AN ENHANCED EVALUATION FRAMEWORK FOR DEFENCE R&D INVESTMENTS UNDER UNCERTAINTY

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SUMMARY

The effective and objective evaluation of defence R&D investments is both an important and challenging issue. There is ever increasing pressure on decision makers to demonstrate effectiveness and objectivity in the evaluation of the substantial public investments in defence R&D programmes. Quantitative evaluation methods are apparently more objective but existing methods have difficulties dealing with the uncertainties and strategic nature of returns on defence research and development investments. These methods also neither consider the system sufficiently nor encourage innovations.

This project develops a theoretical framework for the dynamics of defence technological innovations by building on the body of knowledge in strategic and technology management and using case studies in historically significant defence technological innovations. Innovations are created by capabilities which could be built on (1) technological pursuit and subsequent identification of military applications or (2) technology development initiated by military demand. Adopting the theoretically attractive real options lens, defence R&D investments can be framed as building a value robust portfolio of real options in capability options and human capital amidst environmental and technological uncertainties.

Upon this theoretical framework, we develop an objective evaluation framework for defence R&D investments, which effectively considers the strategic issues in the innovation system and highly uncertain return on

investments, and encourages innovations. While real option is a theoretically attractive model for defence R&D investment, there are limitations to the classical real option valuation methods. Using our improved understanding of defence technological innovations, we propose that the appropriateness and boundaries of the real option model and suitability of the valuation method are contingent on the nature of the investment. As arbitrary selection of evaluation techniques for R&D investments may result in misleading or even wrong conclusions, we develop an evaluation methodology which advises the appropriate real options model and suitable evaluation method. Scoring method is the most favourable method for R&D project evaluation because of their ability to deal with multiple dimensions of R&D problems and their simplicity in formulation and use. However, it lacks consideration of risk and uncertainty. We propose improvements to the scoring method for evaluation of defence R&D investments by adopting the real options approach to consider risk and uncertainty. The enhanced scoring method is integrated into our evaluation methodology for defence R&D investments. The applications of our theoretical framework and evaluation methodology are illustrated using three contemporary defence technological innovations in Singapore.

This project does not adopt a pure mathematical or technology management approach. A framework is first developed through theory building, and an evaluation methodology is subsequently built upon this theoretical framework. The good and novel positioning has led to a unique research with theoretical as well as practical contributions to the body of knowledge on strategic and technology management, real options and systems engineering. Our research demonstrates the validity of concepts from these theories within the defence context, and develops a theoretical framework for defence R&D innovations by building on these theories, and empirical evidences from defence technological innovations. This theoretical framework contributes to our understanding of the dynamics of defence R&D innovations and forms the foundation of our proposed evaluation framework for defence R&D investments. The latter enables the effective and objective evaluation of defence R&D investments and supports good decision making amidst uncertainties in the innovation process.

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1. INTRODUCTION

The evaluation of defence research and development (R&D) investments is both an important and challenging problem. Many governments make substantial investments in defence R&D programmes and there is ever increasing pressure on decision makers in the public service to demonstrate efficiency, transparency and accountability in the evaluation of the substantial investments in defence R&D programmes to achieve good return on investment. However, quantitative evaluation methods are not frequently used despite the apparent greater objectivity due to weaknesses in the methods.

1.1 Nature and degree of investment in defence R&D

For most of history, advances in military weaponry have been associated with applications of new knowledge, new materials, and new techniques. Science and technology have enabled the creation of new military capabilities with weapons of greater destruction, longer range, finer precision, and many other aspects of military utility. The tank, submarine, radar, nuclear bomb, rockets, and ballistic missiles are examples of new capabilities that changed the nature of conflict and the course of nations. Disruptive military capabilities and challenges from adversaries who develop and use breakthrough technologies can negate current advantage in key operational areas. A revolutionary technology and the associated military innovation can fundamentally alter long-standing concepts of warfare (DoD, 2009). Besides the discontinuities apparent in revolutionary technological leaps, continuous incremental innovations are also made in the evolutionary processes of technological development (Ross, 1993; Hacker, 2005).

Since national security, prestige, and influence have been and continue to be determined in part by military strength, nations spend considerable effort to have, or have access to, the scientific and technological skills and facilities necessary to obtain military capability (Perry, 2004). The ability to support this strategy requires a broad range of supporting technical and scientific skills and facilities (Hermann, 2008). Substantial amount of public funds worldwide is invested into defence R&D.

The level of defence R&D spending in 2001 for the top ten defence R&D nations in the Organisation of Economic Cooperation and Development (OECD) and Russia is approximately US$65 billion (Hartley, 2006). Please see Table 1.1 for the level of defence R&D spending in these countries. In Singapore, where defence budget is consistently maintained at about 6% of the Gross Domestic Production (GDP), approximately 4% of this budget, or S$400 million, is invested on R&D (Teo, 2010).

	2001 US$ billion	2004 US$ billion
USA	46.21	67.46
Russia	4.80	6.10
France	3.71	4.06
UK	3.27	4.68
Spain	2.22	NA
Germany	1.23	1.41
Japan	1.00	1.15
South Korea	0.97	NA
Italy	0.41	NA
Sweden	0.30	0.67
Canada	0.23	NA

Table 1.1. Level of defence R&D spending for major defence R&D nations, 2001 prices and 2001 ppp rates (Hartley, 2006)

In many of the other developed countries, defence R&D investments are made amidst government attempt to reduce defence expenditures while retaining their military influence. Examples include the United Kingdom and France which have been among the biggest defence spenders in the world (Kirkpatrick, 2008; Straits Times, 2010b). In emerging powers such as China and India, defence R&D investments are increasing for strategic reasons (Erickson and Walsh, 2008; Straits Times, 2011d, 2011f, 2011g, 2011h). Despite their limited resources, many small countries such as Singapore and Taiwan, also invest in indigenous defence R&D. They cannot develop the full range of technologies required for their defence and do not enjoy the economies of scale of scale of the larger countries. Hence, their defence R&D investments are usually driven by strategic considerations and foreign policy (Jan, 2006; Thompson, 2006; Matthews and Zhang, 2007). These considerations include the withdrawal of foreign sources of military capabilities and limited access to technologies and industries that are critical to a desired military posture. The availability and/or vulnerability associated with asymmetric attributes must all be considered in light of the cultures, aspirations, and incentives of the participants (Hermann, 2008). In Singapore, for example, the defence R&D investment is deemed “a necessary and important investment as the technologies we need may not be available on the open market or those which are available may not fulfil our requirements.” (Teo, 2010)

The substantial defence R&D investments are frequently strategic and aim to provide value robust technological capability to help sustain the national long term defence capability in the uncertain time horizon. Value robustness refers to the ability of a system to continue to deliver stakeholder value in the face of changing context and needs (Ross and Rhodes, 2008). For example, the US Defense Research and Engineering (R&E) Strategic Plan (DoD, 2009) reiterated the DoD R&E management principle to continually develop new and enhanced capability options for operational commanders and strategic policy makers. Other goals include (1) investments on new technologies and applications to refresh the U.S. military capability advantage, (2) enhance the affordability of Systems and Capabilities through the balanced development or insertion of advanced technology, (3) develop technology which will enhance sustainment and upgrade for existing weapon systems, and (4) minimise the probability of technology surprise by hedging against the uncertainty brought about by disruptive technologies and partner with the intelligence community to identify them early. In Singapore, the aim of defence R&D is to deliver solutions to meet “requirements that are specific to .. [its] needs, environment and fighting concepts" as "[not] all the required technological solutions are available because of commercial and proprietary reasons" and "[the] ability to customize and improve elements of its weapon systems also gives .. [it] an edge over similar systems which have not been so improved". Another aim is to allow the creation of "surprises on the battlefield and to come up with quick fix solutions should the need arise" (Teo, 2006).

There is an increasing interest in the evaluation of public investments largely due to the ever increasing pressure on public service to demonstrate that it creates value and is prudently managed fiscally. There is a need for better understanding of why governments should invest in research, how they should do it and what the public gets in return (Piric and Reeve, 1997). Public service faces value squeeze under which it seeks to increase outcomes while reducing costs. Although public managers' budgets remain tight, taxpayers demand more and better service from public service organisations. The increasing use of the Internet has further raised the bar on the level of expectation of the public service (Cole and Parston, 2006). There is also a demand for a greater focus on accountability and transparency in policy, and the desire to minimise distortions arising from government actions while maximising their impact (OECD, 1997; Piric and Reeve, 1997).

The increasing public R&D investments coupled with the increasing interest in evaluation of public investments necessitate a high level of effectiveness and accountability in these investment decisions. For example, the US Department of Defense (2009) commits to "provide value for the taxpayer" and "those who execute the DoD R&E programme will invest each tax dollar as if it were their own" in fulfilling their responsibility to their "primary shareholder .. the American taxpayer"**.** Highly visible decision makers in the public service are accountable for the return on the substantial public fund invested in defence R&D (Gansler, 1980). They need to demonstrate that decision making for defence R&D investments is objective and the defence R&D portfolio delivers good return on investments (ROI).

1.2 Challenges

Despite the apparent greater objectivity of the quantitative evaluation methods, they are less often used than qualitative assessment approaches in public R&D project evaluation. The evaluation of public R&D investments is fraught with challenges as the return on investments is difficult to evaluate due to the uncertainty of the outcome of the R&D programmes and measuring the return on investment. In particular, quantitative evaluation of defence R&D investments is very difficult due to uncertainties resulting from the unpredictable outcomes, costs and schedule inherent in defence research and development efforts (Ross, 1993). Greiner et al (2001) highlighted that in contrast to the estimate that 50% of sales within commercial firms are generated from new products introduced within the past five years, the average development time for all major U.S. weapon systems development from 1965 to 1995 is nearly nine years. Parnell et al (1999) pointed out that the time from identification of new R&D concepts to deployment as military weapon systems is 10–25 years but significant uncertainties exist about future political military states of the world and the value of these future systems may depend on the eventual state of the world. Despite the efforts of Military Intelligence, no one can know how political, military, technological and economic variables are likely to develop over this extended period.

Furthermore, the returns on investments are frequently strategic in nature and aim to develop a value robust technological capability which is difficult to measure. For example, the objectives of the US Defense R&E Strategic Plan (DoD, 2009) include the continual development of new and enhanced capability options for operational commanders and strategic policy makers, as well as, minimising the probability of technology surprise by hedging against the uncertainty brought about by disruptive technologies and partnering with the intelligence community to identify them early. Similarly, the aim of defence R&D investment in Singapore is to develop technologies to meet specific requirements as not all the required technological solutions are available because of commercial and proprietary reasons, and to create technological surprises on the battlefield (Teo, 2006). Quantitative evaluation methods are inadequate in the consideration of these strategic issues in the innovation system and encouragement for innovations (Schmidt and Freeland, 1992; Martino, 1995; Miller and Morris, 1999).

Finally, the difference in innovation regime may necessitate different considerations in developing an evaluation framework for defence R&D investments. Technologically superior weapon systems today can be traced to R&D activities conducted many years prior. Examples of these systems in the U.S. include the E-3 Sentry Airborne Warning and Control System (AWACS), E-8A Joint Surveillance Target Attack Radar System (Joint STARS), Low-

Attitude Navigation and Targeting Infrared for Night, AGM-65 Maverick TV-guided air-to-ground missile, AIM-120 Advanced Medium-Range Air-to-Air Missile and the F-117 Stealth Fighter, all of which were developed based on R&D efforts conducted in the 1960s to 1980s (Greiner et al, 2001). The large-scale mission oriented projects in defence R&D investments aim to develop specific technologies under high appropriability and high cumulativeness (at the firm level) conditions. These lead to a Schumpeter Mark II Model of innovation regime (Breschi et al., 2000), characterized by "creative accumulation" and the importance of experience in innovative efforts. This differs from the Schumpeter Mark I Model frequently observed in the commercial innovation regime in which the entrepreneur helps to unleash innovation into the marketplace and creates "gales of creative destruction" (Schumpeter, 1937).

1.3 Organisation of thesis

This thesis is organised in the following manner:

1. Introduction. The preceding paragraphs describe the research background and the need for an improvement in the effective and objective evaluation approach for defence R&D investments.

2. Literature Review. The existing literature on R&D investment evaluation is reviewed in this chapter.

3. Research objective and methodology. This chapter defines the research objective and describes the research methodology.

4. Case studies in several historically significant defence technological innovations are conducted to support the theory building.

5. Discussion of the emergent theoretical framework. This chapter compares the emergent theoretical framework with the extant literature to improve the theory building with the corresponding validity, theoretical level, and construction definitions.

6. Applications of our defence technological innovation framework in proposing strategic heuristic for defence technology management and defence R&D investments.

7. Propose a defence R&D investment evaluation framework based on our defence technological innovation framework. Three cases of defence technological innovations in Singapore are used to illustrate the contemporary validity of our theoretical framework and applications of the strategic heuristic and evaluation methodology.

8. Discussion & conclusion. We conclude the thesis with a discussion of the limitations of the research, implications of this work on research and practice, and proposed future work.

2. EVALUATION METHODS FOR R&D INVESTMENTS: A LITERATURE REVIEW

In the previous chapter, we have highlighted the need to improve the evaluation approach for defence R&D investments for effective and objective evaluation. In this chapter, we review the literature on the state of the practice in the evaluation of public and defence R&D investments. We begin with a discussion on the limitations of the classical valuation methods of R&D projects before reviewing possible approaches to address these weaknesses. The identified gap would help in our definition of the research problem. In this project, the definitions of Easterby-Smith (2001) for the terms methodology and method are adopted. A methodology is defined as a combination of techniques used to enquire into a specific situation, and a method is defined as an individual technique for data collection analysis, etc.

2.1 Commercial R&D Project Selection

The R&D project selection process defines whether a project is to be undertaken on the basis of the evaluation made. This process is of strategic importance to the organisation because it is the means by which technology strategies are actually implemented (Ramsey, 1987).

Meade and Presley (2002) reviewed the literature and summarised three major research themes relating to R&D project selection:

1) Relate Selection Criteria to Corporate Strategy: Many companies are coming to consider their R&D function as a competitive tool to be managed strategically. To ensure effective decision-making, R&D strategy and planning must be tied to corporate strategy. For many organizations, R&D represents a major portion of many organizations' investments. Wrong decisions can result in the tying up of significant resources and lead to loss of strategic and market position.

2) Consider Qualitative Benefits and Risks: Too often, R&D project selection is made based solely on financial criteria such as net present value (NPV) and internal rate of return (IRR). While these are important criteria, other less easily quantifiable criteria such as market share and corporate image must be considered. R&D projects are multidimensional in nature and have risky outcomes and decisions and must consider strategic and multidimensional measures. R&D projects are often committed to long term activities, result in uncertain outcomes, are cost intensive, and in many cases, demand special project management.

3) Reconcile and Integrate Needs and Desires of Different Stakeholders: R&D decisions impact the entire enterprise and must be compared to other functional contributions in the enterprise. Therefore, R&D decisions must not be made in isolation or based solely on what the R&D organization feels is important.

2.2 Classical evaluation approach for R&D projects

There is a long history of developing formal models for project selection which adopt a quantitative approach to compare projects within a programme by their technical merit and potential returns according to the selection criteria of the programme (Betz, 2003). The considerable amount of literature developed has been reviewed by many researchers, including Schmidt and Freeland (1992), Martino (1995), and Henriksen and Traynor (1999). Martino (1995) reviewed the existing R&D project evaluation techniques and proposed the following classification:

- Ranking methods: Pairwise comparisons, Scoring models, Analytical Hierarchy Process (AHP)
- Economic methods: Net present value (NPV), Internal rate of return (IRR), Cash flow payback, Expected value
- Portfolio optimisation methods: Mathematical programming, Cluster analysis, Simulation, Sensitivity analysis
- Ad hoc methods: Profiles, Interactive methods, Cognitive modelling
- Multi-stage decisions: Decision theory

Another classification for R&D project evaluation methods, proposed by Poh et al (2001), is:

- Weighting and ranking methods which compute relative weights and rank a set of proposed projects in order of preference. The most common types of weighting and ranking methods are comparative method, scoring method, and Analytic Hierarchy Process (AHP).

- Benefit contribution methods which examine projects to determine how well they satisfy the basic R&D objectives of an organisation. Methods classified under this category are economic analysis, cost/benefit analysis and decision tree analysis.

Even with the vast number of proposed models, the R&D selection problem remains problematic and few models have gained wide acceptance. Most surveys on the use of capital budgeting techniques show that almost all large corporate firms use NPV calculations for investment decisions (Kogut and Kulatilaka, 2001). NPV calculations are useful when there are insignificant uncertainty in the project and little uncertainty in the estimation of cash flow (Winter, 1987). R&D investments, however, are highly volatile and uncertain. They could be highly risky while offering opportunities for great returns. R&D projects may span over a long period of time and the know-how developed in a project may create options to pursue development downstream. R&D success may also depend on the success of interdependent developments such as complementary technology and assets. Hence, a mere factoring of risks in the traditional valuation methods is inadequate to model R&D ventures.

Liberatore and Titus (1983) conducted an empirical study on the use of quantitative techniques for R&D project management and found that most R&D organizations use one or more traditional financial methods for determining project returns, often in conjunction with other methods. Mathematical programming techniques such as linear and integer programming are not commonly used in industry, primarily because of the diversity of project types, resources, and criteria used. They also found that many managers do not believe that the current methods for project selection improve the quality of their decisions.

Assessing the potential value of a proposed R&D project to an organisation is complicated as the probability of technical success of the project is uncertain at the onset. Even if there is certainty that the technical objectives can be achieved, the ultimate impact of those results is uncertain in advance. Hence, many of the traditional techniques used to evaluate and select projects of relatively low level of uncertainty are not appropriate for R&D projects (Henriksen and Traynor, 1999).

Many researchers have also criticised the classical "decision-event'' approach which models R&D project selection as a constrained optimization problem (Schmidt and Freeland, 1992). They argue that models should be adapted to existing organisational processes and assist in coordinating decisions about selecting and monitoring a project portfolio. Project selection models should be used as decision aids to facilitate communication and provide insight into organisational processes.

Schmidt and Freeland (1992), Martino (1995), and Miller and Morris (1999) summarised some of the deficiencies of these methods as follows:

- Inadequate consideration of the organisational issue:
    - Ignoring the organizational context and decision process
    - Failure to build support and consensus from stakeholders

- Failure to model the project selection problem as an on-going process rather than a once a year decision event
- Inadequate treatment of project parameters:
    - Inadequate treatment of risk and uncertainty
    - Inadequate treatment of multiple, often interrelated, criteria
    - Inability to recognize and treat non-monetary aspects
    - Failure to recognise the time variant property of parameters
    - Inadequate treatment of interactions, both benefit contribution and resource utilisation.
- Inadequate treatment of the portfolio effect
    - Inadequate treatment of project interrelationships
    - Inadequate consideration for need to establish and maintain balance in the programme; basic versus applied; offensive versus defensive; breakthrough versus improvement; product versus process; high risk/ high payoff versus low risk/ low payoff.
- Inadequate support for the innovation process

Poh et al (2001) noted the lack of study on identifying and analysing the criteria or guidelines necessary for choosing the most appropriate method from among different methodologies available. As arbitrary selection of evaluation techniques for R&D investments may result in misleading or even wrong conclusions, there is a need to develop formal procedures or guidelines for the selection of the R&D evaluation technique for a specific R&D investment.

Poh et al (2001) proposed an Analytic Hierarchy Process (AHP) based framework for comparative analysis of R&D evaluation methods.

2.3 Evaluation approach for public R&D investments

Many researchers have noted the uniqueness of public R&D investments and contributed to the literature on the management of these investments. To begin with, the reasons for investments in public R&D are generally different from private R&D investments (Stoneman, 1999). While the objective of the latter is usually profit, public funds are more frequently invested in R&D due to market failures or the need to produce knowledge as a public good. The returns from public R&D investments also possess different characteristics. The economic, social, environmental and cultural benefits sought in the investments may be intangible and difficult to quantify (Piric and Reeve, 1997). Moreover, the benefits and costs of investing in a particular segment of the economy does not necessarily coincide with all the benefits and costs experienced by the individuals residing within the area (Mishan and Quah, 1998). This poses a challenge in considering the total benefits and costs of the investment.

Not surprisingly, perhaps, different considerations are involved in the project selection for public investments. For example, different factors are considered in project selection at public and private R&D institutes (Lee and Om, 1996) and public sector organizations have specific requirements towards project portfolio management (Martinsuo & Dietrich, 2001). Evaluation of public

R&D investments aims to determine both the costs and benefits of publicly financed projects in R&D. This can be used to justify a public investment in R&D and improve the efficiency and effectiveness of that investment (Piric and Reeve, 1997). A wide variety of methods are used in the evaluation of public R&D projects. These methods can be classified as quantitative and qualitative methods.

Qualitative assessment approaches are more often used than quantitative evaluation methods in project evaluation despite the apparent greater objectivity of the latter. In particular, peer review is the most widely used method of evaluation. These methods, however, may lack objectivity and may be less appropriate for measurement of R&D outputs or economic impacts (Capron and van Pottelsberghe de la Potterie, 1997).

The quantitative evaluation of public R&D investments is fraught with challenges as the return on investments is difficult to evaluate due to the uncertainty of the outcome of the R&D programmes. Furthermore, the returns on investments are frequently strategic in nature and difficult to measure. In particular, quantitative evaluation of defence R&D investments is very difficult due to uncertainties resulting from the unpredictable outcomes, costs and schedule inherent in defence research and development efforts (Ross, 1993). Jan (2003) observed that building defence technology requires enormous resources, generally takes longer than the development of technologies for civilian industries, and its benefits are less immediately tangible. Several decades may be required from technology investment to mass production, and the impatient executive may not understand the evolutionary process involved.

2.3.1 Evaluation methods for public R&D investments

The relevance and drawbacks of the evaluation methods for public R&D investments are summarised in Table 2.1. Cost benefit analysis (CBA), which estimates the costs and benefits for a given programme, is the most frequently used quantitative method in estimating a public R&D programme's net benefits. The major problem with CBA is it requires measurable factors in financial terms but the value assigned to intangible benefits can be highly debatable (GAO, 1993). Another problem with CBA is the difficulty in dealing with externalities that have been produced by R&D and requires identifiable projects for evaluation. Since most R&D projects are characterised by a high degree of sophistication and externalities, the former poses a problem for the science and technology community. The data for analysis come from well-defined and completed projects, and therefore has limited accuracy. In addition, CBA does not provide significant insight into strategic objectives since it focuses only on economic factors and is unable to calculate spin-off or external effects of R&D activities.

Evaluation methods	Qualitative/ Quantitative	Relevance	Drawbacks
Peer review	Qualitative	• Evaluation by experts • Screens of project and research orientation • Relative simplicity • Widely used and significant experience	• Subjective • Partial forecasts • Lack of independence • Expensive and time consuming
Questionnaires	Qualitative		
Interviews	Qualitative		
Technometrics	Quantitative		
Matrix approaches	Quantitative	• Rich information • Rationalise and simplify choices • Profiles project and R&D planning	• Difficult to collect information • Subjective
Systemic approaches	Quantitative	• R&D strategies • Considers evolutionary character of system • Systemic consideration	• Difficult to implement
Cost benefit analysis	Quantitative	• Measure marketable outputs and commercial resources • Simple instruments	• Difficult to collect information • Some factors cannot be financially assessed • Difficult to estimate time-lag between R&D and highly variable results
Ratio methods	Quantitative		
Programming models	Quantitative		
Portfolio models	Quantitative		
Option pricing	Quantitative	• Provides optional value of R&D	• Difficulties with adequate data
Technological forecast methods	Qualitative	• Considers social transformation and interdependence	• Subjective

Table 2.1. Evaluation methods (adapted from Capron and van Pottelsberghe de la Potterie, 1997; Piric and Reeve, 1997)

Vonortas and Hertzfeld (1998) argued that in the selection of R&D Projects in the public sector, conventional methods for evaluating long-term investments in R&D such as NPV suffer from two shortcomings. First, these methods largely ignore the uncertainty of the outcome, the choice of the timing of the investment, and the irreversibility of committed resources. Given that these factors are major characteristics of strategic long-term R&D, inadequate accounting for them may seriously distort decision making based on the potential benefits of investments in government-sponsored R&D programs. Second, these methods are likely to use inappropriate discount rates that blend time discount and risk adjustment factors, thus creating the false impression that project risk follows a time path with no predictable pattern. These constant discount rates also do not account for the fact that the product of R&D is often better information that will decrease uncertainty (and risk) over time. Official discount rates required by the U.S. government for analysis of federal programs, for example, disregard the significant differences among R&D projects, technologies, and industries.

2.3.2 Evaluation methods for defence R&D investments

In the United States, the criteria for decision making in weapon procurement is meeting a genuine strategic requirement by the cheapest method. In the early 1960s, the Secretary of Defense Robert McNamara sought to revolutionalise defence procurement in the United States by bringing in professional analysts to prepare technical cost-benefit analyses of variables, limitations and options to present to decision makers (McNaugher, 1988). This approach aims to base weapons acquisition on precise judgements about cost-effectiveness and can be summarised in three basic stages: (a) threat analysis and the definition of requirements; (b) responses to these requirements; and (c) evaluation of options and choice. There are many more recent Department of Defense (DoD) requirements for analytical techniques to evaluate the risk and value of defence R&D investments (Mun and Housel, 2006). For instance, the Clinger-Cohen Act of 1996 mandates the use of portfolio management for all federal agencies. The Government Accountability Office's "Assessing Risk and Returns: A Guide for Evaluating Federal Agencies' IT Investment Decision-Making," Version 1, (February 1997) requires that IT investments apply ROI measures. In his Defense Reform Initiative Report, Defense Secretary William S. Cohen addressed his drive to identify and implement commercially proven practices into the DoD acquisition process citing "DoD support systems and practices that were once state-of-the-art are now antiquated compared with the systems and practices in place in the corporate world, while other systems were developed in their own defense-unique culture and have never corresponded with the best business practices of the private sector. This cannot and will not continue." (DoD, 1997) DoD Directive 8115.01 issued October 2005 mandates the use of performance metrics based on outputs, with ROI analysis required for all current and planned IT investments. DoD Directive 8115.bb implements policy and assigns responsibilities for the management of DoD IT investments as portfolios within the DoD enterprise when they defined a portfolio to include outcome performance measures and an expected return on investment. The DoD Risk Management Guidance Defense Acquisition Guidebook requires that alternatives to the traditional cost estimation need to be estimated because legacy cost models tend not to adequately address costs associated with information systems or the risks associated with them.

In the United Kingdom, the Ministry of Defence adopts a structured cost/effectiveness analysis approach for strategic investments in comparing the alternative costs of achieving a specified level of effectiveness which is not assigned a monetary value (Kirkpatrick, 1996). This seeks to identify from alternatives the option which most economically achieves a specified objective of defence policy, which may be a higher-level objective relating to the capability of UK Services or a lower-level objective relating to the output of a particular military unit or branch.

Stockholm International Peace Research Institute (SIPRI) conducted a survey of the arms procurement decision making in several countries (Singh, 1998a). China conducts cost-effectiveness analysis at each stage of the arms procurement decision-making process in order to ensure that actual expenditure does not exceed the funds budgeted. The cost-effectiveness evaluation is completed before the process of selecting the weapon system begins. The basic steps to be completed in this stage include: (a) determining the objectives of the cost-effectiveness analysis; (b) constructing and selecting alternatives; and (c) analysing the effectiveness of alternatives, including inherent capability, reliability, maintainability, durability, survivability, safety and human factors. An assessment of the quantitative relationship between total costs and the effectiveness index of the weapon system in terms of the probability of it being used for several different missions must also be undertaken. A decision is then made to continue to implement, revise or abandon the plan. The estimates of the life-cycle costs are based on: (a) R&D, including costs paid for R&D as well as a part of supporting costs, namely, feasibility and concept formulation, design and trial production, and tests and evaluation; (b) purchase costs, including auxiliary equipment, installation, training and support, and so on; (c) operating costs, which are paid for operating and supporting the equipment during its commission in peacetime or wartime, including operating costs, maintenance costs, support costs and technical upgrading costs; and (d) the costs of decommissioning. Israel similarly adopts a cost/effectiveness analyses approach and recognises that the assumption of 'complete information' is unrealistic given the conditions of great uncertainty (Steinberg, 1998). Despite the efforts of Military Intelligence, no one can know how political, military, technological and economic variables are likely to develop over a period of 5 or 10 years, and in an increasing number of cases even longer. In an effort to limit the effects of uncertainty, various techniques are used, including the Delphi method and decision tree analysis. In the Delphi method a group of experts is questioned, usually remotely, in an iterative process. In each round, participants are given information about the responses of other participants, in an effort to reach a consensus. This method has been used by the Interdisciplinary Center of Technological Assessment and Forecasting at the University of Tel Aviv. A similar but less structured 'brain-storming' approach has also been suggested for reducing the impact of uncertainty in decision making. The decision tree analysis method is used to assess the overall potential and utility of technologies under consideration. It involves breaking down a particular decision to the lowest level of analysis. For each option, the different possible outcomes are assessed and the possibilities of each path are estimated. Strategic attributes and values for each outcome are assigned by the Israel Defence Force and the Ministry of Defence. Tactical attributes of weapons are based on evaluations provided by field commanders.

