog: Astronaut. Aeronaut.* (Eds A. K. Noor, S. L. Venneri, and P. Zarchan), 1997, vol. 172, pp. 144–156 (AIAA, Washington).
24 **Birch, N. T.** 2020 vision: the prospects for large civil aircraft propulsion. *Aeronaut. J.*, August 2000, 347–352.
25 **Clean Sky JTI Workshop.** Brussels, 1 June 2006. Organised by ASD, available from www.asd-europe.org.
26 **Community Research and Development Information Service** (CORDIS). Available from http://cordis.europa.eu/en/home.html.
27 **McNerney, J.** Innovation and the global economy. Distinguished Lecture Series in International Business, St Louis University, 16 May 2006, available from http:www.boeing.com/news/speeches/.
28 **Rothwell, R.** Towards the fifth-generation innovation process. *Int. Mark. Rev.*, 1994, **11**, 7–31.
29 **European Space Agency (ESA).** What is concurrent engineering? Available from http://www.esa.int/SPECIALS/CDF/SEM1OF1P4HD_0.html, accessed 10 June 2006.
30 **Kesseler, E.** and **Vankan, W. J.** Taking collaborative engineering to the sky: formation flying with knowledge management. European Conference for Aerospace Sciences (EUCASS), Moscow, 4–7 July 2005, Paper no. 6, Session 1.3 (available on CD-ROM).
31 **Mowery, D. C.** and **Rosenberg, N.** Technical change in the commercial aircraft industry, Ref. 192501975. *Technol. Forecast. Soc. Change*, 1981, **20**, 347–358.
32 **Acha, V., Brusoni, S.,** and **Prencipe, A.** *Exploring the miracle: the knowledge base in the aeronautics industry*. ESCR Centre for Complex Product Systems (CoPS) Working paper series, No. W023, SPRU, Brighton, UK, 2003.
33 **Vincenti, W. G.** The innovation of flush riveting in american airplanes. *Technol. Culture*, 1986, **16**, 540–576. Cited by Acha *et al.*, 2003.
34 **Rutan, B.** Scaled composites. In a documentary interview, *ca.* 1996.
35 **Chapman, C.** and **Ward, S.** *Project risk management: processes, techniques and insights*, 1997 (John Wiley & Sons, Chichester, UK).
36 **Crossland, R. J., Sims Williams, J.,** and **McMahon, C.** The practical application of design risk assessment models. *J. Engng Manufact.*, 2003, **217**, 227–234.
37 **Browning, T. R., Deyst, J. J., Eppinger, S. D.,** and **Whitney, D. E.** Adding value in product development by creating information and reducing risk. *IEEE Trans. Engng Manage.*, 2002, **49**, 443–458.
38 **Valerdi, R.** and **Kohl, R. L.** An approach to technology risk management. Engineering systems division symposium, MIT, Cambridge, MA, 29–31 March 2004.
39 **Mankins, J. C.** Technology readiness levels: a white paper, office of space access and technology. NASA, Advanced Concepts Office, 6 April 1995.
40 **Graettinger, C. P., Garcia, S., Siviy, J., Schenk, R. J.,** and **Van Syckle, P. J.** *Using the technology readiness levels scale to support technology management in the DODs ATD/STO environments*. Report of Carnegie Mellon Software Engineering Institute, CMU/SEI-2002-SR-027, September 2002.
41 **Nolte, W. L., Kennedy, B. C.,** and **Dziegiel, R. J. Jr.** Technology readiness level calculator. NDIA Systems Engineering Conference, 20 October 2003. Presentation available from http://www.dtic.mil/ndia/2003systems/nolte.ppt.
42 **US Department of Defense (DOD).** DOD Deskbook 5000.2-R, available from http://www.acq.osd.mil/actd/FY06/TRL50002R.doc.
43 **Scranton, P.** Urgency, uncertainty, and innovation: building jet engines in postwar America. *Manage. Organ. Hist.*, 2006, **1**(2), 127–157.