2.4 Recent development in evaluation methods

2.4.1 Evaluation of intangibles

In public R&D investments, many of the benefits generated from the investments including economic, social, environmental or cultural benefits, are intangible, and could not be considered directly in quantitative R&D evaluation models. Table 2.2 summarises some of the methods used by economists to value intangibles in their cost and benefit analysis. In addition many methods have been proposed to value intellectual capital which is gaining strategic importance in the knowledge-enabled economy. These methods include the Accounting Methods, Direct Intellectual Capital Methods and Market Capitalization Methods.

In defence R&D investments, the returns are frequently measured in terms of cost effectiveness of achieving a mission and quantified using the revealed preference approach (O' Hanlon, 2009). Greiner et al (2001) adapted the Cost of Delay Analysis (CoDA) and demonstrated the calculation of the weapon system value in an example aircraft new engine development project.

Method	Applications	Value type	Reference
Contingency Valuation Method	Many public goods	Willingness to pay	Benefits, stated preference
Hedonic Pricing Method	Specific attributes	Hedonic pricing	Benefits, revealed preference
Travel Cost Method	Recreational values	Travel costs	Benefits, revealed preference
Production Factor Method	Public goods used in production processes	Market price, economic rent	Damaged costs, revealed preference
Averting Behaviour Method	Natural qualities effecting consumer behaviour	Prevention, costs	Prevention costs, revealed preference

Table 2.2. Methods used in social economics to evaluate intangibles (summarised by Buurman, 2007)

2.4.2 Multi criteria decision making

Multi criteria decision making methods, such as scoring, have been applied in considering the multiple criteria for allocation of resources to a set of competing and often disparate project proposals. A scoring method evaluates projects by giving each project a score reflecting how well it meets the defined objectives on some scale (Poh et al, 2001). The model could involve a mathematical formula or algebraic expression that produces a score for each project under consideration using a formula which incorporates those factors believed to be important (e.g. Henriksen and Traynor, 1999).

As discussed earlier in Section 2.2, Poh et al (2001) developed a comparative analysis framework for R&D evaluation methods. Using their framework, they studied six evaluation methods using seven proposed criteria. The evaluation methods compared were (1) scoring method, (2) Analytic Hierarchy Process (AHP), (3) decision tree analysis, (4) economic analysis, (5) cost-benefit analysis, and (6) comparative method. The seven criteria proposed by the authors were (1) multiple objective, (2) risk and uncertainty, (3) simplicity, (4) data availability, (5) adaptivity, (6) nature of data, and (7) cost. Based on their subjective evaluation, scoring method is the most favourable method for R&D project evaluation. Poh et al (2001) reported that this is consistent with literature comments that scoring methods are popular because of their ability to deal with multiple dimensions of R&D problems and their simplicity in formulation and use.

Due to its relative simplicity and practicality, scoring has been widely adopted in practice. An example is the project selection method based on a scoring model developed for the Corporate R&D Division of a heavy electrical equipment manufacturer dealing with different types of research (Rengarajan and Jagannathan, 1997). Farrukh et al (2000) described the process of developing an in-company R&D project selection method based on a scoring model at British Aerospace.

Scoring methods can be made less subjective and more reliable with the introduction of appropriate techniques. A widely used technique is that of the AHP which helps decompose a complex decisional problem building a multi-layer hierarchical structure and improves the reliability of the subjective judgment of the decision makers. The Analytic Network Process (ANP), a general form of AHP, has also been proposed as a potentially valuable method to support the selection of R&D projects (Meade and Presley, 2002).

2.4.3 Fuzzy theory

The uncertainty of subjective judgment and the lack of complete and precise information during R&D project selection process make decision making difficult. The decision mechanism is also constrained by the uncertainty inherent in the determination of the relative importance of each attribute element. Fuzzy logic can be used to emulate the human reasoning process and make decisions based on vague or imprecise data (Machacha and Bhattacharya, 2000). Fuzzy theory can also be combined with other R&D project selection method. For example, Wang et al (2005) proposed a system for evaluating the outcomes of multidisciplinary R&D projects using a framework with a “vertical” AHP and “horizontal” fuzzy scoring.

2.4.4 Systems models

R&D project-selection has traditionally been modelled in the management science literature as a constrained optimization problem. Many researchers have criticised this classical “decision-event’’ approach which models R&D project selection as a constrained optimization problem and proposed changes to the philosophy underlying R&D project selection models (Schmidt and Freeland, 1992). They argue that models should be adapted to existing organisational processes and assist in coordinating decisions about selecting and monitoring a project portfolio. Project selection models should be used as decision aids to facilitate communication and provide insight into organisational processes. “Decision-process” or systems approach research emerged in the 1970’s in response to these proposed changes. This approach seeks insight into R&D project-selection models and focuses on facilitating the process of making project selection decisions rather than attempting to determine the decision. The models can be categorised into planning (adaptation) model, coordination model and transformation model. Most of the work on systems models has been fragmented and has focused on a wide range of issues. Few concrete results or methods are currently of direct use to practitioners (Schmidt and Freeland, 1992).

2.4.5 Real options theory

An investment in a real option conveys the right, but not the obligation, for a firm to make further investments or defer such investments (McGrath and Nerkar, 2004). Originally conceived as a model to consider a firm’s growth opportunities (Myers, 1977), real options theory has made unique contributions by providing a theoretical explanation for investment decisions that differ from the prescriptions of the NPV approach, and proposing that real options value may comprise a substantial portion of the economic value of projects, lines of business, and firms. Real options thinking has already made an impact on strategic management theory in the last decade through its ability to view investment opportunities as corporate real options. Tong and Reuer (2007) pointed out that two streams of real options research which emerged in the 1990's had focused on strategic management concerns with firms' strategic choices and their economic performance. One stream of research has investigated investment and divestment decisions as well as investment mode choices, including employing real options analysis to evaluate firms' investments under uncertainty and to model the optimal conditions for undertaking such investments. The other stream has focused on the organisational performance implications of creating and exercising real options. More recently, research has paid increasing attention to the competitive environment surrounding firms' investments and the strategic aspects of real options, which have important implications for competitive strategy (for example, Smit and Trigeorgis 2004). Research has also used real options theory to analyse investments in building strategic resources, such as R&D, and other corporate development activities, such as acquisitions and diversification, in the broader context of corporate strategy (for example, Bernardo and Chowdhry, 2002). Recent works in real options have considered issues such as agency and economic incentive problems, transaction costs, resources, capabilities and learning, and competitive structure and game-theoretic aspects of investment. Tong and Reuer (2007) provided an excellent review of these recent works. These extensions of real options build on critical differences between financial options and real options. For example, real options are created and exercised at the discretion of managers, and managerial decisions may be subject to agency and transaction costs problems. Similarly, managerial decisions are enabled and constrained by the resources and capabilities available to the organisation, and learning occurs in an adaptive, sequential investment process as well as across investment projects.

Finally, real options may not be proprietary but shared, and their economic value may be affected by endogenous competitive interactions. By incorporating these strategic issues into a real options framework, real options theory have not only been enriched but also brought closer to the heart of strategic management.

McGrath (1997, 1999) and McGrath and MacMillan (2000) used real options thinking to guide initiating or amplifying the impact of technology investments. As investments in physical assets, human competence, and organisational capabilities that provide the opportunity to respond to future contingent events (Kogut and Kulatilaka, 2001), real options could be viewed as flexibility options or growth options. The former gives a company the ability to change its plans in the future. Management can purchase the option to delay, expand, contract, switch uses, outsource or abandon projects. The latter gives a firm the ability to increase its future business. Examples include R&D, brand development, mergers and acquisitions, leasing or developing land, and launching a technology initiative.

2.4.5.1 Framing R&D as real options

Real options theory is a powerful valuation tool to evaluate and structure investments under uncertainty by visualising assets, decisions and cash flows as a stock option. Bowman and Hurry (1993) propose real options theory as an alternative valuation lens for technology and strategic investments under uncertainty. Real options valuation (ROV) has been advocated by researchers for use in R&D valuations as it better models the returns of R&D investments under uncertainties and considers the value of flexibility and opportunities. Lee and Paxson (2001) view the R&D process and ultimate discovery as sequential (compound) exchange options. R&D investments can be modelled as real options as these investments present the right - but not obligation - of commercialising the R&D output (Mitchell and Hamilton, 1988). The real options approach accommodates uncertainty with the recognition that learning which takes place during R&D provides ample opportunities to change course, and the knowledge with which to do so intelligently if it becomes necessary (Miller and Morris, 1999). If the decision is not to make the follow-up investment necessary to capitalise on the R&D programme, the loss is the cost of the programme which in general is smaller than the follow-up investments. When investing in an R&D option, a company commits to funding only the first iteration of the research process, instead of committing up front to fund an entire programme of research, development, manufacturing and marketing for a particular innovation. At the end of this stage, newly developed knowledge and understanding of the evolved conditions in the market will make it apparent whether to pursue further investment or drop the project. A second option continues the project to the next knowledge threshold, beyond which additional stages can also be undertaken if the results call for them. Committing a step at a time as new knowledge is developed enables future learning to be taken into considerations in the subsequent stages of decision making, as the search for new knowledge that is inherent in the innovation process will progressively impact on how we understand a problem, and even how we define it. Because uncertainty is reduced as the search progresses, progressively better decisions are possible. This approach also provides greater flexibility for projects that may show significant promise, but lack one or two vital components that are not yet available due to technological limitations. Such projects can be suspended until the missing technology is available rather than being scrapped altogether.

ROV have been applied to pharmaceutical research (Loch and Bode-Greuel, 2001) and R&D in the service sector (Jensen and Warren, 2001). Many major companies in the pharmaceutical and health care industries, including Merck and Eli Lily, have used ROV for their R&D decisions (Boer, 2002). Reiss (1998) also reported many cases of ROV applications in R&D investments.

In the literature on public R&D management, Piric and Reeve (1997) proposed that real options could be used in the evaluation of public R&D projects to provide (1) an analogy which will help in persuading investors of the value of R&D projects, or (2) numerical data as an alternative evaluation method. Vonortas and Hertzfeld (1998) highlighted that research administrators in public sectors have long used the value of technological options as a qualitative argument to support strategic, long-term research. This is the value of the opportunity (option) opened up by an early-stage R&D project to invest subsequently in a new technological area. Traditional methods based on estimates of future cash flows disregard the value of such opportunities, and the decision making based on these methods allocates less than optimal resources in strategic R&D. Vonortas and Hertzfeld (1998) proposed a real options approach to R&D project selection for a more proper accounting of the merits and drawbacks of highly uncertain R&D programs. By explicitly recognizing the choice to invest offered by earlier-stage R&D projects, this mechanism will greatly enhance the ability of decision makers to justify long-term R&D investments made by the public sector.

2.4.5.2 Boundaries of real options

Mitchell and Hamilton (1988) proposed that technical programmes are aimed at a wide range of strategic objectives. Most of the technical work involves development and engineering and is clearly directed toward a well-understood business investment and evaluated using capital budgeting methods such as Return of Investment (ROI). At the other end of the spectrum, much of the exploratory or fundamental work is clearly aimed toward knowledge building. The business impact is often poorly defined and wide ranging, and the most appropriate financial approach is to consider this R&D as a cost of doing business. An important segment of the technical work including applied research, exploratory development, and feasibility demonstration, is concerned with the technological transition, reducing technical uncertainties and building strong technical position to the point where the firm feels confident it can turn its technical strength into a profitable investment. The two prevailing funding models are not suitable as the expenditures are often too large to treat them as an overhead or cost of doing business yet the potential impact of the programmes is often still sufficiently uncertain to preclude meaningful ROI measurements. Mitchell and Hamilton (1988) argued that the R&D for strategic positioning must be recognised as the creation of an option as it is committing relatively modest R&D expenditures now to provide the opportunity to make a profitable investment at a later date.

Adner and Levinthal (2004) examined the boundaries along which real options logic is strained. As we move from a world of real options on tradable assets to real options on strategic opportunities, the clean demarcations between investment stages begin to blur and the application of real options becomes more challenging analytically and organizationally. In the former, the firm has no hand in resolving uncertainty and the set of possible actions in response to this uncertainty resolution can be specified at the time of the initial investment. In the latter, the outcomes of the real options could be intimately linked to the firm action.

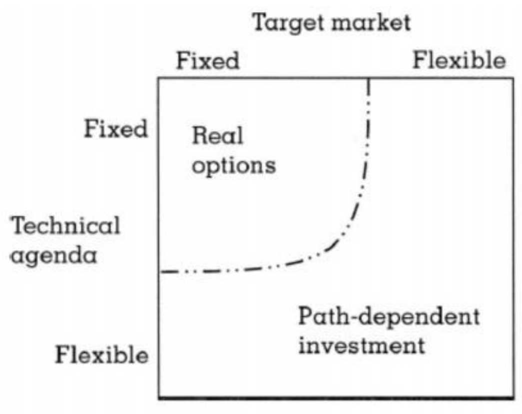


Fig 2.1. Boundaries of Applicability for Real Options and Path-Dependent Opportunities (Adner and Levinthal, 2004)

When target markets and technical agendas are flexible (see Figure 2.1), the discrete investment logic of real options is eroded, and activities may be characterized more appropriately as more generic path-dependent processes that fall under such labels as probe and learn (Lynn et al, 1996), incremental search (Nelson & Winter, 1982), or innovation journeys (Van de Ven et al, 1999). Alternatively, if the scope of the option investment is fixed a priori— that is, if the opportunities on which one is taking an option can be clearly specified at the inception of the option— then the decision to abandon an initiative can be clearly articulated and the flexibility associated with an option investment can be readily maintained.

MacMillan and McGrath (2002) proposed that R&D projects should be treated as one of three types of real options, depending on their degree of technical and market uncertainty. Positioning options are taken out to preserve a company's opportunity to compete in some future and still unclear technological arena. Scouting options are used to learn about the market by probing or offering prototypes to potential early adopters. Where market and technological uncertainty are high, stepping-stone options are created to systematically build both market insight and technical competence to move a company forward without exposure to potentially catastrophic downside risks.

2.4.5.3 Limits of classical real options valuation

The classical valuation approach for real options is founded on financial options valuation (for example, Dixit and Pindyck, 1994; Trigeorgis, 1998). This approach, however, is often criticised for its complexity and involves practical difficulties in (1) finding a model whose assumptions match those of the project being analysed, (2) determining the inputs to this model, and (3) being able to mathematically solve the option pricing algorithm (Lander and

Pinches, 1998). Bowman and Moskowitz (2001) note that many of the assumptions underlying financial option valuation models do not hold in the strategic contexts of resource development and deployment, where many of the explicit features of exchange-traded options are absent. The most frequently cited classical real option valuation method is probably the Black-Scholes (1973) model and the literature is filled with clean-cut applications of this model. The assumptions of the Black-Scholes model include (Hull, 2006):

1. The stock price follows the Ito process where percentage changes in the stock price in a short period of time are normally distributed and the volatility of the stock price can be observed from the market.

2. The short selling of securities with full use of proceeds is permitted.

3. There are no riskless arbitrage opportunities.

4. Security trading is continuous.

While widely used in financial options valuation, there is a growing body of evidence that the assumptions underlying the standard Black-Scholes model pose a few problems when applied to pricing options on many real assets (Bruun and Bason, 2001).

Kulatiliaka & Perotti (1998) pointed out that in the world of financial options, the holder of an option has the exclusive right to exercise that option, and exercise by one firm does not affect the exercise decision by other firms. The firm has, in other words, monopoly over the opportunity, and the market is perfectly competitive, since exercise by one firm will not affect the price of the underlying asset. However, in a real investment, for example an R&D

investment, the firm undertaking the investment is in effect purchasing an option on possible commercialization or further development, and competing firms can make similar investments. Thus, R&D success and exercise of the option by one firm will decrease the market value of the options held by the other firms.

The requirement for market prices of risk parameters for the stochastic variables in the Black-Scholes model also poses a few difficulties (Bruun and Bason, 2001). Angelis (2000) highlighted the difficulty in estimating the value of R&D projects, and suggested using predictions of revenue and cost. The model also ignores many of the complications associated with intangibles like intellectual capital (Sudarsanam et al, 2005). The pragmatism of direct use of financial option pricing for the very different real options is also questionable, due to the difficulty in the identification and estimation of several of the option parameters needed in the model. In particular, the estimation of volatility is very difficult since the underlying investment opportunities are not traded. Historical data is also frequently unavailable due to the exploratory nature of the activities. Compared with the financial market information, the analogous R&D information is less quantitative and frequently not expressed in financial terms. Piric and Reeve (1997) propose that alternative for those financial terms is a type of substitute in the form of different qualitative outcomes, e.g. “reasonable”, “optimistic” and “pessimistic” merits in assessment of outcomes.

Kogut and Kulatilaka (2001) conceded that modelling the risk profile of the value of the innovation based on quality adjusted prices is problematic because (1) the quality adjusted price is derived from a model of the industry pricing behaviour and can suffer from "modelling error", (2) may not perfectly track the value of the innovation and introduce a "tracking error", (3) not being a security price, the quality adjusted price can embed a convenience value that is not easily observed or estimated. For the arbitrage based valuation approach to work, the error components must be independent of each other and have no systematic risk. Kogut and Kulatilaka (2001) proposed using expert opinion to provide a superior method to form probability distributions of possible future market conditions for the new business in radically new landscapes.

Amram and Kulatilaka (1999), however, maintained that many of the difficulties with the Black-Scholes approach can be overcome using Monte Carlo simulation which is able to roll out thousands of possible paths of evolution of the underlying asset from the present to the option maturity or exercise date. The method can handle many aspects of real-world applications including complicated decision rules and complex relationships between the option value and the underlying asset. Simulation models can also solve path-dependent options, where the value of the options depends not only on the value of the underlying asset but also on the particular path followed by the asset. For example, investments in further customer relations initiative depend on the profitability of past customer relations. Amram and Kulatilaka (1999) also noted the growth in the number of instruments traded on financial market and suggest that, increasingly, a suitable source of volatility information can be identified.

In addition to the variations of the classical approach, two other valuation approaches for the flexibility inherent in a project have been developed more recently with different assumptions concerning the nature of the market with respect to real investment projects (Schneider et al, 2008). The integrated approach assumes partially complete market while the Marketed Asset Disclaimer (MAD) approach assumes incomplete market (Copeland and Antikarov, 2001). The MAD approach uses the present value of the underlying risk asset without flexibility as if it were a marketed security. In their proposed four step process for valuing real options, Copeland and Antikarov (2001) further assumed that properly anticipated prices (or cash flows) fluctuate randomly. The implication is that regardless of the pattern of cash flows that a project is expected to have, the changes in its present value will follow a random walk. This allows the combination of any number of uncertainties into a spreadsheet by using Monte Carlo simulation, and to produce an estimate of the present value of a project conditional on the set of random variables drawn from their underlying distributions. Thousands of iterations produce an estimate of the standard deviation of shareholder returns that is then used for the up and down movements in a binomial lattice. These two assumptions simplify the process of applying real options methodology in real-world settings, where the presence of more than two sources of uncertainty would have made analysis very difficult, by reducing many sources of uncertainty to only one.

Vonortas and Hertzfeld (1998) proposed a real options approach for public R&D programmes, which begin by differentiating the various stages in the programme and evaluating them in sequence. Each stage provides information (scientific and technological) for the next. In addition, the intervening time facilitates the collection of other information (for example, market) relevant to the appraisal of the program. It is the earlier, strategic R&D stages that have presented analytical difficulties for conventional financial methods of ex ante program appraisal. In their proposal to adopt real options for the evaluation of public R&D investments, Piric and Reeve (1997) noted that the real option approach is similar to a decision-tree approach, but the major difference is that real option uses an appropriate discount rate rather than an arbitrarily chosen discount rate. The crucial point is that the value ascribed to an option evolves with the time that is analogous to the R&D project implementation. Real options usually employ the statistical assumptions that are linked with random walk and Brownian motion. The advantages of real options are that no decision-tree analysis is required and a more comprehensive set of future options is covered, while the only key number that is required to delineate the set is the volatility. Volatility is the expected standard fluctuation of stock prices, which is based on previous experience in the respective field. The most used technique in estimating volatility is a time series linked to recent historic data. The option price can be calculated by using several factors: exercise price, stock price, constant-time at expiry, variable-time, risk-free interest rate and volatility. The risk-free interest rate is the rate on government bonds over the respective period, and since the public investment in R&D is committed by a government, the same rate should be applied. In the evaluation of R&D projects, the data should include the aggregates and timing of cash inputs and outputs and certain estimates for each project's extra value which is generated for the respective organisation. Data should be collected for a set of projects which at the beginning of each number of projects in this set should be large enough for a statistically useful curve of number of outcomes vs profit/loss to be obtained, generating estimates for the return and standard deviation in the usual way that is applied in financial analysis.

2.4.5.4 Systems engineering research

We have previously discussed the difficulties in handling non-financial returns and the realism of the assumptions made when applying a financial method for real options valuation. Some recent works in system engineering research, which have built upon existing work in various disciplines to develop methods to evaluate system flexibility, could be more suited for the generic valuation of the non-financial flexibility and value robustness generated in a defence R&D investment.

One approach is a stream of research which enhances practical tools from various disciplines for the valuation of the flexibility embedded in the real options within a system. For example, Cardin et al (2007) leveraged on the Value @ Risk (VaR) approach - more widely used in financial analysis for the robustness of an investment portfolio – for the valuation of system flexibility. The VaR is the loss in market value over a time horizon t that is exceeded with probability (1-p), where p is the confidence level. VaR is essentially a special type of downside risk measure. Instead of producing a single statistic or expressing absolute certainty, it makes a probabilistic estimate for the maximum expected loss over a specified time period with a given confidence level. Another example is Zhang et al (2008) who leveraged on Genetic Algorithm and Monte Carlo Simulation to develop an innovative approach to evaluate the real options embedded in a maritime system.

Neely and de Neufville (2001) developed a hybrid real options valuation approach to evaluate flexible projects. Decision analysis is popularly used to evaluate staged projects with risky and asymmetric returns as it deals effectively with multiple scenarios and management decisions to truncate specific lines of development. Project risks are unique to the project and can be guarded by diversifying investments so that unexpected losses in one project are compensated on average by unexpected gains in others. Project risks do not require a discount rate adjusted to reflect unavoidable risk. They can be properly analysed through an expected value decision analysis using a constant discount rate. This rate represents the return expected on investments that have no uncertainty. Market risks require a different treatment as they stem from external markets and cannot be avoided by diversification. Decision analysis cannot deal effectively with market risks over extended time. In practice, decision analysis assumes that the discount rate is the same over the entire life of the project, although discount rates should depend upon the relative risk associated with a situation. Only options analysis is equipped to treat these market risks properly and account for the constant variation in the level of risk as it changes through time based on the statistical measurement of historical risk associated with the underlying assets associated with the project, specifically on their performance in the market and their volatility compared to the overall market. However, this standard approach for valuing real options is generally inadequate for many new risky projects and products because the right data are not available. Decision analysis cannot deal with the fact that the discount rate ought to reflect the changing levels of risk over time, and options analysis requires data that are rarely available for major technological systems, especially for innovations for which there cannot be a meaningful historical record. Hence, Neely and de Neufville (2001) approach combined decision analysis for the project risks and options method for the market risks. This approach is illustrated in Fig 2.2. Options analysis is used to deal with the issue of constantly varying discount rates through "risk-neutral" valuation thereby adjusting the project outcomes so that the risk-free rate can be applied. This process requires detailed statistical information on the price and volatility of an asset that is closely related to the project or product at hand. The market risks, once the outcomes are adjusted to allow for risk-neutral valuation, are integrated with the project risks into the decision analysis.

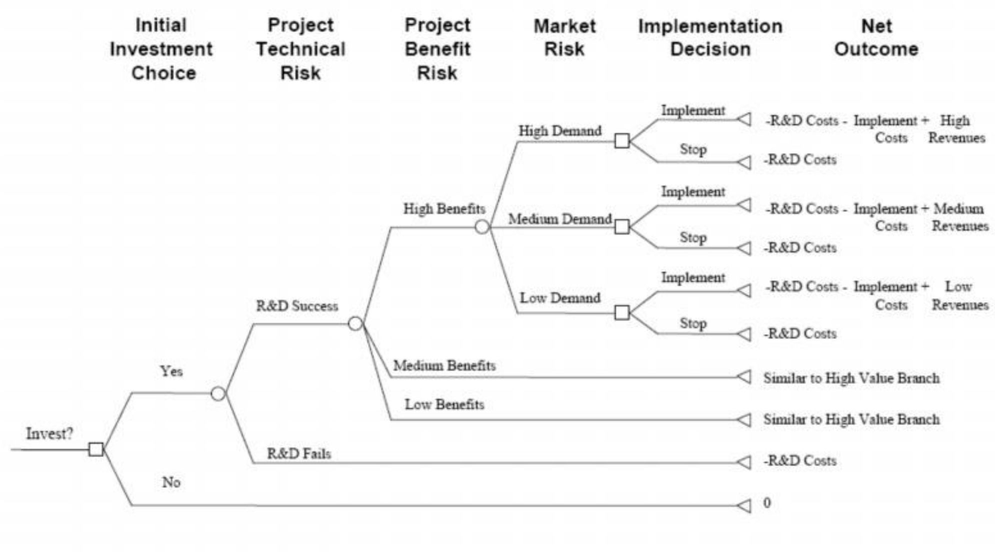


Fig 2.2. Hybrid real options valuation (Neely and de Neufville, 2001)

Another potentially powerful approach adopted in system engineering research is scoring method. These simple and practical methods can handle non-financial returns and avoid unrealistic assumptions such as the financial methods for real options valuation. Ross et al (2007) developed a metric approach to evaluate the flexibility of systems. Within a system development programme consisting of capital and R&D investments, the embedded flexibility (real option) enables one configuration of the system to evolve into another. For example, a real option embedded in system 1 can be exercised at a cost to enable the system to evolve to system 2, while another real option can be exercised at another cost to enable the system to evolve to system 3 (see Fig 2.3). The value of the real option, hence, is the difference between the value of switching from one system to another and the exercise cost of the option. The Filtered Outdegree (Ross and Rhodes, 2008) can be used to measure the flexibility of the real options embedded within a programme by the number of paths a system can evolve and the cost of exercising the options. As the number of paths increases or cost of exercise decreases, the flexibility within the system increases and the real option value increases. When considering a potential investment against other candidate investments, the utility value of the different projects can be computed and plotted. A Pareto frontier can be obtained from the plots. By varying the range of parameters, different values and plots for the projects and different Pareto frontiers can be obtained. The frequency of a project appearing on the range of Pareto frontier is its Pareto Trace Number (Ross et al, 2007.) This generic metric is a measure of the value robustness of the project.

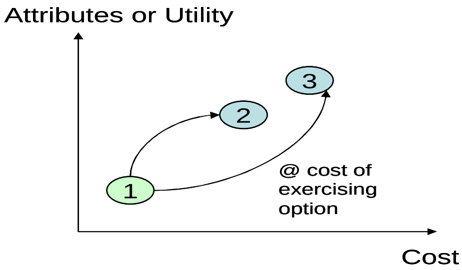


Fig. 2.3. Evolution of a system through exercise of embedded options.

The systems engineering approach to evaluate real options is a practical method which is able to handle the non-financial real options and value robustness generated in defence R&D investments and avoid the unrealistic assumptions of the financial methods for real options valuation. Monte Carlo simulation is able to roll out thousands of possible paths of evolution of the real options and the VaR approach can be used to estimate the returns of the options probabilistically. The scoring method is a simple and practical approach to evaluate defence R&D projects by giving each project a score reflecting how well it meets the defined multiple dimensional objectives on some scale. We propose building on these works possibly in a hybrid manner to develop a practical valuation approach to handle the non-financial real options and value robustness generated in defence R&D investments.

2.4.5.5 Applications of real options in defence management

In recent years, there has been widespread interest in applying real options in defence business management. Housel (2003) suggested that defence activities are comparable to capital market activities and proposed a real options analysis model to evaluate investment in joint forces planning. A framework to manage uncertainty in defence acquisition was proposed by Ceylan and Ford (2002). Glaros (2003) proposed the use of ROV method in evaluating defence businesses. More recently, Setter and Tishler (2005) proposed using the real options concept for investment policies in defence R&D programmes.

Current literature on real options modelling for R&D investments and defence business management generally does not offer suggestions on characterising defence R&D investments for modelling as real options. Rouse and Boff (2004) is an important exception. They suggested that defence R&D investments can be modelled as real options and proposed a real options methodology to valuate these investments. As ROV requires quantification of returns and "defence investments do not yield profits for the public that invests in these capabilities", they argued that the "investments yield desired military capabilities and effects" and proposed "[t]aking these desires as requirements or "givens"" to "characterize the returns on investing in a new technology in terms of potential cost savings in meeting given requirements within this technology". The modelling of real options as cost savings obtained by deferring the decision for acquisition is useful in valuation of investments in hardware assets. The direct application of this approach in R&D valuation, however, ignores some important elements of R&D investments. In addition to the value of an R&D investment to create the option to commercialise the R&D product, the R&D investment also creates capabilities as real options. This is the compound option to pursue further technological development, hence, creating the option to create more options. This is essentially an American sequential options (Lee and Paxson, 2003).

As discussed earlier in Chapter 1, capability development is a strategic consideration in defence R&D investments. In addition to delivering short term operational payoff, their investments frequently aim to develop indigenous technological capabilities and create the more upstream knowledge of the firm to mitigate risks in technology sourcing and gain a competitive advantage over their adversaries. This capability resides in the human capital created and generates the option to create more technology options. In particular, the human capital option is the lever of the small countries to gain a competitive advantage over its more resource rich competitors through technological innovation in the uncertain future. This is a compound option with the option to create technological options.

Using the framework of Macmillan and McGrath (2002) discussed in Section 2.4.5.2, the challenges in evaluation of real options in defence R&D investments can be summarised as follows in Table 2.3.

	Low application uncertainty	High application uncertainty
High tech Uncertainty	Positioning options to create “Modular innovation”. E.g. quantum leap in existing weapon systems performance. Evaluation is challenged by difficulty in estimating probability of successful R&D amidst high technological uncertainty.	Stepping-stone options to create “Radical innovations”. E.g. R&D investments in emerging breakthrough technology. Strategic investments in knowledge of the firm. Evaluation is very difficult due to high technological and operational uncertainties.
Low tech uncertainty	Enhancement & platform launches to create “Incremental innovation”. E.g. upgrading weapon systems. Uncertainty and corresponding real option value is low.	Scouting options to create “Architectural innovation”. E.g. fielding existing technologies in new doctrine of operation. Evaluation is difficult because of uncertainty in the evolving operational scenario.

Table 2.3. Challenges in evaluation of real options in defence R&D investments

2.5 Conclusion

Quantitative evaluation methods are apparently more objective for the evaluation of defence R&D investments. However, as seen in Sections 2.2 and 2.3, classical quantitative evaluation methods are inadequate in their consideration of organisational issues, project parameters, portfolio effect, and support for the innovation process. In particular, defence R&D investments are highly uncertain due to the unpredictable outcomes, costs and schedule inherent in the projects. Furthermore, the returns on investments are frequently strategic in nature and difficult to measure.

Systems models, which adopt a different philosophy from the classical approach, have also emerged. While these models could consider the holistic system properties, current models are unable to offer direct use to the practitioners. Recent development, such as real options theory, multi criteria decision making and fuzzy theory, attempts to address some of the shortcomings of the classical models. In particular, real option is a theoretically attractive model for R&D investment. We reviewed the literature on the evaluation of the real options embedded in R&D projects with highlights on (1) limitations in the classical real options valuation methods, (2) advances in the research of real options, and (3) prior work in framing and evaluating defence R&D investments as real options. There are on-going research on real options theory to improve the model and these areas include the validity of assumptions, implementation and portfolio effects. The improvements achieved in the recent development efforts are summarised in Table 2.4.

Criteria	Classical methods	Recent development
Consideration of the organisational issue	Inadequate generally.	Systems models consider systemic issues but the current models are unable to help the practitioners in project selection.
Treatment of project parameters	Inadequate generally.	Multicriteria decision model can consider multiple criteria and the time variance. Fuzzy approach can consider uncertainties in the input. Real options model can treat project risk and uncertainty, and time variance. Portfolio approach can be used to consider the interrelations.
Treatment of the portfolio effect	Inadequate generally.	Portfolio approach can be used to treat the portfolio effect.
Support for the innovation process	Innovation not considered.	Genetic algorithm can consider the innovation process.

Table 2.4. Comparison of existing and recent development in evaluation methods for R&D investments

An effective and objective approach is needed to evaluate defence R&D investments and support good decision making amidst uncertainties in the innovation process. The evaluation framework also needs to consider the strategic objective to guard against risk and uncertainty in the horizon and ensure value robustness of the R&D investment portfolio. The highlighted weaknesses point out the need for further research into alternate models specifically addressing these issues.

3. RESEARCH OBJECTIVE AND METHODLGY

3.1 Research objective

In Chapter 1, we presented the importance and challenges for effective and objective evaluation of defence R&D investments. In Chapter 2, we reviewed the strengths and weaknesses of existing evaluation methods and more recent works in evaluation methods. Quantitative evaluation methods are apparently more objective for the evaluation of defence R&D investments. However, existing methods have difficulties dealing with the uncertainties resulting from the unpredictable outcomes, costs and schedule inherent in defence research and development efforts. Furthermore, the return on investments are frequently strategic in nature and difficult to measure. The quantitative evaluation methods also neither consider the system sufficiently nor encourage innovations.

Fig 3.1 illustrates the phases in the lifecycle for weapon system acquisition development projects in the US Airforce, and the decision milestones regarding the selection and allocation of resources (Greiner et al, 2001). Similar processes are adopted in many other armed services. Within the Identify Needs and Opportunities phase, efforts focus on planning by identifying needs and requirements based on application (emerging threats, identified deficiencies, and changes in military strategy) or technological opportunities. Upon entry into the Define Development Project phase, a need or requirement has been identified and approved, and decision-makers are now concerned with assessing the feasibility of approving the project for entry into the next phase, the Development Process. It is during this phase that senior leadership must make decisions regarding the ability of a project to meet mission needs and the probability of project success, and weigh those factors against proposed development costs. They must then compare it with other projects competing for the same pool of limited resources.

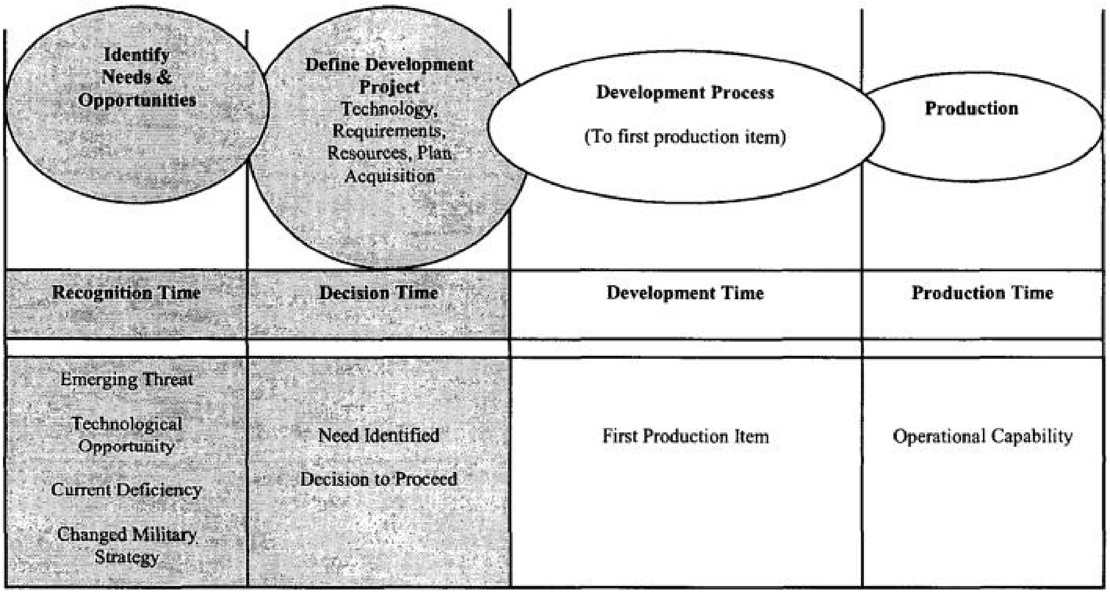


Fig 3.1. Critical Phases within Weapon Systems Acquisition Development (Greiner et al, 2001)

This project aims to develop an effective and objective approach to evaluate defence R&D investments and support good decision making amidst uncertainties in the innovation process using the following strategy:

1. Develop a theoretical framework for the dynamics of defence technological innovations, and upon this theoretical foundation

2. Develop an effective and objective evaluation framework for defence R&D investments, which considers the system and highly uncertain return on investments, and encourages innovations.

3.2 Theory building research methodology

Langley (1999) suggested that theory building involves three processes: (1) induction (data-driven generalization), (2) deduction (theory-driven hypothesis testing), and (3) inspiration (driven by creativity and insight).

Often in science, theory is developed through incremental empirical testing and extension (Kuhn, 1970). Thus, the theory building process relies on past literature and empirical observation or experience as well as on the insight of the theorist to build incrementally more powerful theories. In the research of process theory and dynamic phenomena, this approach can be adopted by formulating a priori process theories and testing them using coarse-grained longitudinal time series and event-history methods (Langley, 1999). The main advantage of the hypothesis-testing approach is that there is initial clarity about what is to be investigated and hence information can be collected speedily and efficiently. Clarity of method means that it is easier for another research to replicate the study, and hence any claims arising from the research can be subjected to public scrutiny.

Another approach is to plunge itself deeply into the processes themselves, collecting fine grained qualitative data and attempting to extract theory from the ground up (Langley, 1999). Eisenhardt (1989b) suggested that building theory from case study research has the following strengths: (1) generation of novel theory, (2) emergent theory is likely to be testable with constructs that be readily measured and hypotheses can be proven false, and (3) resultant theory is likely to be empirically valid. Building theory from case study research is particularly appropriate in introducing freshness in perspective to an already researched topic. Case study typically combines data collection methods such as archives, interviews, questionnaires, and observations. In particular, the grounded theory approach (Glaser and Strauss, 1967) develops theory through 'comparative method' by looking at the same event or process in different settings or situations.

Langley (1999) proposed that both inductive (data-driven) approaches and deductive (theory-driven) approaches can be used iteratively or simultaneously in theorizing from process data.

3.2.1 Assessment of theory building research

Pfeffer (1982) suggested that good theory is parsimonious, testable and logically coherent. Assessment of research also depends upon empirical issues especially strength of the method and the evidence grounding the theory (Eisenhardt, 1989b). Classical text books of methodology distinguish between three main kinds of validity: construct, internal and external validity (Easterby-Smith et al, 2001). Construct validity (or validity) asks whether the instruments are accurate measures of reality. Internal validity (or reliability) asks whether the research design is capable of eliminating the bias and the effect of extraneous variables. External validity (or generalizability) involves defining the domains to which the results of the study may be generalised. There should also be sufficient evidence for each construct to allow readers to make their own assessment of the fit with theory.

Yin (1994) demonstrated that case studies may contain the same degree of validity as more positivist studies. A key suggestion for dealing with construct validity is to use multiple sources of evidence. For internal validity, he stresses the importance of building cases over time in order to eliminate alternate explanations, and for external validity, he points out that case studies rely on analytic rather than statistical generalization.

3.2.2 Strategy for data analysis

Langley (1999) described and analysed seven strategies for the analysis of process data. She considers these strategies as generic approaches and categorises them as (1) grounding strategies (grounded theory and alternate template), (2) organizing strategies (narrative and visual mapping), and (3) replicating strategies (quantification, temporal bracketing, and synthetic). These strategies can be used in combination to produce better understanding of the data. For example, the grounding strategies can contribute to the construction of narratives and visual maps, as well as comparative analysis of cases in synthetic strategy. The organizing strategies can serve as intermediary databases for the identification of constructs (synthetic strategy), and for the formulation of hypotheses and propositions.

3.3 Proposed methodology

As discussed in Section 3.1, we aim to develop a theoretical framework for the dynamics of defence technological innovations and upon this theoretical foundation develop an effective and objective evaluation framework for defence R&D investments, which considers the system and highly uncertain return on investments, and encourages innovations. We would adopt a qualitative method in gathering data for the development effort of the theoretical framework. This approach allows triangulation, or the confirmation of findings through the convergence of multiple data, to take place. There is more than one method of triangulation. Triangulation can happen by data source (persons, times, places, etc.), by method (observations, interviews, etc.), by use of different researchers on the same subject, by theory and by data type (texts, numbers, etc.) (Miles and Huberman 1994). In this project, the following combination of strategies would be adopted to better understand the defence technological innovation process.

3.3.1 Case study

Theory building approach founded on case study research would be leveraged to view the already researched topic of defence technological innovations through a fresh lens. Strauss (1987) recommended familiarising with the prior research and aware of previous work conducted in the general field of research before starting to generate one’s own theory. Eisenhardt (1989b) proposed a framework for building theory from case study research and introduces innovative ideas such as a priori specification of constructs (please see Table 3.1). Prior research in the dynamics of technological innovations, especially defence technological innovation, would help formulate a priori specification of constructs to help shape the initial design of research and measure constructs more accurately.

Ross (1993) proposed studying the dynamics of military technology in the context of broader work on technology dynamics to counter the insular tendencies of international security analysis. Drawing on the analysis of the dynamics of non-military technologies, even basic conceptualisation of the nature of technology, is fundamental to this linkage. Military technology is but one form of technology. Military technological change, therefore, should be placed in the context of broader technological change and the development of military technology should be examined in the context of the development of other technologies. Inquiry focused on these linkages will not only aid in efforts to explain historical patterns and dynamics, but also better enable analysts to anticipate future patterns and dynamics of military technology.

Steps	Activity	Reasons
Getting started	• Definition of research question • Possibly a priori constructs • Neither theory nor hypotheses	• Focuses efforts • Provides better grounding • Retains theoretical flexibility
Selecting cases	• Specified population • Theoretical, not random, sampling	• Constrains extraneous variation and sharpens external validity • Focuses effort on theoretically useful cases
Crafting instruments and protocols	• Multiple data collection methods • Qualitative and quantitative data combined • Multiple investigators	• Strengthens theory by triangulation of evidence • Synergistic view of evidence • Fosters divergent perspectives and strengthens grounding
Entering the field	• Overlap data collection and analysis • Flexible and opportunistic data collection methods	• Speeds analyses and reveals helpful adjustments to data collection • Take advantage of emergent themes and unique case features
Analysing data	• Within-case analysis • Cross-case pattern search using divergent techniques, e.g. (1) select categories or dimensions, then look for within-group similarities coupled with intergroup differences, (2) use a 2x2 or other cell design to compare several categories at once	• Gains familiarity with data and preliminary theory generation • Look beyond initial impression and see evidence thru multiple lenses
Shaping hypotheses	• Iterative tabulation of evidence for each construct • Replication, not sampling, logic across cases • Search evidence for 'why' behind relationships	• Sharpens construct definition, validity, and measurability • Confirms, extends, and sharpens theory • Builds internal validity
Enfolding literature	• Comparisons with conflicting literature • Comparisons with similar literature	• Builds internal validity, raises theoretical level, and sharpens construction definitions • Sharpens generalizability, improves construct definition, and raises theoretical level
Reaching closure	• Theoretical saturation when possible	• Ends process when marginal improvement becomes small

Table 3.1. Process of building theory from case study research (adapted from Eisenhardt, 1989)

We would combine the use of archival data and observation in the data collection for the longitudinal case studies in major historical defence innovations. This would be used to gain fresh insight into these well documented defence technological innovations in the next chapter. More contemporary defence innovations in Singapore would be subsequently studied using archival data and observation. These latter case studies are reported in Chapter 7 and used as a contemporary comparison for the emergent framework. Each case would be written up for within-case analysis to gain familiarity with data and preliminary theory generation. As suggested by Eisenhardt (1989b), these descriptions are central to the generation of insight because they help researchers cope early in the analysis process with the often enormous volume of data.

The use of archival data and observation in data collection has been well established in the literature. For example, Tushman and Anderson (1986) used existing archival sources in their study of the industries of domestic scheduled passenger airline transport, Portland cement manufacture and minicomputer manufacture. The sources include books which chronicle the history of the industries as well as industry directories, trade journals and product listings. Henderson and Clark (1990) used interview data, published product literature and scientific press in their construction of the technical history of the semiconductor photolithographic alignment equipment industry. The constructed technical history was circulated to key individuals who had a detailed knowledge of the technical history of the industry, who corrected it as appropriate. To ensure accuracy of the cases, our constructed cases of defence technological innovations would be similarly reviewed by technology managers in the Defence Science & technology Agency (DSTA), Singapore, who are knowledgeable in defence technological innovations.

3.3.2 Visual mapping strategy

The dynamics of defence technological innovations in our case studies would be mapped. Graphical and matrix form allows the simultaneous representation of a multiple dimensions, and can be used to show precedence, parallel processes, and the passage of time (Miles and Huberman, 1994).

3.3.3 Synthetic strategy

The process of defence technological innovation would be taken as a whole as a unit of analysis and global measure constructed from the descriptive data. These measures could be used to compare different processes of defence technological innovation. An example is Eisenhardt (1989a) who compared 8 cases of decision-making in high-velocity environments. Similarly, 9 cases of historical important defence technological innovations and 3 cases of contemporary defence technological innovations in Singapore would be compared in our project to ensure sufficient cases to allow satisfactory comparison and conclusion drawing.

The theoretical framework which emerges with the data analysis of defence technological innovations would be compared with the extant literature. Through comparison with the literature in technology management and defence management, the theory building can be improved along with the corresponding validity, theoretical level, and construction definitions. The developmental effort for an effective and objective evaluation framework for defence R&D investments and application to defence R&D strategic heuristic would build upon this theoretical framework as well as past literature and empirical observation or experience. The real options theory is a theoretically attractive model for defence R&D investments but the appropriateness and boundaries of the model and suitability of the valuation method is contingent on the nature of the investment. We would develop an evaluation methodology which considers the defence R&D investment and advise the appropriate model and suitable evaluation method. Scoring method is a very popular evaluation method due to its practical means and simplicity in formulation. However, it lacks consideration of risk and uncertainty. We would improve the scoring method by adopting the real options approach to consider project risk and environmental uncertainty.

4. CASE STUDIES

We begin our case study research with a review of the literature in the dynamics of defence technological innovation, technology and new product development, and technology maturity to help define the a priori specification of constructs. This would help to focus our effort and provide better grounding. Neither theory nor hypotheses would be formulated at this point to retain theoretical flexibility. The data selected for the case studies are several of the most important defence technological innovations (van Crevald, 1989; Perry, 2004). These case studies in the submarine, aircraft, tank, rocket, radar, nuclear bomb, jet engine and strategic missiles, are selected for their significance and their exhibition of both discontinuous and continuous technological changes over time. The sources for the data include books which chronicle the history of these innovations, scientific press, and other literature on these innovations.

4.1 Dynamics of defence technological innovation

Strategic management literature has long sought to understand the dynamics of technological development and suggests that innovation can be driven by the external requirements of the market (Schmookler, 1966), as well as by the activities and internal capabilities of firms (Dosi, 1982).

The development of technology in the defence realm can happen in different ways (White, 2005). A discovery may stem from a single, inspired idea prompted by a random occurrence in the turmoil of battle. The development of this idea may then follow a torturous path. An alternative route begins with a piece of open research conducted in universities or commercial centres which attracts the attention of the military which then provide the resources for an accelerated development programme. The end result is then used in military applications.

In defence management research, two conceptual models have been used to explain the emergence of new technologies (Ross, 1993). The first model, variously known as discovery-push, autonomous technology or technology push in the literature, emphasises the central role of basic research, the relative autonomy of the technology development process, and the likelihood that the process will yield unexpected results. The second model has been termed demand pull, command technology, requirements pull or user pull in the literature. This model stresses 'the specific need that exists to be filled' (Szyliowicz, 1981) and 'the determinative role of intentions in technological evolution' (Kincade, 1987). These two models are summarised in Table 4.1.

Szyliowicz (1981) noted that discovery-push creates its own demand in the market, while demand-pull responds to market demands. The latter tends to yield incremental, or evolutionary technological advances, rather than non-incremental, revolutionary, or what he terms 'breakthrough', advances that tend to be the result of the discovery-push process. Demand-pull, then, can generally be associated with technological continuity, and discovery-push with technological discontinuity. In the literature on the impact of technology on the contemporary conduct and preparations for war, nuclear weapons and selected advances in non-nuclear weapons technology, especially precision-guided munitions (PGMs), are frequently viewed as revolutionary in nature. On the other hand, much of the literature on post-World War II technological developments tends to underscore the incremental, evolutionary nature of military technological change (Ross, 1993).

Characteristics of development process	Szyliowicz (1981)	Kincade (1987)	Cooper and Shaker (1988)	Holland (1997)
Emphasises central role of basic research, the relative autonomy of the technology development process, and the likelihood that the process will yield unexpected results	Discovery-push	Autonomous technology	Technology push	Technology push
Stresses 'specific need that exists to be filled' and 'the determinative role of intentions in technological evolution	Demand-pull	Command technology	Requirements-pull	User pull

Table 4.1. Conceptual models for the emergence of new defence technologies

Discovery-push and demand-pull should be viewed as complementary rather than mutually exclusive process. One need not rule out or negate the other. The two processes may also operate simultaneously, though it would be difficult to integrate them effectively. A country's armed forces, or specific services, may draw on discovery-push and demand-pull concurrently (Ross, 1990). Cooper and Shake (1988) argue in a brief analysis that in the United States, the Air Force tends to emphasise discovery-push, the Army relies primarily on demand-pull, and the Navy has shifted an earlier emphasis on demand-pull to a more recent emphasis on discovery-push.

4.1.1 Discussion

Strategic management literature suggests that innovations can be driven by external requirements or internal capabilities. Defence management research similarly proposes that defence R&D investments can be driven by discovery-push or demand-pull. The distinctiveness of the discovery-push or demand-pull processes is widely appreciated, as are their respective implications for the autonomy and mastery of technological innovation. However, the analytical potential of these models has not yet been fully exploited (Ross, 1993). Ross (1993) suggested that matrices could be constructed to prompt investigations of relationships among different dimensions and the questions generated by such juxtapositions could serve as a useful starting point for synthesizing work on the multiple dimensions of the dynamics of defence technology.

Our case study research would consider the dynamics of several defence technological innovations variedly driven by discovery-push or demand-pull. These traditional views are static. We would consider the innovation dynamics in our case studies by juxtaposing against the additional dimension of time to prompt further investigation as proposed by Ross (1993). We would map the innovation path of each defence technological innovation as progress is made over each of the two dimensions of demand (i.e. clarity of defence application) and technology (i.e. maturity of technology) over time.

In the former, the demand for a defence application may be latent or even non-existent at the outset. For example, caterpillar tractors had been used in the military as a means of hauling cargo or pulling very large artillery pieces but few people were struck by the idea of arming caterpillar tractors before World War I (Humble, 1977; Ogorkiewicz, 1991). During the war, the opposing armies were held to a deadlock as the traditional infantry attacks had become difficult due to increasingly effective firepower and extensive use of entrenchment and barbed wire deployed in defence. Consequently, the potential application for armoured assault vehicles, which would crush the barbed wire and whose protection would enable them to approach enemy trenches under machine-gun fire, was defined. Hence, the process for clarifying the need for a defence application could be highly uncertain where the outcomes were random but governed by an unknown probability model. On the other hand, the outcomes in the technological dimension were unknown but generally governed by probability distributions known at the outset. For example, by the late 1950s, aircraft designers realized that very large Radar Cross Section (RCS) reductions to avoid aircraft detection by radar would not be accomplished simply by coating an otherwise conventional aircraft with Radar Absorbent Material (RAM) (Aronstein and Piccirillo, 1997). From the 1950s onward, efforts were made to incorporate stealth elements into various new aircraft designs and research was actively pursued on various aspects of RCS reduction. By the early 1970s, a variety of materials had been developed and characterized, and specific purposes such as reducing specular reflections (reflections normal to the surface) had been identified.

Breakthroughs in the ability to design low observable aircraft appeared were achieved by 1975, and the US Air Force issued a contract in 1976 to Lockheed Advanced Development Projects to produce and flight test two low RCS technology demonstrator aircraft which eventually formed the prototype to the world's first stealth operational aircraft.

In this thesis, we labelled the unknowns in the technology and application dimensions as "Uncertainty". It is important to note that the unknowns in the technology and application dimension may be termed "Risk" and "Uncertainty", respectively, if one follows Knight's (1921) distinction between risk and uncertainty. Uncertainties are things that are not known, or known only imprecisely (McMauns and Hasting, 2005). Many Uncertainties are measurable but some are not (e.g. future events). They are value neutral and not necessarily bad. Uncertainties lead to Risks or Opportunities. Risks are pathologies created by the uncertainties that are specific to the program in question (McManus and Hastings, 2005). In addition to technical failure, other risks such as cost and schedule need to be considered. Risk has a negative connotation, but uncertainty may also create positive opportunity. In the example of the low observable aircraft, the technology risk is an uncertain realization from a well-specified probability distribution, and decision making rules can be applied in consideration of an estimation of the risk. In contrast, in the example of the armoured assault vehicle, the demand for this vehicle was an inherent unknowability that characterizes Knightian uncertainty. This Uncertainty in the application dimension poses a significant challenge for probabilistic model and characterising key parameters such as means and variances. De Weck and Eckert (2007) proposed that sources of Uncertainty could be endogenous or exogenous. The former could arise from product and corporate contexts, while the latter could arise from user, market and political and cultural contexts. In particular, uncertainties arising from the political and cultural context include great changes in political and cultural trends, such as the changing nature of warfare. An example is the challenge faced by the US troops to maintain readiness rates on key combat systems such as the M1 Abrams tank in Iraq (de Weck and Eckert, 2007). For M-1 Abrams tanks combat readiness had declined to 78% instead of 90%., in part because they were driven 3000 to 4000 miles a year, 5 times their use when used at their home bases for training. The M1 Abrams tank was developed in the 1980s, when the cold war was still raging and the main theatre of war was expected to be central Europe with a moderate climate. Due to the unanticipated use in the Middle East, sand clogged up the mechanisms and parts failed much earlier than expected. Unexpected military use upset the availability of spare parts and the profitability of service contracts.

4.2 Clarity of defence application

The clarity of application can be defined using constructs developed in the New Product Development (NPD) and Technology Development (TD) literature.

The Fuzzy Front End is the portion of the NPD cycle between when work on a new idea could start and when it actually starts (Reinertsen, 1999). Khurana and Rosenthal (1997) proposed that the front end processes comprise the phases illustrated in Fig 4.1. In the Pre-Phase Zero, companies generally begin work on new product opportunities when they first realise, in a semi informal way, an opportunity. If the newly defined opportunity is worth exploring, the company assigns a small group to work on the product concept and definition in Phase Zero. In Phase One, the company assesses the business and technical feasibility of the new product, confirms the product definition, and plans the NPD project. Thus the development team identifies the new product, its development, and the business rationale for proceeding. The front end is complete at the end of this phase when the business team presents the business case and the business unit either commits to the funding, staffing and launch of the project or kills the project.

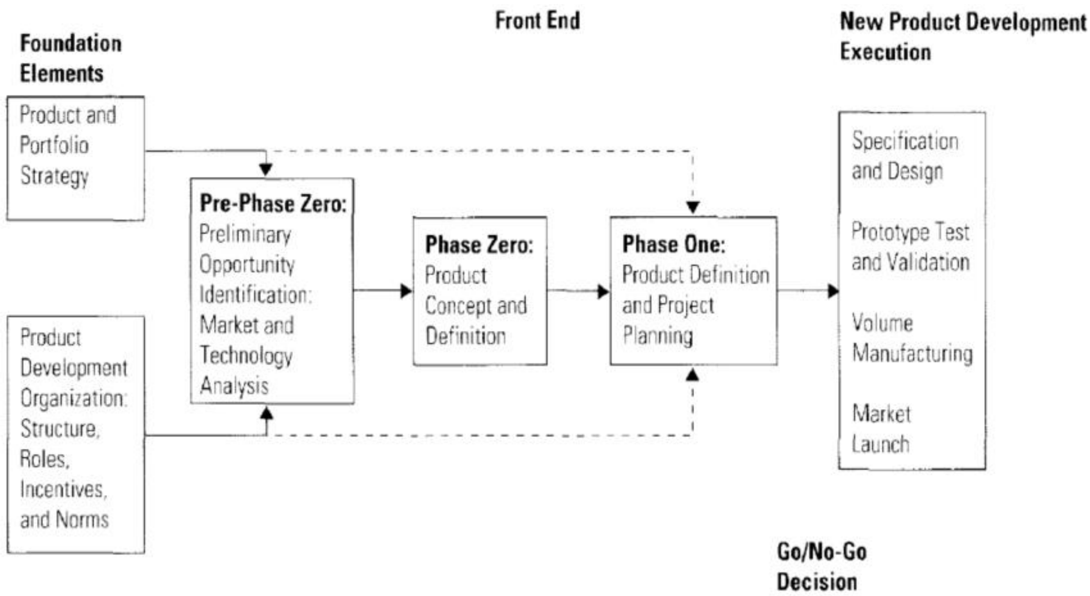


Fig 4.1. A model of the New Product Development Front End Process (from Khurana and Rosenthal, 1997).

Cooper (2006) argued that TD projects are different from other development projects. They are fragile and need to be managed by non-traditional techniques. The typical TD process which has been adopted by leading companies conducting fundamental research is illustrated in Fig 4.2. The trigger for this staged-gated process is the first stage, involving Discovery or idea generation. The purpose of the subsequent Scoping stage is to build the foundation of the research project, define the scope of the project, and map the forward plan. During the Technical Assessment stage, the technical or laboratory feasibility of the idea is demonstrated under ideal conditions. In the Detailed Investigation stage, the full experimental plan to prove the technological feasibility and define the scope of the technology and its value to the company is implemented.

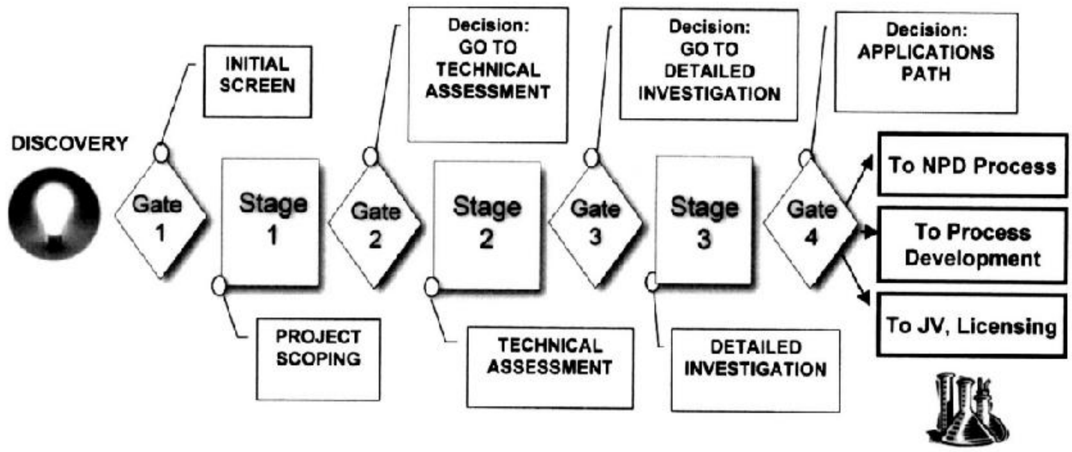


Fig 4.2. Typical Technology Development process (Cooper, 2006)

4.3 Maturity of technology

Technology maturity can be defined using the Technology Readiness Level (TRL) framework used by the United States government agencies and many of the world's major companies and agencies to assess the maturity of evolving technologies prior to incorporating that technology into a system or subsystem. The most common definitions are those used by the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA) in the United States. These frameworks are described in Annex C and the TRL are summarised in Table 4.2. Recent studies and reports on the acquisition process have found that ensuring sufficient technology maturity levels, supported by adequate test and evaluation and manufacturing assessment, is an excellent way to reduce technology risk in acquisition programmes (DoD, 2009).

Technology Readiness Level (TRL)	
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 (ground or space)
7	System prototype demonstration in a space environment
8	Actual system completed and 'flight qualified' through test and demonstration (ground or space)
9	Actual system 'flight proven' through successful mission operations

Table 4.2. Technology Readiness Levels (Mankins, 1995)

4.4 Case studies

Archival data and observation are used in the data collection for the longitudinal case studies of major historical defence innovations to gain fresh insight in well documented defence technological innovations. A brief description of these cases is summarised in Table 4.3.

S/n	Case study	Description and sources	Examples of sources
C1	Submarine	Development of vessels to navigate and attack from beneath the water surface.	Clancy (1993), Volkman (2002), US Navy (2011)
C2	Rocket	Development of propelled munitions to hit targets at large distances.	Hambling (2005), Volkman (2002), NASA (2011)
C3	Tank	Development of a motorised all-terrain armoured vehicle for overland attack.	Gudmundsson (2004), Humble, (1977), Ogorkiewicz (1991)
C4	Radar	Development of a remote detection system for aircrafts.	Hambling (2005), Volkman (2002), RAF (2011)
C5	Nuclear bomb	Development of a bomb to capture the powerful forces of the atom.	Siracusa (2008), Delgado (2009), FDR (2011)
C6	Military aircraft	Evolutionary development of the flying machine for various military applications.	Higham (1972), Glancey (2006)
C7	Jet engine	Development of a powerful engine for the aircraft.	Hambling (2005), Scranton (2006), Glancey (2006)
C8	Ballistic missiles	Development of ballistic munitions to hit targets at very large (e.g. intercontinental) distances.	Hacker (2005), Hacker (2006), NASA (2011)
C9	Stealth	Development of technology to avoid remote detection of aircraft.	Aronstein and Piccirillo (1997), Matricardi (2007), FAS (2011)

Table 4.3. Brief description of case studies.

The sources for the data include (1) books which chronicled the history of these innovations, for example Aronstein and Piccirillo (1997) which chronicled the development of the first stealth fighter, (2) scientific press, for example the textbook by Ogorkiewicz (1991) on tank technology, and (3) other published literature on weapons technology, for example, Black (2007), Cook and Stevenson (1980), Dupuy (1990), Macksey (1986), and Perry (2004). To cope early in the analysis process with the enormous volume of data, each case is written up for within-case analysis to gain familiarity with data and preliminary theory generation. For each case, the innovation path is mapped as progress is made over each of the two dimensions of demand (i.e. clarity of defence application) and technology (i.e. maturity of technology) over time. This graphical form allows the simultaneous representation of multiple dimensions, and can be used to show precedence, parallel processes, and the passage of time. To ensure accuracy of the constructed cases of defence technological innovations, the cases have been reviewed by several technology managers who are knowledgeable in defence technological innovations, including the Deputy Chief Executive (Strategic Development) and Director (Defence Masterplanning and System Architect) of the Defence Science & Technology Agency (DSTA), Singapore. The defence technological innovation case studies are summarised in Fig 4.3 to 4.5. The write up of the case studies is attached in Annex A.

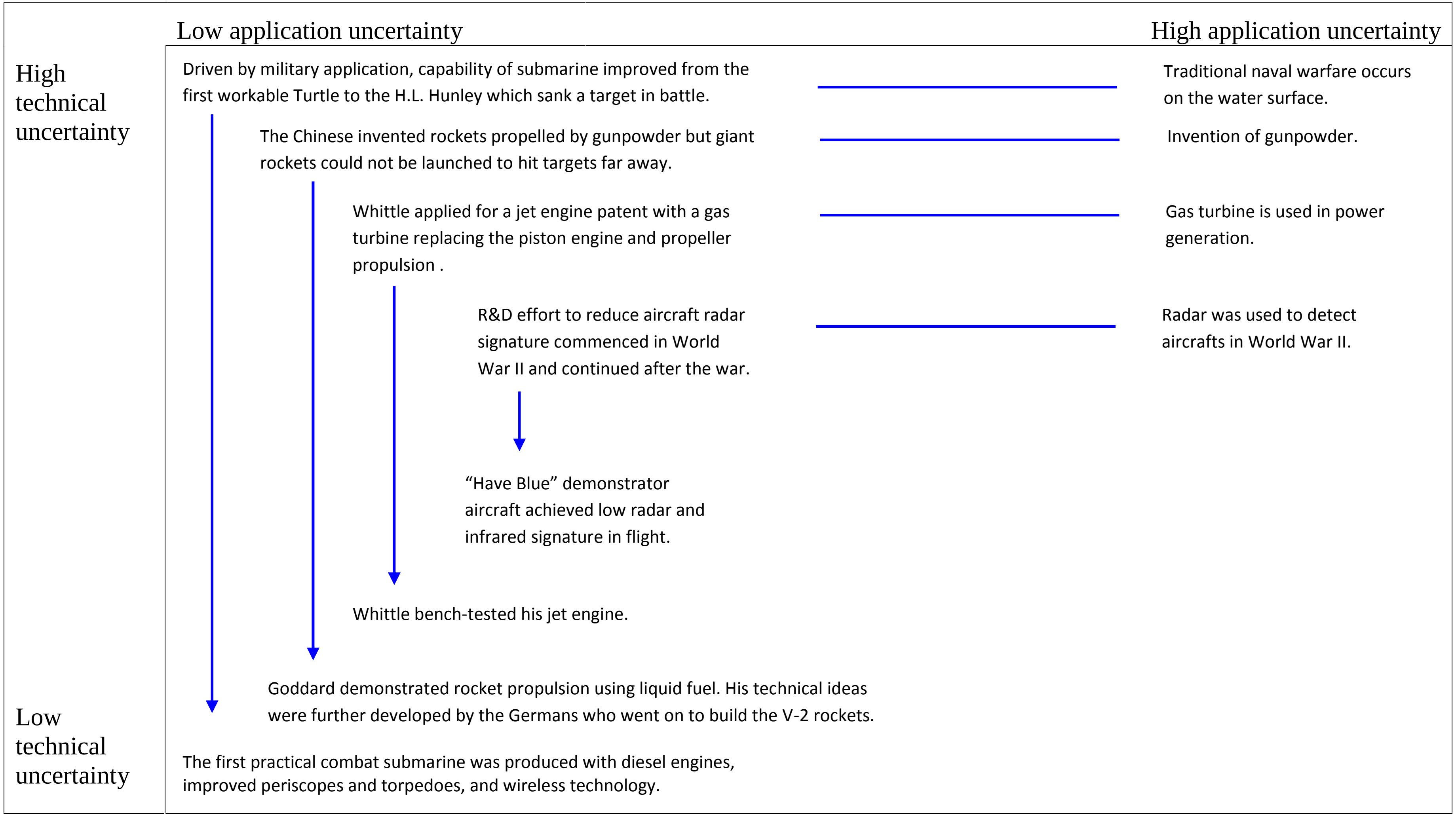


Fig 4.3. Defence technological innovations: submarine, rocket, jet engine and stealth

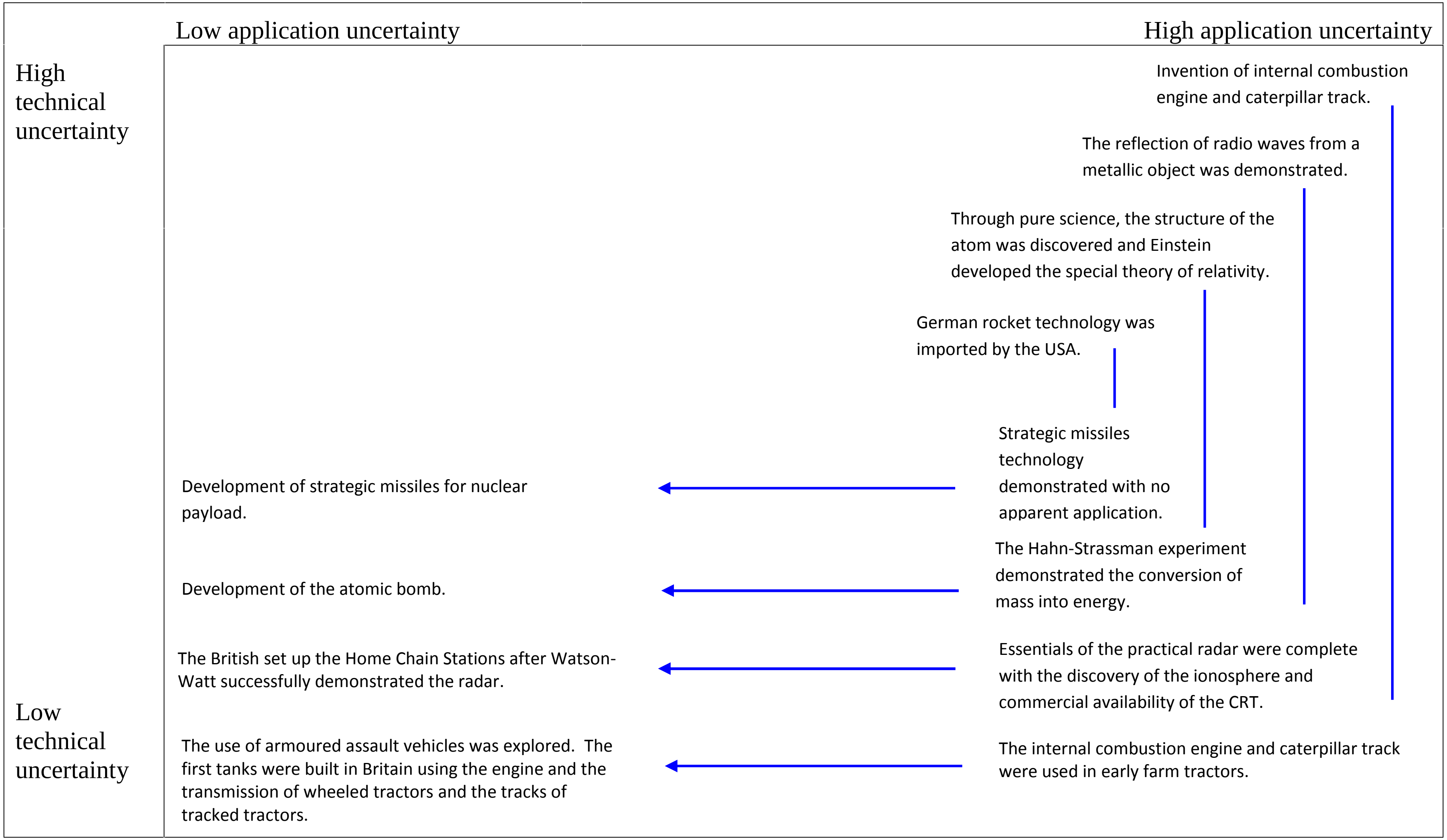


Fig 4.4. Defence technological innovations: tank, radar, nuclear bomb and strategic missiles

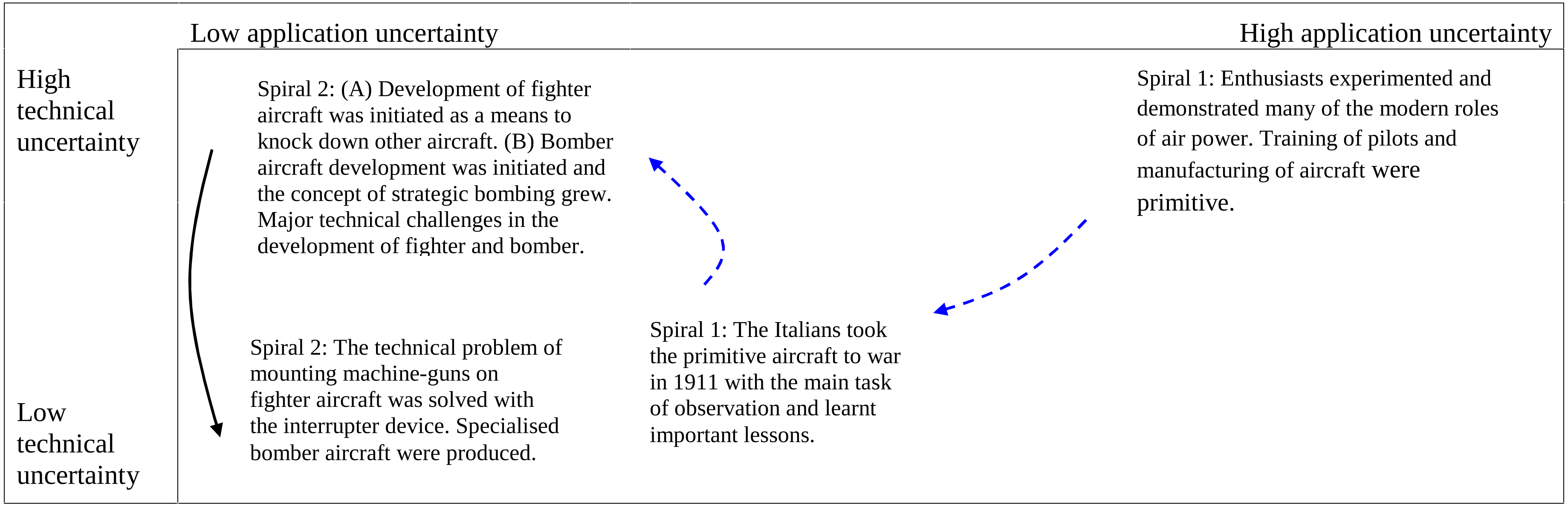


Fig 4.5. Spiral defence technological innovation: military aircraft

From Section 4.2, we have seen that the generation of idea initiates the Front End of the NPD and TD processes which in turn clarifies the case for a new product or technology. Hence, idea generation is an important milestone in the demand dimension (i.e. clarity of defence application) of defence technological innovation. For the other dimension of technology (i.e. maturity of technology), we have discussed in Section 4.3 that technological maturity can be measured by the TRL framework. Where technology development had started prior to clear definition of application, the technology could be relatively matured and at a higher TRL by the time the idea for its application is generated. In technology development initiated with the genesis of an idea, the technology could be relatively less mature and at a lower TRL. These constructs for each of the defence technological innovation case studies are summarised in Table 4.4.

Technology	Spiral	Technology development started prior to clear application	Application defined prior to technology development	Maturity of technology when idea is generated
Submarine			X	TRL1
Rocket			X	TRL1
Tank		X		TRL4
Radar		X		TRL4
Nuclear bomb		X		TRL4
Military aircraft	1	X		TRL7
	2		X	TRL2
Jet engine			X	TRL2
Ballistic missiles		X		TRL4
Stealth			X	TRL2

Table 4.4. Summary of case studies analysis

4.5 Emergent framework for Defence R&D Innovations

Strategic management literature suggests that innovations can be driven by external requirements or internal capabilities. Defence management research similarly proposes that defence R&D investments can be driven by discovery-push or demand-pull. We studied several historically significant defence technological innovations which exhibit discontinuous and continuous military technological changes over time. The innovations are variedly driven by discovery-push or demand-pull, and juxtaposed against the time dimension in our analysis. The data was analysed using a combination of strategies for data analysis: (1) “grounded theory” was used to help construct (2) visual maps, as well as comparative analysis of cases for (3) synthetic strategy. The visual mapping helps in the identification of application uncertainty and technological uncertainty as constructs which are compared across the cases under the synthetic strategy.

From Fig 4.3-4.5, there appears to be three different types of innovation. In defence technological innovation driven by discovery-push, technological capabilities were created with the development and maturing of technology. These capabilities created technological options which could be further developed into field application once the application was identified. In demand-pull defence technological innovation, application definition preceded and drove the development of supporting technological capability. With maturity, the technology could be inserted into a field application. Sometimes, with the fielding of an application, the need for a new application could be discovered, hence, driving the development of new supporting technological capability. This creates a spiral development. A simplified visual mapping of these different types of innovation is presented in Fig 4.6.

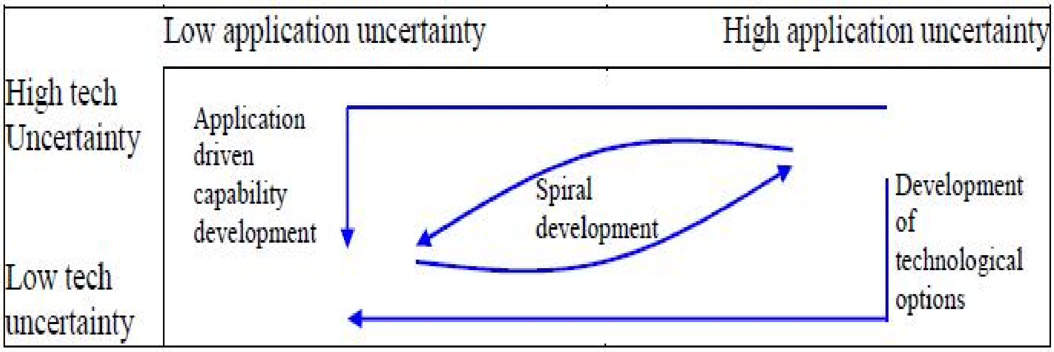


Fig 4.6. Emergent framework for defence R&D innovations

5. DISCUSSION OF THE EMERGING FRAMEWORK: COMPARISON WITH THE EXTANT LITERATURE

As discussed in our research strategy (Section 3.3), the framework which emerges with the data analysis would be compared with the extant literature. Through comparison with the literature in strategic, technology and defence management, the theory building can be improved along with the corresponding validity, theoretical level, and construction definitions.

From our preliminary literature review in Chapter 2 and our case studies in Chapter 4, an emergent framework for the dynamics of defence technological innovations had emerged. Innovations are created by capabilities which could be built on (1) technological pursuit and subsequent identification of military applications or (2) technology development initiated by military demand. In this chapter, we review the extant literature on the dynamics of technological innovations and capability development to compare with and sharpen our emergent framework. In particular, we discuss adopting the real options lens, the appropriateness of which as a model for defence R&D investments had been observed in Section 2.4.6. In this chapter, we review the strategic flexibility created by defence R&D investments in building a value robust portfolio of real options in capability options and human capital amidst environmental and technological uncertainties.

5.1 Capabilities and innovation

As innovations can be driven by external requirements or internal capabilities, the creation of capabilities is crucial in an R&D investment. By the term capability, we refer to a firm's capacity to deploy its resources, tangible or intangible, to perform a coordinated task or activity in an effort to achieve a performance outcome (Maritan and Alessandri, 2007). Besides the goal of developing particular technologies to meet expected market applications in the foreseeable future, the strategic objective of R&D investments is to develop firm-specific capabilities (Helfat, 1994) and the means to sustain competitive advantage for the long and uncertain term (Clarke and Pitt (1996), Cohen and Levinthal (1989), Kogut and Kulatilaka (2001)). The capabilities developed through R&D investments enable firms to produce incremental innovation and create technological variation or adopt technological change quickly to move with the unpredictable technological discontinuities which punctuate the technological life cycle (Tushman and Anderson, 1986). For example, R&D capability reflects a firm's strength in discovery and innovation and enables it to value, assimilate and exploit new knowledge (Cohen and Levinthal, 1989). Practitioners such as Andrew and Sirkin (2006) also recognise knowledge acquisition as an indirect benefit of innovation. The strategic importance of the development of indigenous defence technological capabilities in defence R&D investments has also been highlighted (Jan, 2003; DoD, 2009; Straits Times, 2011d and 2011f).

Strategic management literature proposes that firms' strategies are strongly influenced by their current position and by the specific opportunities open to them in future. This path dependence is due to constraints in (1) the present and likely future state of technological knowledge, and (2) the limits of corporate competence (Tidd et al, 2005). Pure technological development has its own internal logic, which helps to define where firms will find innovative opportunities. Present state of knowledge may not enable innovation to be done. Specific firms are also constrained by their capability of learning and exploiting. Innovation requires improvements and changes in the operation of complex technical and organisational systems. This involves trial, error and learning. Learning tends to be incremental, since major step changes in too many parameters both increase uncertainty and reduce the capacity to learn. As a consequence, firms' learning processes are path-dependent, with the directions of search strongly conditioned by the competencies accumulated for the development and exploitation of their existing product base. Moving from one path of learning to another, even if possible, can be costly given cognitive limits.

Furthermore, firms cannot easily jump from one major path to another through hiring individuals with the required competencies. Corporate competencies are rarely those of an individual, and most often those of specialised, interdependent and coordinated groups, where tacit technical and organisational knowledge accumulated through experience are of central importance. This is why firms perform most of their innovative activities in-house. And even when competencies come from outside the firm as part of a corporate acquisition, different practices and cognitive structures may make their assimilation costly or impossible.

Hence, there is a technological trajectory (Nelson and Winter, 1982; Dosi, 1986) which can be applied to a technology, constrained by knowledge limits, and to a firm, constrained by limits of competence. It can also be applied to a country, which will often have more than one trajectory.

5.2 Real options theory

5.2.1 Framing capabilities as real options

Firms and their environment are engaged in a co-evolutionary dynamic, coupled in turn to the co-evolution of capabilities within the firm. Technology and organization co-evolves where the matches of a technology and organizing principle are constrained to reasonable set-to-set correspondence, and improvements in technology and organization are correlated through experiential learning (Dosi and Kogut, 1993). Technology and organization are dynamically coupled in their evolution as the costs of altering tightly coupled components of technology and organization imply that firms will persist in their old ways beyond the recommendation of the net present value. This persistence defines a range of inertia, or what is called a hysteresis band (Kogut and Kulatilaka, 2001). Since organizational change is disruptive and hence discontinuous, managers hesitate to change radically their organizations, hoping perhaps that future states of the world would provide more appealing environments. Because of uncertainty over the evolution of the value of variety and the costs of adoption, managers might also choose to persist with inferior techniques before they are confident of future developments. Thus, contrary to the normative value in responding flexibly, inertia is rationally encouraged in highly volatile environments if change is costly and the environment is granular. Inertia reflects expectations regarding the value and costs of change, and increases with uncertainty because managers are rationally hesitant to incur the cost of change to capabilities that may become easily worthless if the environment reverts to its previous state. Thus, the dynamics by which capabilities interact and are learned pose a complex combinatorial problem. The static analysis of deciding to allocate effort to exploration and exploitation activities is complicated, because efforts in short-term efficiencies can overwhelm long-term efforts of exploration.

A real option is an investment in physical assets, human competence, and organizational capabilities that provide the opportunity to respond to future contingent events. A capability has a range of potential uses in addition to its current use. Bowman and Hurry (1993) argued that a firm's capabilities represent a bundle of options for future strategic choice. There is uncertainty about the value of a capability in future uses. Future applications of the capability will require additional investment; however, the firm has the choice of whether or not to make the investment to use the capability in these future ways. Should conditions not be favourable for the future application, the additional investment does not have to be made.

Noting the correspondence between exploration of new capabilities and the evolution of the market environment, Kogut and Kulatilaka (2001) proposed that the theory of real options provides an appropriate theoretical foundation for the heuristic frames to identify and value capabilities and exploratory activities. They use the real options approach to marry the theory of financial options to foundational ideas in strategy, organizational theory, and complex systems and identify three pairs of concepts: scarce factor and the underlying asset in option theory, inertia and irreversibility, and the ruggedness of landscape and option values. Using the concept of scarce factor markets determining the valuation of a competitive asset, Kogut and Kulatilaka (2001) argued that real option theory derives its heuristics of investing in exploratory search by inferring future value of today's investments from market prices. They apply the three conceptual pairs to the evaluation of capabilities as real options through a formal descriptive model. The valuation of core capabilities is derived from observing the price dynamics of correlated strategic factors in the market. Because of inertia, managers cannot easily adjust the wrong set of organizational capabilities to the emergence of market opportunities. However, firms that have made investments in capabilities appropriate to these opportunities are able to respond. From this description, core competence is defined as the choice of capabilities that permits the firm to make the best response to market opportunities. The heuristic framing of capabilities as real options guides the normative evaluation of the balance between exploitation and exploration.

In granular and uncertain environments (Hannan and Freeman, 1977), generalist organizations whose competence corresponds to a broad array of possible environmental outcomes will do better than specialists. In the framing of options, generalists are organizations whose competencies are robust across many future states of the world, but the carrying cost of diversity carries a survival penalty (Kogut and Kulatilaka, 2001). The inertial qualities of an organization are central to understanding the value of a firm's assets for future deployment given the uncertainty and graininess of the environment. As the environment changes more rapidly than organizations, there is value in investing assets to respond to future changes.

A firm should experiment in activities that promote its future survival by investing in platforms that correspond to expectations regarding the evolution of the external environment (Lewin and Volderba, 1999). Investments in exploration create capabilities which are platforms that create a generic set of resources and represent investments in future opportunities (Kogut and Kulatilaka, 1994a). Platforms are technological and organizational investments that permit a firm to enter into a wide menu of future markets. Firms that build general platforms are more likely to survive and grow (Kim and Kogut, 1996).

5.2.2 Strategic flexibility

Strategic flexibility is valuable because it allows firms to optimize their investments and value creation as the competitive environment changes quite frequently. From the resource-based view of the firm and the core competence arguments, a firm should invest in specific resources and competencies which will give it a distinctive advantage in pursuing or exploiting a set of market opportunities (Penrose, 1959; Teece, 1982). Teece et al. (1997) further proposed that the dynamic capabilities to adapt in a changing environment rest on distinctive processes, shaped by the firm's asset position and the evolution paths it has adopted or inherited. A firm's resources are most valuable when they are explicitly linked to specific market opportunities. In defining its strategy, a firm must identify growth opportunities in markets and activities in which its distinctive capabilities are relevant, and then put together other complementary resources needed to capitalize on these growth opportunities. Once management understands which of its resources and core capabilities are most important and relevant, it can use option-leverage to enhance its competitive advantage. To better assess the value of such a resource-based competitive strategy, investments in resources must be analysed as links in a chain of interrelated compound investments. The path-dependent nature of investment and resource accumulation along the chain is in itself an important isolating mechanism for follow-on options. To build a distinctive position of resources and capabilities requires a history of systematic investment and patient nurturing by management. As firms evolve over time, they accumulate unique skills, assets, resources and capabilities. The strategic position and evolution of a firm is path dependent, i.e. it depends on the particular path of strategic choices and cumulative investment that the firm has already followed. The unique experiences, know how, relationships, and reputation it has built over time are also embedded in the firm's resources and capabilities. As a result, firms are distinct and creative exploitation of their firm specific resources and capabilities may enable them to appropriate future growth opportunities and achieve a competitive advantage (Kogut and Kulatilaka, 2001).

A proper balance between commercialization of profitable or cash-generating investments and the development of future growth opportunities is necessary for the long-term success of the firm. The investment portfolio requires a balance of projects with short-term profitability and projects with long-term growth potential or strategic significance (Smit and Trigeorgis, 2006). Companies must often pursue parallel strategies, with one focus on today's capabilities while simultaneously developing new capabilities for the future. The balance between the present and future focus partly depends on the situation. The future component acquires more importance during volatile periods, while the present focus component dominates in more stable times. Active management of the firm's portfolio of investment options presumes that we not only consider the current interdependencies or synergies between projects but also their sequential interdependencies with future opportunities across time. With the increased dynamics and volatility of today's business environment, there is a need for portfolio planning to address the uncertainty and build in a degree of flexibility and adaptability in strategic planning.

In pursuing a dynamic process of multiple parallel strategies, companies often colonize a distinctive strategic position while concurrently searching for and cultivating another viable position, and attempt to manage both positions simultaneously while making a gradual transition to the new position as the old one matures or deteriorates (Markides, 1999). Option theory can add significant insight to such an adaptive approach as it does not treat the amount, trajectory, and pattern of related outlays in a static way but rather permits periodic adjustments and revision of decisions depending on market growth and unexpected market developments (Smit and Trigeorgis, 2006). Option analysis allows for adjustment or switching along various alternative paths as the strategy unfolds, making it possible to determine the value (and reap the benefits) of a flexible strategy.

5.2.3 Portfolios of real options

While strategy in the past has been viewed as a portfolio of businesses or as a portfolio of capabilities, it is now surfacing in the knowledge-based economy as a portfolio of opportunities and relationships that arise due to expertise (Venkatraman and Subramaniam, 2002). A portfolio approach is required to optimise the value of a portfolio of technological and capabilities options. Anand et al (2007) pointed out that the literature is still in its initial stages regarding the understanding of portfolios of strategic investments. Bowman and Hurry (1993) has recognised that the option lens provides a view of an organisation’s resources – its capabilities and assets – as a bundle of options for future strategic choice. More recently, it has been pointed out that firms often undertake a portfolio approach to their exploration-oriented investments rather than considering them as independent options (Vassolo et al, 2004).

Luehrman (1998) presented a conceptual portfolio framework for the active management and exercise of real options in option space. Investment opportunities have different time and growth-option profiles in option value space, for example, multi-stage R&D projects do not derive their value so much from direct cash flows from assets in place but from future growth option value. Option-based portfolio planning must recognize that the different stages in the option development chain may have distinctly different risk characteristics.

Two streams of strategic management literature have emerged to address issues related to real options portfolios. One stream relates to the presence of interactions among different real options within a portfolio of investments, while the other relates to the different sources of uncertainty (Anand et al, 2007).

Most real options research in strategic management had not explicitly formalised portfolio effects in real options analysis. Some studies have accounted for portfolio dimensions, such as number, size, scope and prior investments, but they have not fully analysed the nature of the interactions among real options and their effects on portfolio value. For example, in the case of pharmaceutical or biotech research, firms may invest in multiple real options corresponding to multiple approaches to treating a particular medical condition. Over time, one of them may emerge as the dominant paradigm for treatment while others may not turn out to be fruitful investments. But there can also be a complementary effect among technologies, e.g., when the establishment of a dominant design makes other compatible technologies more attractive. For such portfolios of interrelated real option investments, the task of assessing the value of each investment and the optimal composition of the portfolio is complex, but important.

Some research have focus on uncertainty in R&D, such as learning-by-doing and uncertainty reduction over time, incomplete information, or implementation uncertainty. These works study the impact of uncertainty on

R&D value, develop criteria to decide on speeding up or delaying the development process, or examine an optimal R&D subsidy policy. The resolution of uncertainty is important for portfolio planning as it determines the relative attractiveness of growth option value and the time-trajectory of the project evolution in option space. Recent studies have pointed that not all sources of uncertainty lead to growth as some sources might induce switching opportunities (Macmillian and McGrath, 2002). Portfolio effects appear to arise from interdependence among the exercise of the single real options (e.g., exercise one option kills other options in the portfolio) and correlation among the expected returns of the underlying assets. The value of a portfolio depends on both growth and switching options. In particular, taking independent options on positively correlated underlying assets increases the growth values, whereas creating competing options on negatively related assets increases the switching value. It has been long recognised that the value of a portfolio of real options is affected by volatility but, more recently, other factors such as size, exercise constraints, and correlation, have been recognised. Anand et al (2007) also derived a set of general propositions on the effective composition of a real options portfolio based on balancing growth and switching values. This depends on the strategic consideration of the portfolio width (measured by the ratio between total growth options and exercisable options) and correlation among the underlying assets. This balance is critically affected by the relevant source of uncertainty that a firm faces.

5.3 Defence R&D management in practice

We conclude the comparison of our emergent framework with the extant literature with a review of the considerations in the management of the United States defence R&D investment - the world's largest investment portfolio in defence R&D. The 2009 Defence Research and Engineering (R&E) Strategic Plan of the United States (DoD, 2009) articulated their management principles for their R&E programmes including:

1. The R&E programme should "support a sustained supply of scientist and engineers working on national security problems. This is becoming an increasingly critical element of the DoD R&E strategy as there are metrics suggesting that the American advantage in intellectual capital is eroding. Many countries of the world are producing scientist and engineers at a faster rate than the U.S. and the production gap is growing. Although the primary output of the DoD basic research programme is new scientific knowledge the secondary output is scientists and engineers who make up the national security workforce, the bulk of federal funding for scholarships and internships to support research in such areas as electrical and aeronautical engineering at universities comes from DoD investment. The DoD should continue to maintain a strong investment in basic and applied research to sustain the supply of scientists and engineers for the national security programme."
2. Continually develop new capability options for operational commanders and strategic policy makers. Some portion of investment

should be working on new technologies and applications to refresh the U.S. military capability advantage.

3. Reduce technology risk in acquisition programmes by ensuring sufficient technology maturity levels, supported by adequate test and evaluation and manufacturing assessment.
4. Enhance affordability of DoD Systems and Capabilities by reducing acquisition and life cycle costs through the balanced development or insertion of advanced technology.
5. Develop technology which will enhance sustainment and upgrade for existing weapon systems
6. Hedge against the uncertainty brought about by disruptive technologies, and minimise the probability of technology surprise of disruptive military capabilities and challenges from adversaries who develop and use breakthrough technologies to negate current U.S. advantage in key operational areas.

The emphasis of the US DoD appears to be the development of capabilities of various level of technological maturity. In the basic research programme, the primary output is new scientific knowledge while the secondary output is human capital. This creates compound options which can be transformed into technological options through application research and, subsequently, further developed into new capability options for field applications.

The disruptive potential of breakthrough military technology has been illustrated repeatedly in the history of warfare. During the Crimean War, the fighting saw the direct impact of science and technology on the battlefield for the first time (Parker, 2009). The invention of the ‘minie’ bullet for rifled muskets (muskets with spiral grooves cut into the barrel) allowed infantrymen to reach out and hit opponents ranges of upwards of 300 yards. This lead bullet was hollowed at the bottom, which allowed the explosive charge to push out the flanges and make a tight enough fit that the rifling imparted spin and distance and direction, thus tripling the musket’s killing range. Of equal importance was the appearance of steamships in navies which enabled the British and French to transport and supply their forces in Turkey and the Crimea with remarkable ease. Finally, the telegraph allowed governments in Paris and London to communicate with commanders in the field.

The Gulf War of 1991 is a more recent reminder of the overwhelming success of disruptive military technology. Helped by French and Soviet technology, the Iraqis had by 1990 developed a highly sophisticated, integrated air defence system. But it possessed major weaknesses which were exploited by their opponents armed with disruptive technologies. The initial strikes by ‘stealth’ F-117 bombers and cruise missiles in January 1991 attacked the heart of the Iraqi air defence system, particularly the various command nodes, communication centres, and Iraq’s main electrical system. The next stage in the Allied plan sent two massive packages of aircraft, combining jammers, and aircraft carrying anti-radiation missiles, to strike any Iraqi radar installations that still functioned. By then, half an hour into the Allied assault, the Iraqis realized that a major attack was in progress; but breakdown caused by the initial strikes were already causing them considerable difficulties. At this point what appeared to be a massive two-pronged bombing strike aimed at Baghdad appeared on those radar screens still operating – but simply by ‘tuning in’ these installations attracted a large number of anti-radiation missiles. The Iraqi air defences failed to function in a coherent fashion for the rest of the war.

Advances in weaponry that had marked these wars at the tactical level underlined that technology and science were crucial to battlefield success. The side that possessed the disruptive military capability would enjoy an importance advantage over its opponents.

5.4 Discussion

The economic growth theory explains the importance of technology in economic growth. Companies invest in R&D to develop firm specific capabilities to create technological variation and adopt technological changes quickly in the uncertain future. In this evolutionary and complex landscape, real options which convey the right, but not the obligation, for a firm to make further investments or defer such investments, appear to be an appropriate model for R&D investments and the capabilities created. Similarly, the R&D and capability development process can be framed as a real option creation process. The R&D process can be viewed as a process of resource transformation (Schmidt and Freeland, 1992) whereby firms create strategic options by transforming resources into capabilities which offer strategic flexibility. The evolution of capabilities can be modelled by a life cycle involving the stages of founding, development and maturity (Helfat, 2003).

The emergent framework for defence technological innovation from the preceding case studies on historical examples of important defence technological innovation illustrated a capability transformation process. In defence R&D investments, the large-scale mission oriented projects aim to develop specific technologies under high appropriability and high cumulativeness (at the firm level) conditions. These lead to a Schumpeter Mark II Model of innovation regime (Breschi et al., 2000), characterized by "creative accumulation" and the importance of experience in innovative efforts. The R&D process would involve development of capabilities which could be modelled as a capability life cycle (Helfat, 2003). The emergent framework can be seen as a transformation map for this capability development in defence R&D investments. The transformation is a development vector describing the maturing of the technology and resolution of uncertainty in the application. Different driving forces behind the capability development would lead to the development taking different paths and as such, the real option embedded in a technology development programme evolves accordingly. Within this framework, one can examine the relationship amongst defence R&D investments, capability development and options creation for the uncertain future. The real option embedded in a technology development programme evolves as the technological uncertainty decreases with technological maturity and the readiness for field transition increases with identification of application. The framing of defence R&D investments as real options in capability development underscores the theoretical foundation for the application of real option theory to model defence R&D investment.

Building on these works, we refine our emergent defence technological innovations framework using the real options lens (please see Fig 5.1).

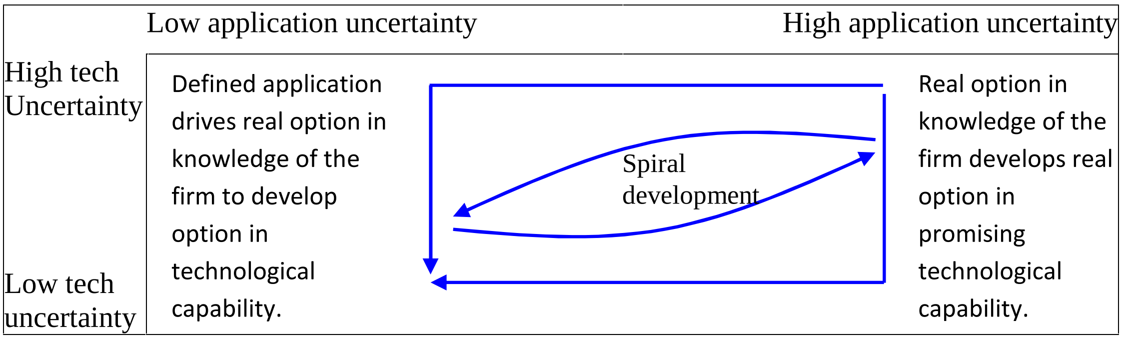


Fig 5.1. Refined defence technological innovations framework

Defence R&D investments are frequently strategic and aim to provide robust technological capability to help sustain the long term defence capability of the nation in the uncertain time horizon. For value robustness, the defence R&D portfolio includes investments driven by applications of different level of clarity and aiming to create real options in capabilities of various level of technology maturity. The R&D process could be view as a process of capability development during which technology matures and application is clarified, and real options creation as complex (compound) options are transformed to simpler (vanilla) options with project progress. Basic research programmes aim to create new scientific knowledge and human capital to create real options in founding stage capabilities and knowledge of the firm (Kogut and Zander, 1992). In investments driven by discovery-push, the human capital leverage on their knowledge to develop promising real options in developing stage capabilities. With the maturing of technology, the maturing stage capabilities created technological options which could be further developed into field application once the application was identified. In demand-pull investments, application definition preceded and drove the development of supporting technological capability. With maturity, the maturing stage technology presents a real option – albeit with very clear application agenda from the onset - which could be inserted into field applications. Sometimes, with the fielding of an application, the need for a new application could be discovered, hence, driving the development of new supporting technological capability. This creates a spiral development.

6. APPLICATIONS OF THE PROPOSED DEFENCE TECHNOLOGICAL INNOVATION FRAMEWORK IN STRATEGIC HEURTISTIC

In the previous two chapters, we developed and further refined our framework for defence technological innovations by theory building. Our approach involves using case studies in defence technological innovations, and concepts of dynamics of technological innovations and capability development from theories in strategic and technology management and real options. Real options appear to be an appropriate model for defence R&D investments which can be framed as capability options. Real options theory also helps to frame the strategic flexibility developed amidst uncertainty within a complex environment.

Normative research suggests particular heuristics, or cognitive representations, can be developed to find appropriate and faster solutions to real-time problems. In this chapter, we use our theoretical framework to propose potential applications in the strategic heuristic for defence technology management and investment strategy.

6.1 Defence technological options

Capability development involves a life cycle comprising founding, developing and maturing stages (Helfat, 2003). Using the Technology Readiness Level (TRL) framework developed by the National Aeronautics and Space

Administration (NASA) and Department of Defense (DoD) in the United States, the capabilities developed in defence R&D can be categorised by the technological maturity level as follows:

Maturing stage capability. This capability enables the direct insertion of a matured technology with a minimum TRL of 7 into a military application system to address an operational requirement. An example is enhancement of operational capabilities with improvement in an existing weapon system. These capabilities offer direct returns on investment to the defence end user, which can be measured in terms of mission effectiveness and quantified using the revealed preference approach.

Developing stage capability. These are vanilla options created from investment in technological capabilities. They offer the end user technological options - the right but not obligation - to further develop the technological capability into system capability. These technological options correspond to the real options in strategic positioning proposed by Mitchell and Hamilton (1988) with a TRL of 4 to 6. In defence R&D investments, they can be framed as vanilla options created from investment in technological capabilities, offering the end user technological options to further develop the technological capabilities into operational weapons.

An example is the exploratory development effort in the innovation of tanks for which the enabling technologies - internal combustion engine and caterpillar track - were mature technologies being used in early farm tractors. Fig 6.1 illustrates this development. The first experimental tank was built in Britain in September 1915 using the engine and the transmission of wheeled tractors and the tracks of Bullock tractors procured from the United States (Humble, 1977; Ogorkiewicz, 1991). The technological capability continued to develop and an improved design was successfully demonstrated in February 1916 when the capability matured. The War Office exercised its technological option and ordered one hundred and fifty similar vehicles. On 15 September 1916, the 49 tanks available were sent on the first ever tank action to help the infantry assault enemy trenches on the Somme. The tank innovation also illustrates the influence of certainty of application. While a few caterpillar tractors had been used in the military as a means of hauling cargo or pulling very large artillery pieces, few people were struck by the idea of arming caterpillar tractors before World War I. During the war, the opposing armies were held to a deadlock as the traditional infantry attacks had become difficult due to increasingly effective firepower and extensive use of entrenchment and barbed wire deployed in defence. Consequently, the use of armoured assault vehicles, which would crush the barbed wire and whose protection would enable them to approach enemy trenches under machine-gun fire, was explored.

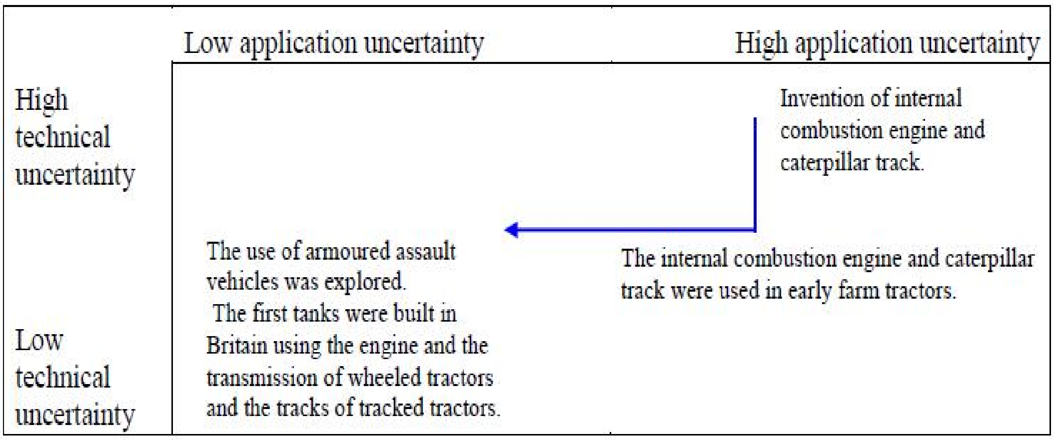


Fig 6.1. Innovation path of the tank

Founding stage capability. These are compound options created from investment in knowledge of the firm. The returns to end user may not be apparent and hence not easily quantified. The knowledge created correspond to TRL of not more than 3, and can be considered as owning a portfolio of options, or platforms, on future developments. An example is investment in human capital. In the development of the atomic bomb illustrated in Fig 6.2, research scientists discovered the structure of the atom in the early decades of the 20th century. The Hahn-Strassman experiment in 1938 demonstrated the conversion of mass into energy, fulfilling Albert Einstein's famous mass-energy equation (Siracusa, 2008). The chain reaction when the uranium nucleus splits apart could set off a huge release of energy in millionths of a second. These discoveries had been pure science but physicists soon recognised that if the chain reaction could be tamed, fission could lead to a promising new source of power. In August 1939, fearing that Nazi Germany would convert the fission process into a weapon, Einstein and fellow atomic scientists wrote to President Roosevelt informing him that recent nuclear research had made it possible to construct nuclear bombs (FDR, 2011). Roosevelt promptly set up an exploratory committee to study uranium. In 1942, Britain and the United States pooled their resources and information on atomic bomb development under the auspices of the Manhattan Project. The project brought together the top scientific minds of the day with the production power of American industry and successfully produced the atomic bomb by the end of July 1945 (Delgado, 2009).

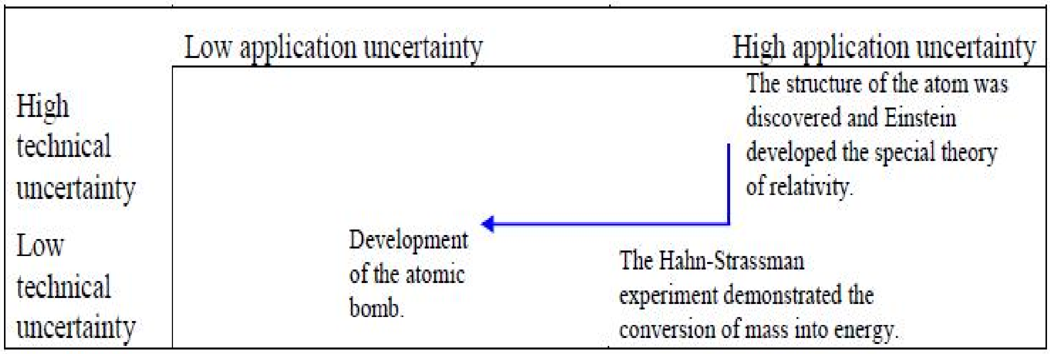


Fig 6.2. Innovation path of the nuclear bomb

The U.S. armed forces emerged from World War II with an array of research and development skills and organisations which tended to focus on applied science, development engineering, and hardware related to the needs of their specific branch of bureau. While technologically oriented applied research had dominated the wartime effort, the post-war world offered wider prospects for military uses of research and value of basic research. For example, the Office of Naval Research (ONR) proved a liberal patron of academic science and accepting the inherent value of basic research, it funded a wide range of projects without insisting they show direct links to naval needs. Inspired by the ONR example, the Army Research Office and the Air Force Office of Scientific Research were created in 1951 and 1952, respectively, to support basic research in these services.

The United States faced a military-scientific crisis after the Soviet Union launched the first artificial satellite on October 26, 1957, and a second eight days later with a dog as a passenger (Volkman, 2002). The Sputniks shook the casual confidence many Americans placed in their country's scientific and technological prowess. The National Defence Education Act (NDEA) was passed in 1958 and provided immense sums of money to channel students into course of study the government deemed useful for national security, with a strong accent on science and engineering. As a major supplier of research funds, the Pentagon exerted increasingly strong effects on the direction of research and even the structure of universities, which came to depend on such funds.

6.2 Transformation of technological options

With creative accumulation in the evolutionary R&D process, options embedded in a technology development programme evolves as the technological uncertainty decreases with technological maturity and the readiness for field transition increases with identification of application. Hence, defence R&D investments into clearly identified applications within matured technological areas in the present instance may also be the fruition of a cumulative breakthrough technological development. An example is the application driven technology development for the submarines illustrated in Fig 6.3. The first workable submarine, the Turtle designed by David Bushnell in 1776, was propelled by a hand-crafted screw and had room for only one crewman. This crewman had to bore a drill bit into the bottom of the hull of the target vessel and attach a waterproof time bomb, then escape before the bomb was detonated by a clockwork fuse (Clancy, 1993). Major technological breakthroughs were achieved over the generations, through the Nautilus designed in the 1800s and the Hunley which successfully sank its target during the American Civil War, before John Holland designed the USS Holland (SS-1), the first practical combat submarine, in the 1900s (US Navy, 2011).

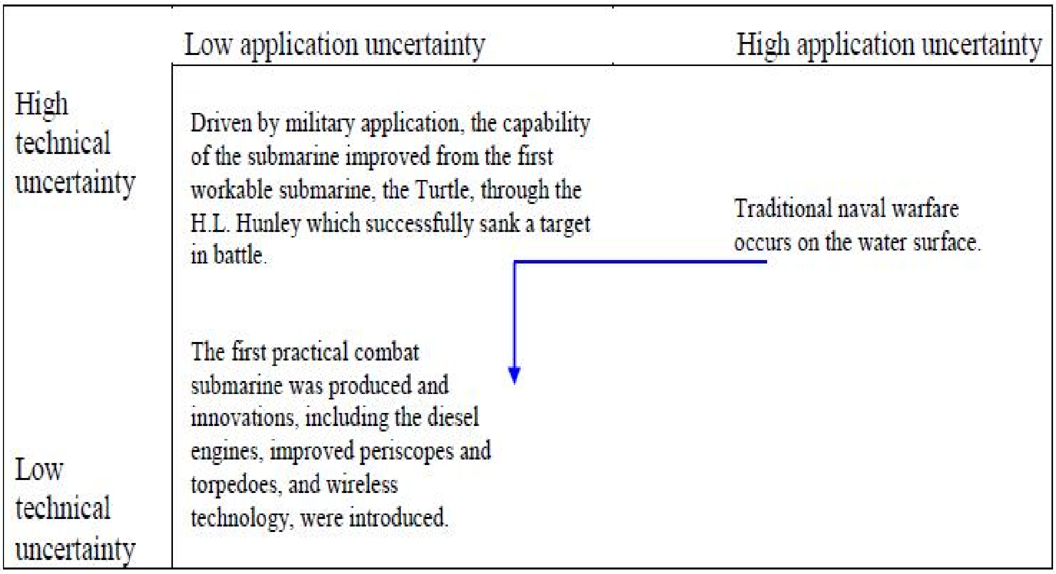


Fig 6.3. Innovation path of the submarine

Defence R&D investments into clearly identified applications within matured technological areas in the present instance could also be the exercising of technological options when the application is identified. The innovation of the tank discussed earlier was serendipitous. The innovation of the radar in Britain was the payoff from the exercise of a technological option by the British Air Ministry after Robert Watson-Watt demonstrated in February 1935 that an aircraft could be detected at long range by radar waves (Hambling, 2005; Volkman, 2002). The reflection of radio waves from a metallic object had been demonstrated in 1855 and the ionosphere discovered in the early 1920s. Coupled with the commercial availability of the cathode ray tube (CRT) screen, which enables the plotting of the position, altitude and course of an aircraft, since 1922, the essentials of the radar were ready for transition.

6.3 Portfolios of strategic options

Strategic flexibility is valuable because it allows optimisation of investments and development of the necessary capability in the fast evolving environment. A country should invest in resources and competencies which will give it a distinctive advantage in pursuing or exploiting a set of opportunities. The competitive advantage and capabilities to adapt in a changing environment rest on distinctive processes, shaped by the country's resource position and the evolution paths it has adopted or inherited. These resources are most valuable when they are explicitly linked to specific opportunities. In defining its strategy, a country must consider its context and identify opportunities in which its distinctive capabilities are relevant, and then put together other complementary resources needed to capitalise on these opportunities. Once management understands which of its resources and core capabilities are most important and relevant, it can use option-leverage to enhance its competitive advantage without inaction due to the huge resource investment and yet limit the exposure to potentially catastrophic downside risk of failure. To better assess the value of such a resource-based competitive strategy, investments in resources must be analysed as links in a chain of interrelated compound investments. The path-dependent nature of investment and resource accumulation along the chain is in itself an important isolating mechanism for follow-on options. The strategic position and evolution of defence capability is path dependent as unique skills, assets, resources and capabilities are accumulated over time. To build a distinctive position of resources and capabilities requires a history of systematic investment and patient nurturing by management.

A proper balance between operationalization of matured technologies and the development of new technologies for future opportunities is necessary for the long-term success of the defence capability. The investment portfolio requires a corresponding balance in projects with short-term operational capability and projects with long-term potential or strategic significance. The defence R&D portfolio would likely include projects with different level of uncertainty in technology development and the fielding of the application. The strategic purposes for defence R&D projects with different level of uncertainty in technological development and fielding of the application would likely vary. Highly uncertain disruptive technology, if successfully developed and fielded, could offer an importance advantage over its opponents. In the first ten hours of the Gulf War in January 1991 a combination of Stealth aircraft, cruise missiles, electronic warfare, and precision-guided munitions of the United States took apart the Iraq's complicated air defence system. Over succeeding weeks an aerial offensive battered Iraq's military infrastructure, wrecked the veteran and numerically superior Iraqi ground forces and inflicted minimal damage on civilian populations.

As the purpose and nature for R&D options are not the same and serve different strategic purposes, the investments could be treated as one of three types of real options, depending on their degree of technical and application uncertainty modelled after McMillan and McGarth (2002) (see Table 6.1). Positioning options are taken out to preserve the defence capability to compete in some future and still unclear technological arena. The long term development of submarine capability discussed earlier is an example of these options. Scouting options are used to learn about the scenario by probing. This is illustrated by the earlier discussed example of tank development which involved the trial of several prototypes much of which leveraging on the existing technologies internal combustion and caterpillar tracks. Where application and technological uncertainty are high, stepping-stone options are created to systematically build both insight of the application and technical competence. Defence R&D investments in technological areas of high technological uncertainty and high uncertainty in applications may aim to create technological breakthrough which would give a secret edge over the adversaries. As discussed in the example of atomic bomb development, human capital was instrumental from the pure science discovery of the power of the atom through the subsequent development process to produce the atomic bomb. The German human capital in science and technology was built up in the aftermath of the defeat by Napoleon (Volkman, 2002). The Americans aim to enhance their science and technological base through the NDEA after the setback in the space race with the Soviet launching of Sputnik. On the other end of the spectrum, defence R&D investments into clearly identified applications within matured technological areas may aim to create continuous incremental innovations. Following the breakthrough innovations of the atomic bomb, incremental but important innovations continued to be made to improve their performance.

	Low application uncertainty	High application uncertainty
High tech Uncertainty	Positioning options to create "Modular innovation". E.g. quantum leap in existing weapon systems performance.	Stepping-stone options to create "Radical innovations". E.g. R&D investments in emerging breakthrough technology.
Low tech uncertainty	Enhancement & platform launches to create "Incremental innovation". E.g. upgrading weapon systems.	Scouting options to create "Architectural innovation". E.g. fielding existing technologies in new doctrine of operation.

Table 6.1. Technological and scenario uncertainties in defence R&D investments (modelled after MacMillan and McGrath (2002))

7. PROPOSED DEFENCE R&D INVESTMENT EVALUATION FRAMEWORK

In the previous chapter, we apply our theoretical framework for defence technological innovations to propose strategic heuristic for defence technology management and R&D investments. In this chapter, we again build on our theoretical framework to develop an effective and objective evaluation framework for defence R&D investments, which considers the system and highly uncertain return on investments, and encourages innovations.

Defence R&D investments aim to build a value robust portfolio of technological options amidst environmental and technological uncertainties. Real option is a theoretically attractive model for public R&D investment and can be used in the evaluation of the flexibility (real options) created through defence R&D investments but the appropriateness and boundaries of the model and suitability of the valuation method is contingent on the nature of the investment. As discussed in Section 2.2, arbitrary selection of evaluation techniques for R&D investments may result in misleading or even wrong conclusions. Hence, there is a need for good formal procedures or guidelines for the selection of the R&D evaluation technique for a specific R&D investment. We would develop an evaluation methodology based on our improved understanding of defence technological innovations and advise the appropriate real options model and suitable evaluation method. Our proposed evaluation methodology shall support the objective evaluation of defence R&D investments, and attempt to improve the state of the practice by considering the system and highly uncertain return on investments, and supporting innovations. This includes the strategic objective of defence R&D investments in building a value robust portfolio of technological options amidst environmental and technological uncertainties, and the evaluation of the flexibility (real options) created through defence R&D investments.

From our previous discussion in Section 2.4.2, scoring method, which evaluates projects by giving each project a score reflecting how well it meets the defined objectives on some scale, is the most favourable method for R&D project evaluation. This is consistent with literature comments that scoring methods are popular because of their ability to deal with multiple dimensions of R&D problems and their simplicity in formulation and use. However, it lacks consideration of risk and uncertainty. We propose improvements to the scoring method for evaluation of defence R&D investments by adopting the real options approach to consider risk and uncertainty. The enhanced scoring method will be integrated within our evaluation methodology for defence R&D investments.

7.1 Proposed evaluation method: An improved scoring method

Using our theoretical framework for defence technological innovations, we have understood a defence R&D project as a process of transformation of capabilities and real options. We propose that the scoring method can be enhanced to evaluate defence R&D investments by incorporating the real options approach to improve the consideration of risk and uncertainty. In

Section 2.4.6, we reviewed the literature of framing and evaluation of R&D investments as real options with highlights on (1) limitations in the classical real options valuation (ROV) methods, (2) advances in the research of real options, and (3) prior work in framing and evaluating defence R&D investments as real options. Real option is a theoretically attractive model for public R&D investment and can be used in the evaluation of the flexibility (real options) created through defence R&D investments. However, the appropriateness and boundaries of the real options model and suitability of the valuation method is contingent on the nature of the investment, and the literature appears to disagree about the approach to evaluate the real option. In particular, the classical ROV adapted from financial option valuation is criticised for its inappropriateness in evaluating real investments. The uncertainty in the environment and the difficulty in estimating the parameters for ROV also challenge the ROV approach.

We have seen in Section 2.4.6 that the systems engineering approach to evaluate flexibility (real options) and value robustness of evolving systems is able to handle non-financial returns and avoids the unrealistic assumptions of financial methods in classical ROV. The embedded real option and value robustness in an R&D project enables the transition of an R&D project to capability with the maturing of technology and clarification of application in a complex co-evolutionary environment. For example, a real option embedded in an R&D project can be exercised at a cost to transition the project to capability A with the maturing of technology and clarification of application.

Similarly, the real option can be exercised at another cost to enable the project to evolve to capability B (see Fig 7.1).

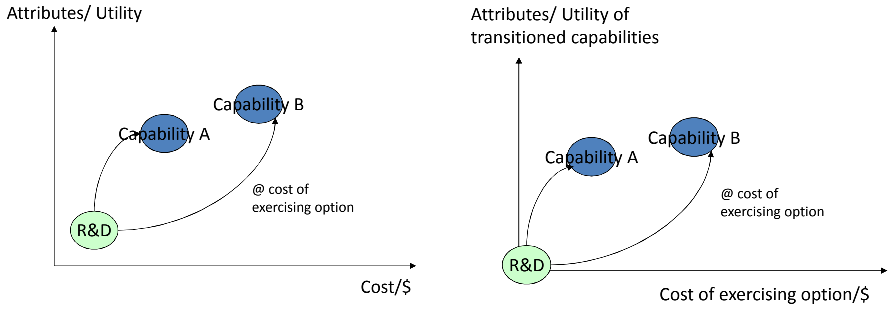


Fig 7.1. Alternative representations: Real options in R&D investments can be exercised for transition to capabilities.

By leveraging on the system engineering approach to evaluate real options, we develop an improved scoring method which, while remaining practical and adaptable, is able to handle the non-financial returns and value robustness generated in defence R&D investments in the creation of capabilities and real options, and avoids the unrealistic assumptions of the financial methods for classical real options valuation.

Our proposed evaluation method involves enhancing scoring method with the Real Options approach to handle the risk and uncertainty. This method is distinct from the ROV method which is more quantitative in nature. Our proposed evaluation method involves the following:

(1) Determining the real option parameters in each transition of R&D to matured capability:

1. *Conditions under which the option would be exercised.* In the development of the tank, for example, the British War Office required

the tank prototype to meet a performance requirement to cross trenches 1.5m wide with parapets 1.4m high.

2. *Cost of exercising the option, K.* Using the development of the tank again as an example, the British War Office exercised its option by ordering and making payment for one hundred fifty tanks after a successful demonstration of the prototype in 1916. This is distinct from the cost of the option which is essentially the quantum previously invested in the prototype development.

3. *Expected return in terms of attribute or utility, S.* The objective of the tank development is to crush the barbed wire deployed by the opposing armies and break the line of defence. Using the US DoD 2009 Defence R&E Strategic Plan discussed in Section 5.4 as a more contemporary example, we may infer the expected utility of their R&D programmes could be functions of capabilities options for the commanders, such as mission effectiveness, and human capital in the defence technological eco-system, such as number of researchers with a prescribed level of competence.

4. The *value of the real option*, *C*, hence, is the greater of (1) the difference between the utility of the capability, S, which can be obtained with the exercise of the R&D option at cost, K, or (2) zero if the option is not exercised. The latter could occur when the utility of the matured capability which can be obtained is less than the cost of exercising the option. This function (illustrated in Fig 7.2) is not symmetrical and the non-negative value can be represented by

$$C = \max(0, S-K). \quad (1)$$

where S is the utility of the matured capability which can be obtained when the R&D option is exercised;

K is the cost of exercising the option

Fig. 7.2. Utility of an application varies with conditions; Value of real option in turn varies with this expected return (where cost of exercising option is held constant).

The cost of the real option is distinct from the cost of exercising the real option, K. The former is the quantum of the initial defence R&D investment. The latter is the quantum to be further invested if a decision is made to proceed with the next phase of R&D. If the value of K and the expected return S can be deterministically estimated, the deterministic value of real option can be calculated using the above method. Sometimes, however, these parameters might not be easily or accurately estimated. For example, the expected applications might not be identified in the path dependent processes during the creation of scouting options which in turn frustrate the estimation of the utility

S. Furthermore, it is useful to analyse the risk in the option value due to uncertainty in the input parameters. A probabilistic approach described in (2) below would be more appropriate in these cases.

2) Simulation and Value-at-Risk (VaR) algorithm: For each transition from R&D to matured capability, the cost of exercising the real option K and the expected return S can be simulated. The VaR approach presented earlier in Section 2.4.6 can be used to make a probabilistic estimate for the minimum expected return over a specified time period with a given confidence level using Monte Carlo Simulation.

3) Capturing the value of opportunities:

Financial returns. If the cost of exercising the option K and the return of the transition capabilities S are expressed in financial terms, the value of option C can be expressed in financial terms. In this case, C is simply computed from max (0, S-K) in the deterministic case, or a probabilistic estimate of max (0, S-K) if the VaR analysis is employed in the probabilistic case.

Non-financial returns. Where the return of the transition capabilities is not expressed in financial terms, the scoring method can be adopted to measure the flexibility (real option) in the R&D project. Clearly, we can score the attribute and utility of the transitioned capability and the cost of exercising the option. Other metrics, such as measure of the degree of flexibility embedded within a programme, can also be constructed. One possible metric, similar to the Filtered Outdegree discussed in Section 2.4.6, is the number of transitions which can be achieved within a defined hurdle rate. This hurdle rate could be a function of attribute and utility of the transitioned capability and the cost of exercising the options. As the attribute and utility of the transitioned capability and the number of paths increase or the cost of exercising the option decreases, the value of the flexibility (real option) increases. Both deterministic and probabilistic approaches can be adopted in these methods.

(4) Value Robustness: A Pareto frontier can be obtained by evaluating the basket of R&D projects under consideration for investment and plotting the results. By varying the exogenous factors to consider external risks and endogenous factors to consider sensitivity, different values and plots for the projects and different Pareto frontiers can be obtained. Using the method presented in Section 2.4.6, the frequency of a project appearing on the range of Pareto frontier is its Pareto Trace Number. This generic metric is a measure of the value robustness of the R&D project.

7.2 Proposed evaluation methodology

We recognise the theoretical attractiveness of real options as a framing of R&D investments and propose the development of an evaluation methodology supported by appropriate real options valuation. The appropriateness of adopting the classical real option valuation approach should be determined in consideration of (1) finding a model whose assumptions match those of the project being analysed, (2) determining the inputs to this model, and (3) being able to mathematically solve the option pricing algorithm. The validity of the assumptions underlying the classical real options valuation model ought to be assessed when applied to pricing options on many real assets (Bruun and Bason, 2001).

We contend that the arguments on the environmental uncertainty and difficulty in parametric estimation overlooked Mitchell and Hamilton (1988) proposal that ROV is appropriate for the valuation of strategic positioning options concerned with the technological transition, reducing technical uncertainties and building strong technical position for the firm. Investments with lower uncertainty could be easily evaluated using capital budgeting approach (Hamilton, 1988; Winter, 1987) while very fundamental research is best considered as an expense (Hamilton, 1988). In this section, we build on these insights to propose a structured approach to evaluate defence R&D investments using a three step evaluation methodology.

With the insight from our theoretical framework for defence technological innovations, we further propose that there are four, rather than three, categories of R&D investments. We adopt MacMillan and McGarth (2002) definitions of enhancement & platform launches, positioning options, scouting options and stepping-stone options. Each of these R&D investments entails different amount of risk and uncertainty, and generate different amount of flexibility and real option. Hence, we propose adopting different evaluation methods for the different categories of R&D investments (please see Table 7.1).

	Low application uncertainty (idea generated)	High application uncertainty
High tech Uncertainty (TRL1-3)	Positioning options are taken to preserve defence capability to compete in some future and still unclear technological arena: Evaluate investment using Real Options Valuation approach.	Stepping-stone options are taken to systematically build both operational insight and technical competence: Treat investments as expenses.
Low tech uncertainty (TRL4-)	Enhancement & platform launches: Evaluate investments using capital budgeting methods.	Scouting options are taken to learn about the operational scenario by probing: Investments are path dependent processes and can be evaluated using the improved Scoring Method.

Table 7.1. Categorisation of real options and selection of appropriate valuation methods

Besides the scoring approach used in our proposed evaluation method, several techniques to handle non-financial returns have been discussed earlier in Section 2.4. Intangible returns (Sudarsanam et al, 2005) can be evaluated using methods discussed in Section 2.4 or the revealed preference approach. Kogut and Kulatilaka (2001) proposed that expert opinion can a good method to estimate the probability distributions of possible future market conditions for new business in radically new landscapes. In defence R&D investments, expert opinions are frequently used, and the returns are frequently measured in terms of cost effectiveness of achieving mission objectives and quantified using the revealed preference approach (O’ Hanlon, 2009).

Clemen and Reilly (2001) propose that creating a decision model requires three fundamental steps:

1. Identifying and structuring the values and objectives. Structuring values requires identifying those issues that matter to the decision maker.

2. Structuring the elements of the decision situation into a logical framework.

3. Refinement and precise definition of all of the elements of the decision model.

Adopting this approach, we propose a three step evaluation methodology for defence R&D investments, comprising a structured approach of first understanding the innovation and subsequently adopt an appropriate evaluation method:

Step 1: Differentiate the various stages in the programme and evaluate stage (project) under consideration.

An R&D programme entails different stages with different amount of risk and uncertainty, and generate different amount of flexibility and real option. R&D projects in the earlier stages involve more risk and uncertainty but offer the choice to invest downstream. The differentiation allows more appropriate accounting that better reflects the differential risks in each stage (Vonortas and Hertzfeld, 1998). The first step of our evaluation methodology is, hence, to identify the R&D stage (project) under consideration and evaluate the level of uncertainty in application (vis-à-vis the New Product Development and Technology Development process) and technological maturity level (benchmark against the Technology Readiness Level framework).

Step 2: Categorise the real option embedded in the R&D investment using our Framework for Defence R&D Innovations.

The appropriate evaluation method depends on the level of uncertainty in its application and technology maturity. The former is defined by (1) the initial identification and analysis of the opportunity leading to (2) discovery or idea generation which would subsequently kick off the technology development process involving project scoping, assessment of idea, and detailed investigation of idea. The latter is defined using the Technology Readiness Level (TRL) framework. Using this framework, a TRL of less than 4, where component and/or breadboard validation in laboratory environment has yet to be achieved, is deemed to be of high technical uncertainty. Based on level of uncertainty in application and technological maturity level, the real options embedded in the R&D investment are categorised using our Framework for Defence R&D Innovations (see Table 7.1).

Step 3: Valuation of real options using an appropriate method (see Table 7.1).

Capital budgeting method can be used for the valuation of an investment in enhancement & platform launches, which are typically of lower technological risk and uncertainty in application.

Stepping-stone options are broad-based options which can be framed as a generic set of resources and form platforms for future development and opportunities. The operational impact of these investments is often too poorly defined and wide ranging, and the investments are best treated as expenses.

Real Options Valuation (ROV) is suitable for the valuation of positioning options where the level of uncertainty is in between the two ends of the spectrum of technological uncertainty. The creation of technological options in specific capabilities driven by application and the scope of these activities is fixed a priori. The decision to abandon the initiative has been clearly articulated and the flexibility associated with the option investment can be readily maintained and evaluated using ROV approach such as the Classical, Revised classical, Integrated and Marketed Asset Disclaimer (MAD) methods.

Scouting options are used to learn about the operational scenario by probing. As the target applications for these options are still flexible, the investments may be more appropriately characterized as generic path-dependent processes, and are most appropriately evaluated using path dependent evaluation methods. The improved Scoring Method appears to be a promising approach to evaluate the returns generated in these scouting options. These returns may be financial or non-financial. The real options approach enhances the consideration of the risk and uncertainty in application and technology, and simulation and VaR techniques can be adopted to consider the path dependent processes. This method can also be easily extended to evaluate the value robustness.

7.2.1 Summary

Our proposed evaluation methodology is distinct from the traditional ROV method with its emphasis on prior understanding of the innovation and categorisation of the real option based on the level of uncertainty in application and technological maturity level. This three step evaluation methodology for defence R&D investment is summarised as follows in Table 7.2.

Step	Description	Proposed technique (evaluation method)
1	Differentiate various stages in programme and evaluate stage under consideration.	Identify relevant R&D stage (project) and evaluate the level of uncertainty in application (vis-à-vis the New Product Development and Technology Development process) and technological maturity level (benchmark against TRL framework).
2	Categorise real option embedded in the R&D investment.	Based on level of uncertainty in application and technological maturity level, categorise real options using our Framework for Defence R&D Innovations.
3	Valuation of real options using an appropriate method	Use our Framework to select appropriate evaluation method. The traditional ROV method can be adopted in the particular case of Position Options.

Table 7.2. Summary of proposed evaluation methodology

7.3 Illustrative examples: Three cases of defence technological innovations in Singapore

We present an illustration of the application of our theoretical framework and the operationalisation of our proposed evaluation methodology using three cases of defence technological innovations in Singapore.

In Singapore, defence R&D efforts have led to the successful development of the Underground Ammunition Facility (UAF), the world's most modern underground ammunition facility and the first large-scale underground containerised facility to be designed and developed within a densely developed and urbanised area. It is equipped with the latest ammunition storage technology and systems developed through a decade of R&D. Another example of operationalised pay-off from R&D efforts is the Unmanned Aerial Vehicles (UAVs). Over a decade, the DSO National Laboratories developed a man-portable mini tactical UAV whose primary mission is to provide Army battalion with real-time video images of its area of operations. These UAVs have since been fielded in the Army, and R&D on UAVs is continuing with the development of a 60 kg class of tactical UAV for use at the brigade level. Other recent successful indigenous development of advanced systems such as the Pegasus Lightweight Howitzer, the Bronco All-Terrain Tracked Carrier and the command and control systems of the frigates have also received widespread publicity and attracted the notice of professionals both locally and internationally. Current R&D projects include the development of unmanned underwater vehicles for underwater surveillance and mine counter-measures, and ground robots (Teo, 2010).

We will illustrate the application of our theoretical framework and evaluation methodology in three contemporary defence technological innovations in Singapore, namely (1) the Underground Ammunition Facility (UAF), (2) Infra-red Fever Scanner System (IFSS), and (3) indigenous Unmanned Aerial Vehicle (UAV).

7.3.1 Applying the defence technological innovations framework

We apply our defence technological innovations framework to analyse the three cases of defence technological innovations in Singapore. The technological and application uncertainties of each case are characterised and summarised in Table 7.3, using the approach adopted in Section 4.4. Similarly, each of the innovations is written up to help in our within-case analysis. The write up and the listing of sources are attached in Annex B. The sources for the data include books and other literature which chronicle the innovations. An example of the former is Tan (2003) which chronicles the development of the IFSS, while the latter includes Ong (2011) which describes the development and deployment of the UAVs in the Singapore Armed Forces (SAF). To ensure accuracy of the constructed cases, the cases have been reviewed by several technology managers who are knowledgeable in defence technological innovations, including the Deputy Chief Executive (Strategic Development) and Director (Defence Masterplanning and System Architect) of the Defence Science & Technology Agency (DSTA), Singapore.

Technology	Spiral	Technology development started prior to clear application	Application defined prior to technology development	Maturity of technology when idea is generated
Underground Ammunition Facility (UAF)			X	TRL3
Infra-red Fever Scanner System (IFSS)		X		TRL7
Indigenous Unmanned Aerial Vehicle (UAV)	1		X	TRL3
	2	X		TRL5

Table 7.3. Summary of case analysis

For each case, the innovation path is mapped as progress is made over each of the two dimensions of demand (i.e. clarity of defence application) and technology (i.e. maturity of technology) over time. This graphical form (please see Fig. 7.3 and 7.4) allows the simultaneous representation of multiple dimensions, and can be used to show precedence, parallel processes, and the passage of time. The case studies provided empirical validation for our theoretical framework in defence technological innovations.

	Low application uncertainty	High application uncertainty
High technical uncertainty	Due to land constraint, an underground ammunition depot was planned for the replacement for Seletar Ammunition Depot. The UAF was successfully developed using technologies developed over a decade of R&D.	Ammunitions and explosives in Singapore are stored in above ground ammunition depot. Infra-red technology is used in various military applications such as detection and surveillance.
Low technical uncertainty	During the SARS crisis, the IFSS was developed using infra-red technology to filter out individuals who have abnormally high body temperature.	Defence Science & Technology Agency, the Singapore Armed Forces, and Singapore Technologies developed infra-red sensors to meet the unique operational requirements in Singapore.

Fig 7.3. Case study of the development of the Underground Ammunition Facility (UAF) and Infra-red Fever Scanner System (IFSS)

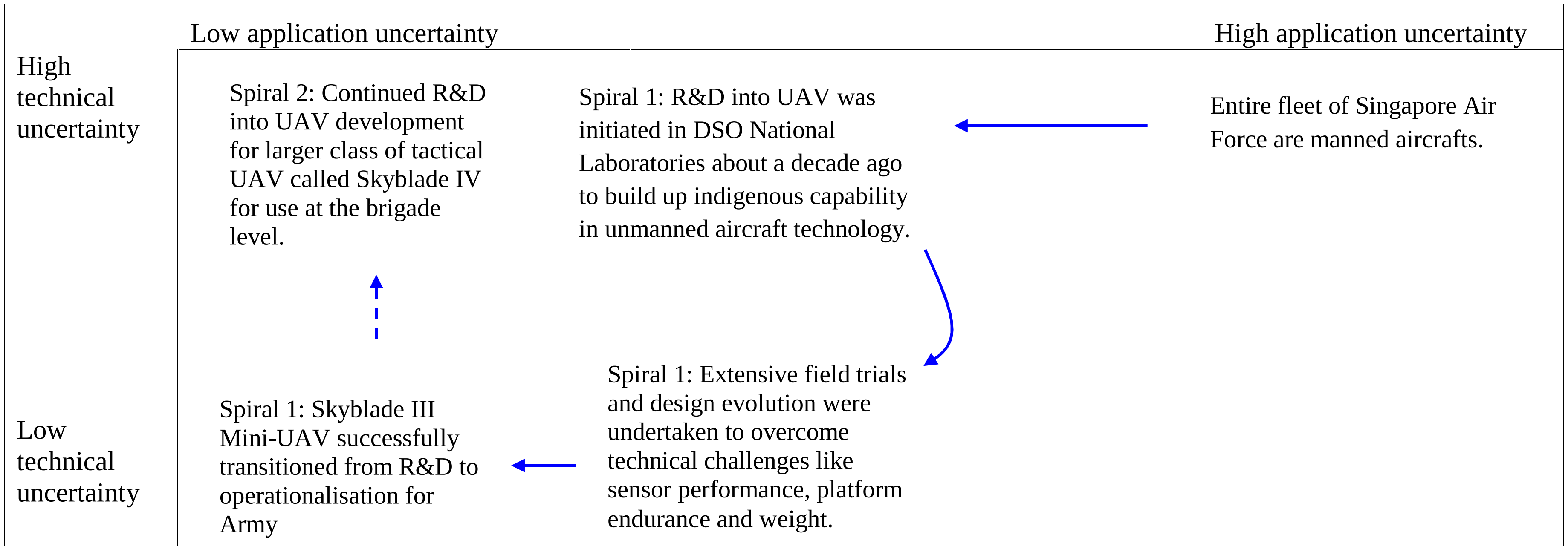


Fig 7.4. Case study of Unmanned Aerial Vehicles development in Singapore

7.3.2 Applying the defence R&D investment evaluation methodology

We apply our proposed defence R&D investment evaluation methodology presented in Section 7.2 to the cases. The results of the three step evaluation process are summarised as follows:

Step 1: Differentiate the various stages in the programme and evaluate the stage under consideration.

The various stages of the cases are differentiated and the stages (projects) under consideration are summarised in Table 7.4. The level of uncertainty in application (vis-à-vis the New Product Development and Technology Development process) and technological maturity level (benchmark against the Technology Readiness Level framework) are evaluated and tabulated.

Technology	Spiral	Founding Stage Capability	Development Stage Capability	Maturing Stage Capability
Underground Ammunition Facility (UAF)	-	Investment in human capital in explosive safety and underground technology and rock engineering.	Idea for UAF generated when technology is at TRL3. Initiate development of technologies in underground explosive storage.	Successful development of technologies in underground explosive safety which can be inserted into UAF development.
Infra-red Fever Scanner System (IFSS)	-	Investment in human capital in sensor technology.	Development of capability in infra-red sensors.	Idea for IFSS generated when infra-red sensor technology is at TRL7. Technology could be adapted within 2 weeks for fielding of IFSS.
Indigenous Unmanned Aerial Vehicle (UAV)	1	Investment in human capital in sensor and platform technologies.	Idea is generated when technology is at TRL3. Initiate development of sensor performance and platform endurance for mini UAV.	Successful development of technologies in sensor performance and platform endurance leading to full scale development then fielding of mini UAVs.
	2	Human capital built up in Spiral 1.	Development of sensor performance and platform endurance for tactical class UAV.	R&D for tactical class UAV in progress.

Table 7.4. Differentiating the stages within the innovation programmes

Step 2: Categorise the real option embedded in the R&D investment using our Framework for Defence R&D Innovations.

The real options embedded in the R&D investments in the various stages of innovations are categorised and summarised in Table 7.5 using our Framework for Defence R&D Innovations. The appropriate evaluation method for each of the innovations depends on the level of uncertainty in its application and technology maturity.

	Low application uncertainty (idea generated)	High application uncertainty
High tech Uncertainty (TRL1-3)	Development of technologies in (1) underground explosive storage and (2) sensor performance and platform endurance for UAV: Positioning options which can be evaluated using Real Options Valuation approach.	Investment in human capital: Stepping-stone options which are best treated as expenses.
Low tech uncertainty (TRL4-)	With technology maturity and user evaluation, product launch of the UAF, IFSS and UAV can be evaluated using capital budgeting methods.	Developing and sustaining our competency in sensor technology: Scouting options are can be evaluated using Systems Engineering approach.

Table 7.5. Categorisation of real options in cases and selection of appropriate evaluation methods

Step 3: Valuation of real options using an appropriate method.

Capital budgeting method, such as the Net Present Value method, can be used for the valuation of the investment in the facility development of the UAF, system development of the IFSS, and platform launch of the UAV, which are of relatively lower technological risk and uncertainty in application.

Investments to develop founding stage capabilities, for example human capital in explosive safety, create broad based stepping-stone options which can be framed as a generic set of resources and form platforms for future development and opportunities. The operational impact of these investments is often too poorly defined and wide ranging, and the investments are best treated as expenses.

Real Options Valuation (ROV) is suitable for the valuation of positioning options where the level of uncertainty is in between the two ends of the spectrum of technological uncertainty. The creation of technological options in underground explosive safety and sensor performance and platform endurance is driven by application and the scope of these activities is fixed a priori. The decision to abandon the initiative has been clearly articulated and the flexibility associated with the option investment can be readily maintained and evaluated using ROV approach such as the Classical, Revised classical, Integrated and Marketed Asset Disclaimer (MAD) methods.

Scouting options are used to learn about the operational scenario by probing. As the target applications for our development capabilities in sensor technology are still flexible before the Severe Acute Respiratory Syndrome (SARS) pandemic, the investments may be better modelled as generic path-dependent processes. These are most appropriately evaluated using our improved scoring method. This simple method can evaluate both financial and non-financial returns. The real options approach considers the uncertainty and risk in the applications and technology. While the simulation and Value-at-Risk (VaR) techniques can be adopted to consider the path dependence.

8. DISCUSSION AND CONCLUSION

In this final chapter of our thesis, we would conclude with a discussion of the assumptions, limitations and contributions of our project and possible future work.

8.1 Assumptions and Limitations

This project develops a theoretical framework for the capability development during defence R&D process and proposes applications in strategic heuristic and evaluation of defence R&D investments. Many related topics, which are adequately discussed in the literature, are not considered here to avoid diluting our focus. These include important issues such as the impact of defence R&D spending on the economy, dual use technology, and defence procurement.

8.2 Comparison with current evaluation methods

8.2.1 Evaluation method for defence R&D investments

The Analytic Hierarchy Process (AHP) comparative analysis framework proposed by Poh et al (2001) offers a formal and objective comparison of the strengths and weaknesses of our improved scoring method and the various existing R&D evaluation methods.

Table 8.1 shows the result of the comparative study on six evaluation methods using seven proposed criteria. The evaluation methods compared were (1) scoring method, (2) AHP, (3) decision tree analysis, (4) economic analysis, (5) cost-benefit analysis, and (6) comparative method. The seven criteria proposed by the authors were (1) multiple objective, (2) risk and uncertainty, (3) simplicity, (4) data availability, (5) adaptivity, (6) nature of data, and (7) cost. Based on their subjective evaluation, scoring method is the most favourable method for R&D project evaluation. This is consistent with literature comments that scoring methods are popular because of their ability to deal with multiple dimensions of R&D problems and their simplicity in formulation and use.

METHODS	CRITERIA							RANK
	Multiple objective 0.309	Risk & uncertainty 0.254	Simplicity 0.141	Data availability 0.099	Adaptivity 0.094	Nature of data 0.064	Cost 0.039	
Scoring	0.306	0.133	0.316	0.278	0.266	0.270	0.134	1
AHP	0.345	0.096	0.153	0.278	0.252	0.309	0.123	2
Decision Tree	0.123	0.238	0.232	0.136	0.125	0.075	0.143	3
Economic	0.043	0.308	0.116	0.145	0.039	0.036	0.304	4
Cost/Benefit	0.126	0.142	0.144	0.083	0.073	0.094	0.253	5
Comparative	0.056	0.083	0.038	0.079	0.245	0.216	0.042	6

Table 8.1. Overall results of comparative study of R&D evaluation methods (Poh et al, 2001)

Using visual inspection of the results of the comparative study and avoiding the problem of rank reversal when introducing a new candidate, we observe that the traditional scoring method is deficient in the ability to handle risk and uncertainty. With the integration of the Real Options approach, the ability of the scoring method to handle risk and uncertainty is improved. While the cost of implementing our method may be higher than the traditional scoring method, our enhanced scoring method is likely to retain the most favourable ranking as Poh et al (2001) has demonstrated that cost of performing evaluation is small when compared with the high value and high stakes of the R&D decisions.

8.2.2 Evaluation methodology for defence R&D investments

We compare our proposed evaluation methodology comprising a structured approach to advise the appropriate real options based evaluation method, against the existing R&D evaluation methods in the literature (see Table 8.2).

8.3 Contributions

The approach of this project is clearly different from mathematical work or pure management of technology research. The good and novel positioning has led to a unique research with theoretical as well as practical contributions to the body of knowledge on strategic and technology management, real options and systems engineering.

Criteria	Literature	Our proposed evaluation methodology	Remarks
Considers the organisational issue	Classical methods generally inadequate. Systems model attempt to consider systemic issues but are not directly used by practitioners.	Structured approach to select an appropriate real options based evaluation method. Various methods to evaluate qualitative benefits cited.	Strategic consideration of defence R&D investments to create real options in capabilities.
Treatment of project parameters	Classical methods generally inadequate. Decision analysis can consider risks and uncertainty.	Real options based structured approach considers uncertainty and risks in application and technology.	Decision analysis and real options differ in the estimation of discount rate.
Treatment of the portfolio effect	Classical methods generally inadequate. Portfolio approach can be adopted to consider portfolio effect.	Methodology can be extended to consider portfolio effect of real options with different strategic objectives and uncertainty.	Consideration of real options portfolio is a key enhancement over classical approach.
Support for the innovation process	Inadequate generally.	Strategic consideration of defence R&D as a process to develop capabilities and create real options.	Consideration of innovation is a key enhancement over existing models.

Table 8.2. Comparison of proposed evaluation methodology against existing evaluation methods

8.3.1 Implications to theoretical research

Our research introduced concepts from theories in strategic and technology management, real options and systems engineering in defence technological innovations and demonstrated the validity of these theories within the defence context.

This project developed a theoretical framework for defence R&D innovations by building on the body of knowledge in these theories, and empirical evidences from historically significant defence technological innovations. This theoretical framework contributes to our understanding of the dynamics of defence R&D innovations.

8.3.2 *Implications to practice*

Building on our theoretical framework for defence technological innovations, we developed a strategic heuristic for defence technology management and R&D investments. This cognitive representation helps to find appropriate and faster solutions to real-time problems, and guide strategic formulation and planning in defence technology management and R&D investments.

In addition, we also build on the framework to (1) develop an effective and objective evaluation methodology and (2) improve an evaluation method for defence R&D investments. The evaluation methodology improves some of the weaknesses in existing methods by consideration of risk and uncertainty and innovation system and support for innovation. In particular, we recognised that real options is a theoretically attractive model for defence R&D investments but its application thus far had been challenged by theoretical boundaries and appropriateness of the evaluation method. Our methodology identifies the nature of the real option embedded in a defence R&D investment and advises the appropriate evaluation method. We also enhanced the scoring method, which is popular for its simplicity but lacks consideration of risk and uncertainty, with the real options approach. The enhanced scoring method has improved consideration of the risk and uncertainty in defence R&D investments.

Finally, we demonstrated the validity of our theoretical framework and illustrated the application of the proposed strategic heuristic and evaluation methodology in several contemporary examples of defence technological innovations.

8.4 Future work

This thesis is concerned with improving our understanding of the dynamics of defence technological innovations and, hence, developing a better strategic heuristic for R&D strategy and investments, and a more effective evaluation framework for defence R&D investments. In addition to a robust strategy and making good go-no go decisions for investments, several other elements are essential for a good defence R&D acquisition process and merit further research. These issues include selection of the defence contractor and contracting strategy. Besides the acquisition process, R&D Style is another important factor influencing the success of defence R&D investments. Research into the successful R&D Style would contribute to the body of knowledge on successful planning and implementation of defence R&D investments. Further research would be welcomed in other dimensions of defence technological innovations such as continuous vs discontinuous innovations. Analysis of the impact of technology on the conduct of and preparations for war tend to underscore either the continuities inherent in evolutionary processes of technological development or the discontinuities apparent in revolutionary technological leaps. An important research question would be the factors which encourage disruptive defence technological innovations. Finally, our proposed theoretical framework and evaluation methodology could potentially be adopted to better understand and evaluate R&D investments outside the defence domain.

8.4.1 Improving the acquisition process for defence R&D investments

Gansler (1980) highlighted the impacts of the U.S. government defence acquisition process coupled with the defence industry structure on defence R&D decisions. For example, as a result of the public visibility and accountability of government decision makers in the acquisition process, decision makers feel they must minimise the risk associated with a R&D programme. Thus, there is a tendency to give the business to large, well-established firms and, similarly, to select very conventional ideas for development. Furthermore, the defence industry is high concentrated with a few large firms. These firms tend to be risk minimisers, and thus tend not to push high-risk inventions involving totally new ideas or applications. This kind of R&D also tends to fit well with the existing structure, to match the form and objectives of the current organisations and to address the questions that these organisations are willing to ask. Singh (1998b) also highlighted that because of the high cost and risks in the defence business, the defence industry and defence R&D organisations tend to seek autonomy and public money in order to build themselves up, using the arguments of defence industrial self-reliance or efficiency in meeting military requirements. However, independent technical evaluation and professional monitoring are essential for efficient defence R&D. Hence, there is a need to improve the decision making over the appointment and management of defence R&D contractors.

Another issue in the acquisition process which would require further research is the contracting mechanism under which the winner of the initial R&D competition dominates the full acquisition cycle. This mechanism encourages "buying-in" for the initial R&D programme involving intentionally bidding below cost in order to obtain the initial contract (Gansler, 1980). Taught by experience, the bidders can make highly optimistic estimates on schedule and cost for the development phase if they anticipate significant design changes coming along during the development programme. These changes result in increased costs for the overall development programme, and stretched out schedule. Hence, there is a need for research into contracting strategy which encourages the most cost effective approach to defence R&D.

8.4.2 R&D Style

Perry (1980) defined "R&D style" as the policies, procedures and preferences that characterise R&D programmes, and proposed that the principle style elements of successful defence R&D could be epitomised in three broad propositions. First and most important, the management of an R&D enterprise must be responsive to the contemporary state and nature of whatever technology is being manipulated. One discriminator is whether “large” advances in system performance can be extracted from a particular R&D programme. Will the state of the technology being exploited support an attempt to leap grandly ahead, or should ambition be limited to smaller and presumably more realistic advances? In the end, it would seem that successful new weapons more often derive from proven technology than from efforts to shape, push, or contrive immature technology. Second, the fundamental goal of R&D is to reduce uncertainty, but uncertainty cannot always be diminished fast enough to ensure programme “success”. Therefore cancellation must be viewed as one acceptable outcome of any R&D project, sometimes vastly preferable to a calculated continuing effort to achieve the unachievable. Third, an unqualified commitment to some means of performing some desirable function can indicate a costly failure or a yet more costly “success”. For example, the late delivery of an expensive military equipment might prove to be of little or no military worth. These are important issues to examine in the conception of defence R&D investment as a real option which conveys the right, but not the obligation, for a firm to make further investments or defer such investments. For example, Adner and Levinthal (2004) proposed that the boundaries of the real options logic should be considered with a more nuanced organizational perspective that incorporates the different views that exist within an organization. The firm cannot be regarded as a unitary actor and the open-ended nature of the R&D success raises organizational challenges to abandoning options that can deter firms from exercising the very flexibility that made the real options approach attractive in the first place.

Some of the perceived differences in R&D styles between countries derive from culture, tradition and dogma. Hence, future contributions can be made with studies of the defence technological innovations in different countries, to improve our understanding of the drivers for different R&D styles and further sharpen our theoretical framework of defence technological innovation. For example, it is a credo in the former Soviet Union that weaponry cannot drive military strategy, but rather that doctrine determines requirements which in turn dictates technology choice (Perry, 1980). In this thesis, several case studies of historically significant technological innovations were used to support the theory building for our theoretical framework of defence technological innovations, and case studies of three defence technological innovations were used to illustrate the contemporary validity of the framework. Future contribution can be made with applications of the framework in countries with varying culture, tradition and dogma. Besides improving the empiricism, these applications would also fine tune the process of applying the framework.

8.4.3 Continuous vs discontinuous innovations

Parker (2009) observed that a series of expensive technological and tactical revolutions have punctured military history: gunpowder weapons, the artillery fortress, the 'ironclad' battleship, the panzer division, nuclear weapons, 'smart' bombs. Each revolution has called forth rapid responses from those adversaries capable of mobilizing the necessary financial resources and of restricting their economy so that military technology could receive sufficient support. An important research question, hence, would be the factors which encourage disruptive defence technological innovations.

Szyliowicz (1981) noted that discovery-push creates its own demand in the market, while demand-pull responds to market demands. The latter tends to yield incremental, or evolutionary technological advances, rather than non-incremental, revolutionary, or what he terms ‘breakthrough’, advances that tend to be the result of the discovery-push process. Demand-pull, then, can generally be associated with technological continuity, and discovery-push with technological discontinuity. In defence R&D, the R&D done by the large firms tends to be more of the exploitation type than of the exploration type (Perry, 1980). This comes in part from the institutional inertia of the large firms, and in part from their internal management decision process. Thus the concentration within the defence industry in a few large firms tends to emphasise low-risk, incremental change rather than the generation of really significant new departures. More recently, the proposal by Christensen (1997) that disruptive technologies with inferior performance can displace established incumbents has had a profound effect on the way in which scholars and managers approach technology competition (Adner, 2002). This includes research into the dynamics of this notion of disruptive technologies, for example, Adner (2002) who identified the demand conditions that enable disruptive dynamics and proposed the characterisation of the relationships among the preferences of different market segments using preference overlap and preference symmetry.

8.4.4 Non-defence R&D investments

Our proposed theoretical framework and evaluation methodology could potentially be adopted to better understand and evaluate R&D investments outside the defence domain. As the framework and methodology were developed in the defence context where the large-scale mission oriented projects aim to develop specific technologies under high appropriability and high cumulativeness (at the firm level) conditions, they would be particularly relevant in other Schumpeter Mark II Model of innovation regime (Breschi et al., 2000). An example is the R&D for new drugs within the pharmaceutical industry where the innovation regime - similar to that of the defence industry - is characterized by “creative accumulation” and the importance of experience in innovative efforts. Pharmaceutical innovations are also highly appropriable as a result of intellectual protection and stringent regulations.

APPENDICES

APPENDIX A: CASE STUDIES OF SEVERAL IMPORTANT DEFENCE TECHNOLOGICAL INNOVATIONS

The data selected are several of the most important defence technological innovations (van Crevald (1989), Perry (2004)). They are selected for their significance and their exhibition of both discontinuous and continuous technological changes over time.

S/n	Case study	Description and sources	Examples of sources
C1	Submarine	Development of vessels to navigate and attack from beneath the water surface.	Clancy (1993), Volkman (2002), US Navy (2011)
C2	Rocket	Development of propelled munitions to hit targets at large distances.	Hambling (2005), Volkman (2002), NASA (2011)
C3	Tank	Development of a motorised all-terrain armoured vehicle for overland attack.	Gudmundsson (2004), Humble, (1977), Ogorkiewicz (1991)
C4	Radar	Development of a remote detection system for aircrafts.	Hambling (2005), Volkman (2002), RAF (2011)
C5	Nuclear bomb	Development of a bomb to capture the powerful forces of the atom.	Siracusa (2008), Delgado (2009), FDR (2011)
C6	Military aircraft	Evolutionary development of the flying machine for various military applications.	Higham (1972), Glancey (2006)
C7	Jet engine	Development of a powerful engine for the aircraft.	Hambling (2005), Scranton (2006), Glancey (2006)
C8	Ballistic missiles	Development of ballistic munitions to hit targets at very large (e.g. intercontinental) distances.	Hacker (2005), Hacker (2006), NASA (2011)
C9	Stealth	Development of technology to avoid remote detection of aircraft.	Aronstein and Piccirillo (1997), Matricardi (2007), FAS (2011)

The sources for the data include (1) books which chronicle the history of these innovations, for example Aronstein and Piccirillo (1997) which chronicles the development of the first stealth fighter, (2) scientific press, for example the textbook by Ogorkiewicz (1991) on tank technology, and (3) other published literature on weapons technology, for example, Black (2007), Cook and Stevenson (1980), Dupuy (1990), Macksey (1986), Perry (2004), van Crevald (1991).

APPENDIX A-1: SUBMARINE

Traditional naval warfare is waged through caravels, galleons, man-of-wars and frigates on the water surface. The capability development for a submarine to attack a surface vessel from underwater is primarily driven by military application. The first workable submarine, the Turtle designed by David Bushnell in 1776, was propelled by a hand-crafted screw and had room for only one crewman (Clancy, 1993). This crewman had to bore a drill bit into the bottom of the hull of the target vessel and attach a waterproof time bomb, then escape before the bomb was detonated by a clockwork fuse.

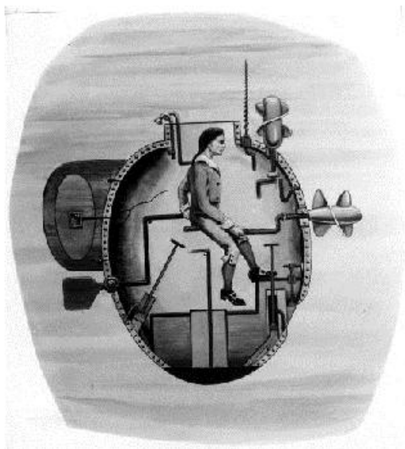


Fig A-1. The Turtle in an 1875 drawing by Lt. Francis Barber

(Source: Web site of the U.S. Chief of Naval Operations, Submarine Warfare Division, http://www.navy.mil/navydata/cno/n87/history/subhistory.html)

The Nautilus, designed by Robert Fulton, was able to cruise under the intended victim, towing the explosive bomb until the bomb contacted the target and detonated with a contact fuse, in successful demonstrations in 1801 and 1805 (US Navy, 2011). This craft had a copper-sheathed hull, equipped with a mast, bowsprit and two sails for surface propulsion and two handcranked screws to travel underwater. Depth was estimated using a barometer, while air was supplied to the four men crew by flasks of compressed air on board. During the American Civil War, the H.L. Hunley of the Confederacy attacked and sank the Union steam corvette Housatonic in 1864 (US Navy, 2011). The Hunely was fitted with bulls-eye glass in two manhole covers fore and aft on the deck, which were secured by rubber gaskets and bolted from within. The iron hull had a keel and contained water-ballast tanks to raise and dive the boat, via pumps and sea-cocks. Diving was assisted by two lateral fins, five feet long, operated by a lever amidships. The propeller was turned by hand by eight crewmen, and the boat made four knots in calm sea. For armament, an explosive mine was secured to a long spar protruding out in front of the craft which is rammed into the side of a target ship and detonated. In 1900, John Holland won a submarine design competition held by the U.S. Navy and went on the design the USS Holland (SS-1), the first practical combat submarine (US Navy, 2011). It included such innovative features as self-propelled torpedoes fired from a reloadable tube, a battery-powered electric motor for submerged operations, and an advanced hull shape to allow it to move efficiently through the seas.

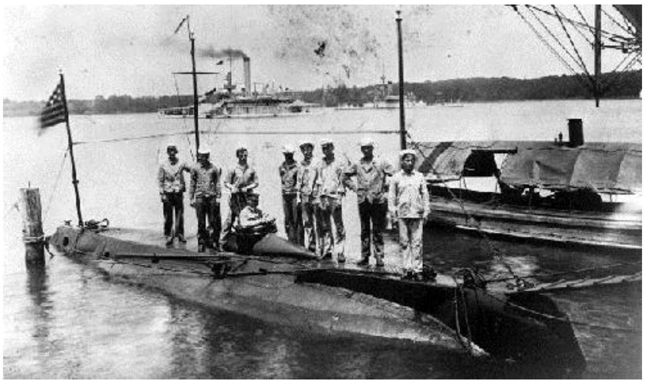


Fig A-2. The USS Holland

(Source: Web site of the U.S. Chief of Naval Operations, Submarine Warfare Division, http://www.navy.mil/navydata/cno/n87/history/subhistory.html)

A number of innovations in military submarines were made in the period before World War I, including the development of diesel engines, improved periscopes and torpedoes, and the development of wireless technology which allowed them to be directed from shore bases (Volkman, 2002).

	Low application uncertainty	High application uncertainty
High technical uncertainty	Driven by military application, the capability of the submarine improved from the first workable submarine, the Turtle, through the H.L. Hunley which successfully sank a target in battle.	Traditional naval warfare occurs on the water surface.
Low technical uncertainty	The first practical combat submarine was produced and innovations, including the diesel engines, improved periscopes and torpedoes, and wireless technology, were introduced.	

APPENDIX A-2: ROCKET

The Chinese was an early user of gunpowder and invented gunpowder-propelled rockets early in the thirteenth century NASA (2011). Many subsequent military thinkers and technicians dreamed of giant rockets that could be launched to hit targets hundreds of miles away but the gunpowder propulsion was insufficient to propel a heavy rocket any significant distance. The rocket also could not be launched beyond the earth's atmosphere as gunpowder would have no oxygen to burn.

Fig A-3. Gunpowder propelled rockets were used by the Chinese against the Mongols in the siege of Kai Fung in A.D. 1232

(Source: Web site of NASA, http://mix.msfc.nasa.gov/abstracts.php?p=849)

Robert Goddard demonstrated in 1919 that these problems could be overcome by rocket carrying its own oxygen supply, a liquid version combined with a fuel that has a very high and powerful burn rate, such as hydrogen (Volkman, 2002). Goddard's work inspired a group of German rocket enthusiasts to adopt his technical ideas for their own rocket experiments. In 1935, this group of German rocket enthusiasts was enlisted by the German army to develop long-range ballistic rockets capable of carrying large explosive warheads. During World War II, the group developed the V-2 rockets which produced 28 tons of thrust from a fuel of liquid oxygen and alcohol, and together with a set of gyroscopes, and flight guidance fins, could launch a 400-pound warhead of high explosives on a target hundreds of miles away (Hambling, 2005; NASA, 2011).

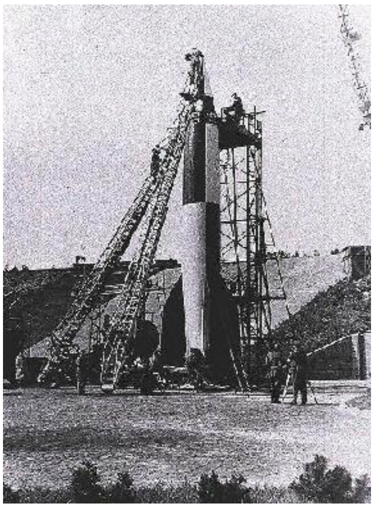


Fig A-4. German V2 rocket being prepared for launch in the early 1940's.

(Source: Web site of NASA, http://www.grc.nasa.gov/WWW/k-12/rocket/gallery/history/hist1.html)

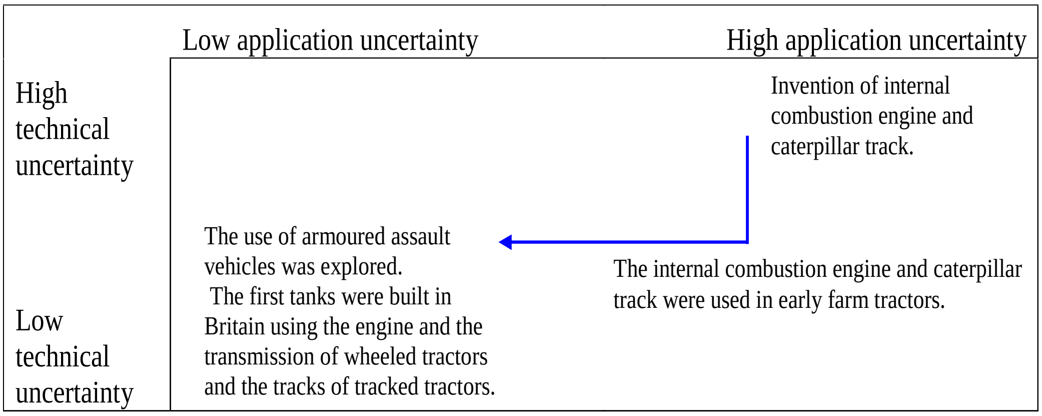
	Low application uncertainty	High application uncertainty
High technical uncertainty	The Chinese invented rockets propelled by gunpowder but giant rockets could not be launched to hit targets a significant distance away.	The invention of gunpowder.
Low technical uncertainty	Goddard demonstrated rocket propulsion using liquid fuel. His technical ideas were further developed by the Germans who went on to build the V-2 rockets during World War II.	

APPENDIX A-3: TANK

The key enabling technologies for the tank - internal combustion engine and caterpillar track – were mature technologies being used in early farm tractors before military innovation of tanks during World War I (Humble, 1977; Ogorkiewicz, 1991). During the war, the opposing armies were held to a deadlock as the traditional infantry attacks had become difficult due to increasingly effective firepower and extensive use of entrenchment and barbed wire deployed in defence. Consequently, the use of armoured assault vehicles, which would crush the barbed wire and whose protection would enable them to approach enemy trenches under machine-gun fire, was explored. The first experimental tank was built in Britain in September 1915 using the engine and the transmission of wheeled tractors and the tracks of Bullock tractors procured from the United States (Humble, 1977; Ogorkiewicz, 1991). An improved design, with much longer and higher tracks to meet a new requirement to cross trenches 1.5m wide and with parapets 1.4m high, was completed and successfully demonstrated in February 1916, and the War Office ordered one hundred and fifty similar vehicles. On 15 September 1916, the 49 tanks available were sent on the first ever tank action to help the infantry assault enemy trenches on the Somme (Gudmundsson, 2004).

Fig A-5. Tanks are first used in battles in Somme in 1916

(Source: BBC, web site: http://news.bbc.co.uk/2/shared/spl/hi/pop_ups/06/uk_battle_of_the_somme/html)



APPENDIX A-4: RADAR

In 1934, Robert Watson-Watt of the National Physical Laboratory informed the British Air Ministry that an aircraft could be detected at long range by radar waves and displayed in three dimensions on the cathode ray tube (CRT) screen commercially available since 1922, and its position, altitude and course plotted (Hambling, 2005; Volkman, 2002). The reflection of radio waves from a metallic object was first demonstrated in 1855 and the ionosphere discovered in the early 1920s had provided the essentials of radar. Using the principle that any solid object will reflect radio waves, by sending radio waves out on a fixed wavelength and recording the 'echo', it is possible to calculate the range and direction of movement of the object. In February 1935, Watson-Watt demonstrated the detection of an aircraft flying at 10,000 feet at a range of eight miles.

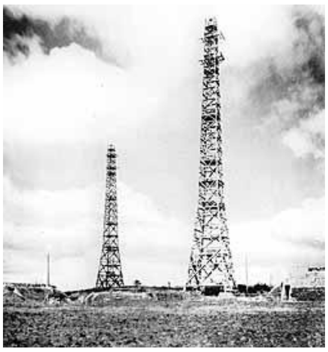


Fig A-6. Chain Home wooden receiver towers
(Source: Web site of Subterranea Britannica, http://www.subbrit.org.uk)

By 1938 the British Chain Home Stations set up to scan the eastern and southern skies were reaching out with 60% reliability to 70 miles at 20,000 feet, and a chain of radar stations was built along the south and east coasts of

Britain by 1939. Linked to a highly efficient control network, this early radar system played a crucial part in detecting formations of enemy aircraft as they approached the coast, allowing fighter command to deploy their resources most effectively, and played a decisive part in the success of the Battle of Britain (RAF, 2011).

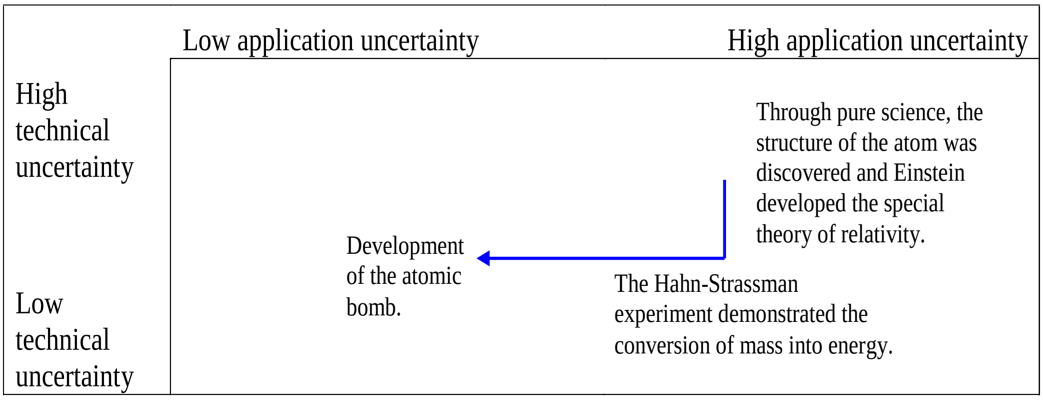
	Low application uncertainty	High application uncertainty
High technical uncertainty		The reflection of radio waves from a metallic object was demonstrated.
Low technical uncertainty	Watson-Watt demonstrated that an aircraft could be detected by radar waves and its position, altitude and course plotted on the CRT. The British set up the Chain Home Stations to scan the eastern and southern skies.	The essentials of the practical radar were complete with the discovery of the ionosphere and commercial availability of the CRT.

APPENDIX A-5: NUCLEAR BOMB

Knowledge about the nature of the atom grew rapidly in the early 1900s and the atomic structure was recognised as a positively charged nucleus surrounded by negatively charged electrons located in defined shells. In 1905, Albert Einstein developed the special theory of relativity, one of the implications of which was that matter and energy are interchangeable with one another. In 1938, Otto Hahn and Fritz Strassman split the uranium atom and demonstrated the conversion of mass into energy in the fission process (Siracusa, 2008). The chain reaction when the uranium nucleus splits apart could set off a huge release of energy in millionths of a second. These discoveries had been pure science but physicists soon recognised that if the chain reaction could be tamed, fission could lead to a promising new source of power. In August 1939, fearing that Nazi Germany would convert the fission process into a weapon, Einstein and fellow atomic scientists wrote to President Roosevelt informing him that recent nuclear research had made it 'probable .. that it may become possible to set up a nuclear chain reaction in a large mass of uranium, by which vast amounts of power and large quantities of new radium-like elements could be generated', leading to 'to the construction of bombs, and it is conceivable – though much less certain – that extremely powerful bombs of a new type may thus be constructed' (FDR, 2011). Roosevelt promptly set up an exploratory committee to study uranium.

In 1942, Britain and the United States pooled their resources and information on atomic bomb development under the auspices of the Manhattan Project (Delgado, 2009). The project brought together the top scientific minds of the day with the production power of American industry and successfully produced the atomic bomb by the end of July 1945. Two designs, one using uranium 235 and another using plutonium, were produced. The uranium bomb (code named “Little Boy”) was a simple design and scientists were confident it would work without testing. The plutonium bomb (code named “Fat Man”) was more complex and worked by compressing the plutonium into a critical mass which sustains a chain reaction. The compression of the plutonium ball was to be accomplished by surrounding it with lense-shaped charges of conventional explosives. They were designed to all explode at the same instant. The force is directed inward, thus smashing the plutonium from all sides. In an atomic explosion, a chain reaction picks up speed as atoms split, releasing neutrons plus great amounts of energy. The escaping neutrons strike and split more atoms, thus releasing still more neutrons and energy. In a nuclear explosion this all occurs in a millionth of a second with billions of atoms being split.

Fig A-6. The first atomic bombs, “Little Boy” and “Fat Man”
(Source: Web site of White Sands Missile Range, http://www.wsmr.army.mil)


Low application uncertainty
High application uncertainty
High technical uncertainty
Low technical uncertainty
Through pure science, the structure of the atom was discovered and Einstein developed the special theory of relativity.
Development of the atomic bomb.
The Hahn-Strassman experiment demonstrated the conversion of mass into energy.

APPENDIX A-6: MILITARY AIRCRAFT

The capability development for the military aircraft demonstrated a different process in which new applications and requirement for technological development were discovered through spiral experimentation and learning process.

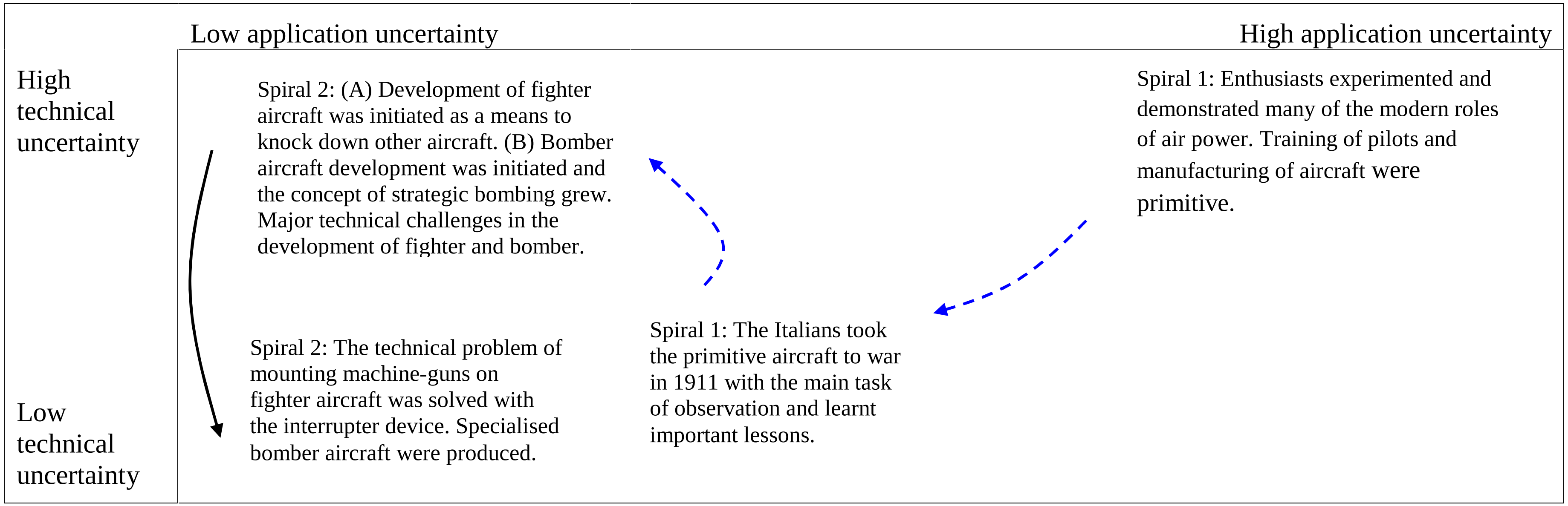
After the Wright brothers demonstrated the first heavier-than-air powered flying machine controlled by a pilot on 17 December 1903, the military of many powers including the United States and Britain were uninterested in aircraft for the next three years (Higham, 1972). Nonetheless, the enthusiasts experimented with bomb-dropping, mounting machine guns and aerial photography, and demonstrated many of the modern roles of air power. Most aircraft were a combination of wooden frames, fabric covering, and wire bracing, powered by an unreliable reciprocating petrol engine, and designed and manufactured by small team and manual operation. Despite their primitiveness, the Italians took aircraft to the war against the Turks in Libya in 1911 with the main task of observation. Many lessons were soon learned: observers were needed to take notes of ground activity; more pilots as well as more aircraft had to be available; these in turn required a better servicing organisation. The requirement for better maps led to aerial photography; observation of bombardment was less fruitful, since airmen could not communicate with the gunners to correct their aim or choice of target. The Italians demonstrated the value of a war for pointing up weakness and showing the lines along which developments might be profitable. The Libyan campaign taught the Italians the usefulness, rapidity and reliability of air reconnaissance; the need for accuracy in bombing, the dangers of ground fire; and the limitations of equipment.

With the deadlock of World War I, reconnaissance aircraft was the only means of (Glancey, 2006) evolved as a means of denying the enemy this invaluable information by arming aircraft to knock down other planes. However, early gunnery was primitive and the pilots were armed only with pistols and hand grenades. To take advantage of rapid diving attacks, a suitable aerial weapon would be a forward-firing machine-gun, sited along the line of the aircraft fuselage, but the difficulty lay in avoiding the propeller blades. Early experiments tried to overcome the problem by fitting deflectors on to the propeller blades but this impaired aiming. The Germans eventually solved the problem with a proper interrupter gear that enabled the pilot to fire fixed guns at random through the propeller arc. This mechanism was incorporated in the Fokker Eindecker 1 by the summer of 1915, which followed by the Mk II and III, tilted the air warfare in favour of Germany until the allies aircraft were equipped with an effective interrupter gear in mid-1916.

Fig A-7. The Fokker Eindecker III monoplane was fitted with an interrupter gear (synchronizer) which enabled a machine gun to fire through the spinning propeller

(Source: Web site of New England Air Museum, http://www.neam.org)

An equally significant development was the development of bomber aircraft and the rapid growth of the bombing role of aircraft. The first bombing raid of the war was carried out by French Voisin bombers on 14 August 1914 against German Zeppelin sheds near Metz (Higham, 1972). Typical of the early bombers, the Voisin was basically a general-purpose aircraft from which up to 124lb of bombs could be dropped by hand. It was only capable of 70mph and a range of 125miles. The development priorities for bomber aircraft, henceforth, were greater power and speed, and to improve on range and payload, and accurate navigation and bombsights. By middle years of the war specialised bomber aircraft were being produced. The Italians developed the large Caproni Ca series, which in its later versions was capable of speeds up to 85mph, had a ceiling of 13,400 feet and could carry a bomb load of up to 1,000lb. These planes had a range of about 300miles and the Italians became the first to carry out true strategic bombing, massing large numbers of aircraft to strike against a single target.



Spiral defence technological innovation: military aircraft

APPENDIX A-7: JET ENGINE

For their first four decades, aircraft were driven by propellers powered by piston engines and the maximum speed of such aircraft is limited by how fast the propeller can push air. Throughout the 1930s, fighters and bombers were designed with ever greater speed and altitude, with the war applying even more pressure. Speed was the trump card in air-to-air combat. A faster bomber could not be intercepted by a slower enemy, and the pilot with the faster machine could always put his foot down and break off the fight if it was going against him. This led to larger and larger engines, which meant more and more weight. By 1938, the Mark I Spitfire had a speed of 350 m.p.h., leaving the Sopwith Camel trailing (Hambling, 2005; Glancey, 2006). By 1944, the Mark XIV Spitfire could manage 450 m.ph. although this required doubling of the engine power, and an increase of 50 per cent in the weight of the aircraft.

More powerful engines needed bigger aircraft to carry them, and the limits were being approached. A better power-to-weight ratio would improve matters, but piston engines were already reaching the theoretical limits. Air resistance also increases with speed. This can be overcome by flying higher, where the air is thinner and there is less resistance – but the efficiency of the piston engine driving the propeller is reduced in the thinner air, so the speed falls off again. A faster propeller can increase the speed, but only up to a certain point. As the speed of the propeller tips approach the speed of sound, they produce shockwaves, making the propeller less efficient at shifting air. The shockwaves also cause vibrations which threaten to destroy the propeller, putting a practical limit on the speed a propeller can achieve (Scranton, 2006).

In 1928 Frank Whittle, then a student at the RAF College, Cranwell, submitted a thesis proposing the basic idea of jet engine which could replace both the piston engine and the propeller altogether (Hambling, 2005; Glancey, 2006). By 1929 he had formulated the idea of using a gas turbine which had previously been used for power generation to power the engine, and applied for a patent for the jet engine in 1930. Whittle recognised that the power-to-weight ratio of the jet engine is much higher than the piston engine, and the speed of the exhaust from the jet and the aircraft it was driving was potentially far greater than anything which could be achieved with a propeller. However, the British Air Ministry was stretched for funding, and their analysis of the available compressors suggested that Whittle's idea was not practical. Whittle was not deterred, and along with two ex-RAF pilots he set up a company, Power Jets Ltd, to develop his ideas. By 1937 Whittle had successfully bench-tested a jet engine, finally proving his theory. The RAF was supportive, but the Ministry remained sceptical noting that the jet turbine required materials of a strength and heat-resistance at the limit of what could then be manufactured. It was not until 1939 when war with Germany was looming that Whittle finally received government backing.

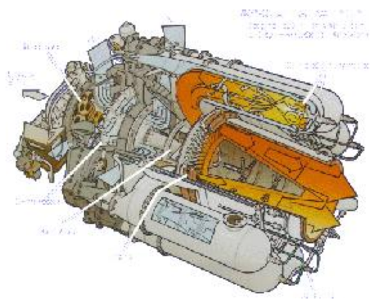


Fig A-8. W2/700 jet engine designed by Sir Frank Whittle and built by Power Jets Ltd. (Source: Web site of Midland Air Museum, http://www.midlandairmuseum.co.uk)

In Germany, Hans von Ohain who invented a jet engine independently and published theoretical work in 1933, had better fortunes (Hambling, 2005). The aircraft maker Ernst Heinkel was actively looking for new types of high-speed propulsion when he received von Ohain's proposal. Von Ohain was given a team of engineers selected from the best in the company and a working laboratory test rig was completed by 1937. The German government was quicker to appreciate the potential of the invention and gave it full support. The first jet-propelled aircraft to fly in August 1939 was a Heinkel 178. It was followed by the Messerschmitt 262, the first operational jet fighter.

Fig A-9. Messerschmilt Me 262 Schwabe twin-engine jet fighter
(Source: Web site of NASA, http://history.nasa.gov/SP-468/ch11-2.htm)

The top speed of the Me-262 at 540 m.p.h. far surpassed any Allied plane (compare that with 450 m.p.h. for the Spitfire), and its high rate of climb made it ideal as an interceptor. But the jet engines had serious drawbacks. They consumed fuel quickly, limiting the range and duration of flights. They behaved differently to propeller-driven aircraft, and getting pilots sufficiently trained to fly the aircraft in combat proved difficult. The accident rate was predictably high. The Me-262 required a long runway to get airborne, which were plainly visible to Allied reconnaissance, marking out the locations of jet bases so they could be attacked. Worst of all, new jet engines were unreliable.

The ‘mean time between failures’, the length of time the engine ran before breaking down on average, was very low. The steel alloys of the turbine blades were not rugged enough. Running at high temperature (700 degrees C), the centrifugal force on the turbine blades caused ‘creep’ in which the metal gradually deformed and the blades lengthened. The engines had to be changed before the creep was dangerous, and the early engines could only work for ten hours before they needed replacing. Improvements in the turbine blades increased the engine life progressively, but after six months of development they still only lasted twenty-five hours. The problem of producing a reliable engine slowed the introduction of the jet fighter. Even with the improved turbine blades, at any given time at least 30 percent of the jets were grounded waiting for engine changes.

When the Me-262 took to the skies, it was not invincible. Allied pilots found that the jets were vulnerable when were at low speed, after take-off and just before landing. Allied aircraft patrolled over German airfields, ready to ambush the jets. Me-262s also frequently came back to find their long runways damaged by Allied bombing, and were lost while trying to land on catered runways. Although the Me-262 gave the German pilots the option of breaking off combat, it did not mean they could win every dogfight which was conducted at relatively slow speed.

Most Me-262s went down in air-to-air combat or in accidents. Although more than 1,200 were delivered to the Luftwaffe, only about 300 saw action and they failed to make much impact of this was simply because of the sheer number of Allied aircraft. Nonetheless, the jet engine demonstrated that once the technology was mature and reliable engines could be produced, jets would leave piston-engined planes standing in a future where the only thing that would be able to catch a jet was another jet.

	Low application uncertainty	High application uncertainty
High technical uncertainty	Whittle applied for a jet engine patent with a gas turbine replacing the piston engine and propeller propulsion.	Gas turbine is used in power generation.
Low technical uncertainty	Whittle bench-tested his jet engine.	

APPENDIX A-8: INTERCONTINENTAL BALLISTIC MISSILE (ICBM)

Stimulated by an exciting new technology, all three branches of the U.S. armed forces were at work on guided ballistic missiles by the early 1950s. The German technologists brought to the U.S. after World War II by Project Paperclip, particularly Wernher von Braun and many of his team working on the V-2 rocket in Peenemunde, gave U.S. rocket research a major boost (NASA, 2011). Although work soon moved beyond the German wartime achievements, intermediate and long-range ballistic missile programmes proceeded with little urgency and many question marks. Intercontinental ballistic missiles (ICBMs), in particular, posed formidable technical problems: nuclear warheads, the most plausible payload, seemed too heavy, guidance systems too inaccurate, for the state of the art in the early 1950s. That changed as rockets and guidance systems improved, but the key breakthrough came in nuclear weapons design. More efficient warheads meant lighter payloads, while the vastly greater power of thermonuclear explosions relaxed demands on guidance by the mid-1950s.

Until the 1950s, manned bombers remained the only feasible means of delivering nuclear weapons to their targets (Hacker, 2005; 2006). The fission bombs dropped on Japan in 1945 weighed 5 tonnes. Each of them rode to its target in a Boeing B-29 (Superfortress). The only airplane large and powerful enough for the job, the B-29 was the culmination of the long-range four–engine strategic bomber through which pre-war theorists had hoped to realise their dreams of airpower. In the war's waning months, fleets of such bombers did in fact devastate Japanese industry, as their predecessors had German. Atomic bombs confirmed to many strategic bombing's war-winning potential. The B-29 and its upgraded version, the B-50 remained by far the most numerous strategic bombers through the early 1950s. In 1955 the first all-jet heavy bomber, the Boeing B-52 (Stratofortress), began to reach operational units.

The United States faced a military-scientific crisis after the Soviet Union launched the first artificial satellite on October 26, 1957, and a second eight days later with a dog as a passenger. Two Sputniks in little more than a week shook the casual confidence many Americans placed in their country's scientific and technological prowess. Soviet satellites represented more than merely a blow to American pride. They also posed a clear military threat. The launch revealed a capability for intercontinental rockets that brought the entire world within striking range, and so made the U.S. vulnerable to Soviet attack, both from first-strike and from counter-strike (Hacker, 2005; 2006). In strategic terms, rockets threatened to give effect to the doctrine of airpower as a war-winning tool advanced in the 1920s and 30s, at the same time as they rendered obsolescent the nuclear capability of the bombers of the American Strategic Air Command (SAC), particularly the B-52s deployed in 1955. Boosters powerful enough to lift a payload to space might just as easily loft a nuclear bomb across oceans, and guidance systems able to place a satellite in orbit might well be capable of putting a warhead on target. A surprise missile attack could destroy Strategic Air Command (SAC)'s manned bombers, upon which the United States relied to carry nuclear weapons to the enemy. Without bombers the nation would be left unable to retaliate. Motivated in part by such concerns, the United States soon began to deploy its own missile force. The threat to the U.S. from Soviet attack was highlighted by the 1957 secret report from the American Gaither Committee. The strategic possibilities offered by nuclear-tipped long-range ballistic missiles made investment in expensive rocket technology seem an essential course of action, since they could go much faster than aeroplanes and, unlike them, could not be shot down.

The U.S. fired its first intercontinental ballistic missile (ICBM) in 1958. The attempt to give force to the notion of massive nuclear retaliation entailed replacing vulnerable manned bombers with less vulnerable submarines equipped with ballistic missiles, and also with land rockets based in reinforced silos. April 1958 saw activation of the first operational squadron of Atlas ICBMs; seven months later an Atlas missile completed its full-range operational test flight, hitting a target area over 6000 miles away. Although it worked, Atlas used cryogenic propellants, making it slow to launch and vulnerable to attach.

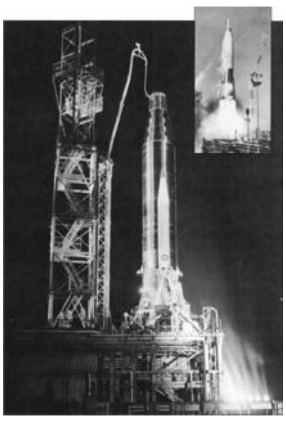


Fig A-10. Atlas missile ready for test launch. The Atlas was the U.S. Air Force's first operational ICBM. (Source: Web site of U.S. National Park Service, http://www.nps.gov/mimi/historyculture/atlas-icbm.htm)

By the mid-1950s research had overturned the belief that solid propellants were inherently unreliable, researchers also found chemically energetic combinations of liquid fuel and oxidiser that did not require temperatures near absolute zero (Hacker, 2005; 2006). Purse strings loosened by orbiting Sputniks allowed development of second-generation ICBMs – the sold-propellant Minuteman and the Titan II with storable liquid propellants – to begin without slowing Atlas. Both missiles could be protected in hardened underground silos ready for immediate launching. They became operational in 1962. By 1967 the American arsenal included a strategic missile force of 1000 Minutemen and 54 Titan IIs to augment its fleet of jet-propelled B-52 bombers with intercontinental range. In July 1960, off Cape Canaveral (subsequently Cape Kennedy), the USS George Washington was responsible for the first underwater firing of a Polaris missile. The following year, the Americans commissioned the USS Ethan Allen, the first true fleet missile submarine. Submarines could be based near the coast of target states, and were highly mobile and hard to detect.

	Low application uncertainty	High application uncertainty
High technical uncertainty		Rocket technology in the U.S. was given a boost by German import after World War II.
Low technical uncertainty	Development of ICBMs for nuclear payload.	Intercontinental ballistic missiles technology was developing with no apparent application.

APPENDIX A-9: STEALTH

Radar-directed weapons first became a serious threat to military aircraft during World War II. Correspondingly, the development of countermeasures against an enemy's use of radar became an important endeavour. Chaff and other countermeasures were developed, and the first attempts were made to reduce the radar signatures of aircraft. These early attempts, during the war and shortly afterward, consisted primarily of applying radar absorbent material (RAM) to all our part of a vehicle's surface. On the whole, the various "parasite treatments" (RAM, paints, and other add-ons to existing aircraft) did not produce any tactically significant reductions in radar detection range (FAS, 2011).

By the late 1950s, those working in the field realized that the very large Radar Cross Section (RCS) reductions necessary to achieve any operational benefit would not be accomplished simply by coating an otherwise conventional aircraft with RAM (Aronstein and Piccirillo, 1997). Many physically small features of an aircraft generate radar returns that are still quite detectable. Not all such details can be covered with RAM because this would interfere with their primary function. The most obvious examples are cockpit canopies and engine inlets. Additionally, locating a radar antenna behind a totally absorptive radome would be clearly unacceptable. Special design approaches and treatments are, therefore, necessary for any device that must pass matter or energy (including information) to or from an aircraft, to allow the device to perform its intended function while minimizing or eliminating the radar return that it generates. Another consideration is that RAM is not 100% absorptive. Whenever electromagnetic waves encounter an obstacle, some radiation will be scattered. Therefore, an aircraft must also be shaped so as to direct the scattered radiation away from its source. A very low RCS must be “designed in” to an aircraft from the outset, with rigorous application of all elements: RAM, special detail treatments, and overall shaping of the airframe and its components. From the 1950s onward, efforts were made to incorporate these elements into various new aircraft designs. Some of the designs existed only as conceptual studies, while others were aircrafts that were actually built. During this time, basic research was also actively pursued. Under Army, Air Force and Navy sponsorship, the major aircraft companies and other defence contractors, commercial and government laboratories, and several universities all conducted research on various aspects of RCS reduction.

By the early 1970s, a variety of materials had been developed and characterized. Specific purposes had been identified, such as reducing specular reflections (reflections normal to the surface), attenuating the waves that travel along a surface, or reducing edge returns (Aronstein and Piccirillo, 1997). Specific approaches had been determined for each purpose. For specular RAM, reasonable good tools existed for designers to use to optimize a multilayer arrangement of absorbent materials. For these applications, materials were available with excellent absorption properties over a large bandwidth (i.e., a broad range of frequencies), and were even lightweight and low cost. However, they achieved their performance primarily through thickness up to several feet, making them clearly unacceptable for use on the surface of an aircraft. The chief challenges for aircraft RAM, then, were achieving good absorption performance over all required threat radar frequencies within acceptable thickness and weight constraints and developing materials and application methods that could withstand the severe mechanical, acoustic, and thermal environments encountered on aircraft. Additionally, complicated multilayer and/or tapered arrangements of absorbers could only be designed if the electrical properties of the basic ingredients were correctly understood. Thus, material characterization and quality control became important. Work progressed toward characterizing new and existing materials. Furthermore, several anomalies between prediction and experiment had been traced to quality control problems; attention to manufacturing processes was necessary to ensure that test samples and actual production materials met their design specifications. Although materials for attenuating surface waves had not yet been as thoroughly studied, it was observed that specular RAM was fairly effective, if not optimal, for the purpose of attenuating surface waves. With edge treatments, government laboratories and several aircraft companies developed ways to construct edges for reduced radar return.

Inlets, exhausts, cockpits, antenna installations, propellers, rotors, and external stores were all recognized as major and sometimes dominant contributors to an aircraft's RCS but most of these problems were bypassed through innovative concepts (Aronstein and Piccirillo, 1997). Inlets and exhausts were perhaps the most challenging. Two main treatment approaches were identified for engine inlets: screens, or RAM lining on the inside of the inlet duct. Inlet screens were fitted to a Boeing B-47 bomber in 1960 and reduced its frontal

RCS to a small fraction of the original value. However, there was a significant penalty in engine performance caused by the pressure loss of the air flowing through the screen. Experimental programmes in the late 1960s achieved some success in developing inlet designs that achieved the same RCS benefits as screens but without the large aero/propulsive losses. RAM lining on inlet ducts also dates back to the early 1960s. In 1962 the entire fleet of North American Hound Dog air-to-surface missiles were retrofitted with RAM on the inlet spike and duct. Measurements indicated a substantial reduction in frontal sector RCS. Exhaust systems are conceptually similar to inlet ducts, but the problem is complicated by higher temperatures and airflow velocities. In general, potentially successful treatment of exhaust systems were only accomplished for fairly low-performance aircraft designs. In a 1972-1973 Quiet Attack aircraft study for the Office of Naval Research, McDonnell Douglas developed a special plug nozzle to conceal the aft face of the huge-bypass, tip-driven turbofan engine. A Teledyne Ryan “Mini-Remotely Piloted Vehicle” (mini RPV), also designed in the early 1970s, concealed its ducted propeller with screens at the intake and exit of the duct. As a partial solution to the exhaust problem, several aircraft designs had the fuselage and/or the tail configured to conceal the exhaust system from the most critical detection aspects.

As of the early 1970s, shaping was the least-understood RCS reduction technique. Most early attempts to design low RCS aircraft, when shaping was considered at all, concentrated on eliminating surfaces that generated a specular return at the most likely detection aspects (Aronstein and Piccirillo, 1997). The designs were characterized by slanted or chined fuselage sides and slanted vertical tails. These efforts achieved moderately low signatures. However, the cross sections resulting from the remaining nonspecular sources were still high enough to be detected at a sufficient range for enemy defensive systems to react effectively. Further improvements depended on understanding and controlling the nonspecular sources. Theories that could predict the nonspecular scattering had not progressed to usefulness for aircraft designers. Some attempts were made to develop shapes with very low radar cross sections through experimentation. Following a series of unsuccessful attempts to reduce the RCS of the U-2 aircraft, the Lockheed Skunk Works worked to determine what kinds of shapes should be used in a new aircraft design to achieve a low RCS. Teledyne Ryan also conducted experiments for developing low RCS aircraft shapes. The AQM-91A had been Teledyne Ryan's first attempt to design a low RCS aircraft from the ground up and had used the typical approach of orienting surface normal away from the critical aspects, together with RAM treatment of certain components. Subsequent experimentation led to abandoning a conventional wing-body-tail design and adopting a simpler, delta-wing concept. Although this design and similar ones still did not meet certain RCS goals at all frequencies, they did provide the first credible indication that an aircraft's signatures could be reduced to the extent that some threat systems would not be able to detect or track the aircraft.

Meanwhile, the subject of aircraft detection and tracking by radar became increasingly urgent. During the Vietnam War, radar-guided surface-to-air missiles and anti-aircraft guns, supplied by the Soviet Union, seriously restricted the ability of U.S. aircraft to perform their missions (Aronstein and Piccirillo, 1997). By the later stages of the war, fewer than half of the aircraft involved in major U.S. air strikes carried weapons intended for primary targets. The rest included tankers, fighter escort, and, increasingly, aircraft dedicated to suppression of enemy air defences. This included nonlethal (jamming) and lethal (anti-radiation missile) forms of suppression. Strike aircraft began to be equipped with on-board chaff dispensers and increasingly sophisticated jamming systems. Electronic countermeasure (ECM) techniques advanced rapidly during the war, but the state of the art in radar-directed threats also improved and the variety of systems increased dramatically. The various systems encompassed a range of different engagement envelopes (speed/range/altitude), frequencies, and guidance modes, making the ECM problem much more complex. An aircraft with inherently lower signatures that would not have to jam or deceive the growing variety of potential threats would be a very appealing solution if it could be developed.

A further demonstration of the lethality of radar-guided air defence systems occurred in October 1973 (Aronstein and Piccirillo, 1997). In the Yom Kippur War, Israel lost more than 100 combat aircraft – a substantial fraction of its front line fighting strength – in just 18 days, most of them to Soviet-built radar-guided surface-to-air missiles and guns operated by Egypt and Syria. This was particularly disconcerting because Israel was using up-to-date Western aircraft, radar countermeasures, and tactics. The complementary elements of the Soviet Integrated Air Defense System (long-range systems with large, fixed radars, coupled with shorter range mobile missile and gun systems) rendered them not only extremely lethal but also nearly invulnerable to attack from the air. The experience of this war led to serious concerns. Predictions were that the U.S. Air Force would be decimated in about two and a half weeks if there were a full-scale against the Soviet Union in Central Europe.

During 1974, the Defense Advanced Research Projects Agency (DARPA) initiated, with U.S. Air Force participation, a programme to study and possibly demonstrate the concept of a very low observable military aircraft. The DARPA studies had two basic objectives: designed to identify signature levels that would permit a tactical aircraft to avoid detection (primary emphasis on radar, also infrared, with visual and acoustic detection as tertiary considerations only) and to define a technical approach for achieving such levels (Aronstein and Piccirillo, 1997). The DARPA studies continued through the summer of 1975, by which time two of the participants – Lockheed and Northrop – appeared to have achieved breakthroughs in the ability to design low observable aircraft. In November 1975, DARPA awarded contracts to these companies to design and test models of low observable demonstrator aircraft. Early on, the U.S. Air Force assumed leadership of the effort. Following a competitive evaluation of large-scale RCS models, which were used to validate the predicted low radar signatures, the Air Force issued a contract in April 1976 to Lockheed Advanced Development Projects (ADP, also known as “Skunk Works”). ADP was requested to produce and flight test two low RCS technology demonstrator aircraft under a highly classified special access programme known as “Have Blue”. By mid-1979, the Have

Blue aircraft had validated the concept of Lockheed's low RCS design approach by proving that its unconventional, faceted configuration could achieve acceptable flying characteristics as well as very low radar and infrared signatures in flight. The jagged edges scatter reflected radio waves in different directions, thus reducing the radar echo. The radar-absorbing paint contains small iron balls, which absorb radio waves and disperse them as heat rather than reflecting them back towards the radar detector.

Fig A-11. Lockheed Martin built the "Have Blue" F-117 prototype for DARPA in the 1970s.

(Source: Web site of the U.S. Air Force Association, http://www.afa.org)

Before completing Have Blue's flight test programme (but after flight performance and preliminary in-flight RCS testing had been accomplished), the Air Force, with strong support from the Department of Defense and key Congressional committees, initiated full-scale development of the F-117A, the first true very low radar signature, low observable (stealth) strike aircraft, under the Senior Trend programme in November 1978 (FAS, 2011). This highly concurrent and streamlined programme applied the new low observables technologies and fielded a weapon system capable of highly survivable precision attacks against vital elements of an enemy's military, political, or economic assets. First flight was in June 1981, a limited F-117A initial operational capability was achieved by October 1983, and the aircraft subsequently played a prominent role in the air campaign against Iraq during Operation Desert Storm in early 1991 (Matricardi, 2007).

Fig A-12. The U.S. Air Force F-117A Nighthawk aircraft is the world's first operational aircraft designed to exploit low-observable stealth technology.

(Source: Web site of U.S. Department of Defense, http://www.defense.gov)

	Low application uncertainty	High application uncertainty
High technical uncertainty	R&D effort to reduce the radar signature of aircraft commenced in World War II and continued after the war.	Radar which could detect aircraft was developed in the 1930s and used in World War II.
Low technical uncertainty	By mid-1979, the “Have Blue” demonstrator aircraft developed by Lockheed “Skunk Works” achieved acceptable flying characteristics as well as very low radar and infrared signatures in flight.	

APPENDIX B: CASE STUDIES OF SEVERAL CONTEMPORARY DEFENCE TECHNOLOGICAL INNOVATIONS IN SINGAPORE

The case studies in three contemporary defence technological innovations in Singapore, namely (1) the Underground Ammunition Facility (UAF), (2) Infra-red Fever Scanner System (IFSS), and (3) Indigenous Unmanned Aerial Vehicle (UAV), aim to underscore the contemporary validity of our emergent theoretical framework.

APPENDIX B-1: UNDERGROUND AMMUNITION FACILITY (UAF)

Identification of requirement

Explosive for the Singapore Armed Forces (SAF) has traditionally been stored in above ground ammunition depot and large tracts of land surrounding a conventional ammunition depot need to be "sterilised" (not used for any other purpose) to ensure a safe distance from the depot to public access areas (Wan, 2008). When the existing Seletar East Ammunition Depot was identified for redevelopment by the Urban Redevelopment Authority (URA), the Ministry of Defence (MINDEF) recognised that replacing it with a traditional above-ground ammunition depot would not be sustainable in land-scarce Singapore. In 1993, the idea of building an underground ammunition facility (UAF) was mooted and conceptual studies were conducted to explore the feasibility of such a facility. The objectives for the project team comprising operational user from the SAF, project manager and engineer from the Defence Science & Technology Agency (DSTA) and builder from the SembCorp Design and Construction were to design and develop an underground ammunition storage facility that would enhance safety and efficiency, while achieving significant land savings in land-scarce Singapore. Site studies were done to find possible locations for the development of the UAF, and Mandai Quarry was eventually chosen because it is located on a granite rock formation of excellent quality.

The engineers from DSTA faced two main challenges: ensuring that operations in the completed UAF could be carried out safely with the ammunition stored underground, and exploring and developing technologies to optimise land use (Ang et al, 2010). Hitherto there was no precedence of a large-scale underground ammunition facility developed within a densely populated and urbanised area. Extensive research and tests were thus carried out to bridge the knowledge gaps and ensure that the UAF, when completed, would achieve its aim of optimising land use while enhancing ammunition storage safety.

Technology development

The hazard zones for underground storage are defined by the three primary effects of an accidental explosion: airblast, ground shock, and debris (Zhou and Kummer, 2011). While ground shock is propagated in the ground to the surrounding area, airblast and debris are propagated from the tunnel exit. If the rock cover is insufficient allowing an overburden breaching, airblast and debris hazards can also result from the crater above the explosion chamber. Debris from a breaching overburden may include geological material in addition to the fragments and technical installations in the facility. Besides ensuring that the design of the UAF could withstand and mitigate the impact of an accidental explosion, the team also carried out ground shock prediction tests, extensive numerical modelling, small-scale testing and large-scale validation testing. The following paragraphs describe some of the achievements to push the boundaries of technology and garnered extensive knowledge on how to create underground space in rock formations. Theoretical research in rock dynamics was pursued at the earlier stage of the technology development, and supported the subsequent development of technological applications to reduced separation distance in the tunnel facility and designs to mitigate debris hazards.

Theoretical research

Zhao et al (1999) reported on the theoretical research on rock dynamics supporting the underground ammunition facility in Singapore. The research programme developed the necessary rock mechanics parameters for the design of the cavern storage facility, such as ground characteristics, rock properties, layout of the cavern complex (separation and depth), and support requirements. The research activities cover the following areas:

- Properties of rock material (strength, modulus, constitutive relations) under dynamic and transient loads
- Properties of rock joints (normal and shear) under dynamic loads
- Shock wave propagation in rock fractures and rock mass
- Discrete element modelling of the rock mass and rock structures

Technological breakthrough: Reducing the separation distance

Most recent studies on underground explosives storage have focused their attention on external safety distances, mostly inhabited distances for airblast, debris, and ground shock. For complex facilities, guidelines on separation requirements to prevent sympathetic detonation are often lacking. DSTA conducted a series of large-scale tests in a rock tunnel facility in Älvdalen, Sweden from 2000 to 2001 (Chong et al., 2002). Based on a comprehensive review of the tunnel damage and results of the field tests and analyses of the ground shock effects and sympathetic detonation, Zhou and Jenssen (2009) rationalised the separation requirements for the various components of an underground storage facility. In addition to the charge weight and rock type, the loading density in a chamber has a significant effect on the required rock separation distance between two adjacent chambers. Based on their analysis of the results from the large-scale tests in Sweden, Zhou and Jenssen (2009) demonstrated that for loading densities up to 10 kg/m^3, requirements for separation distances for hard rock based on the current safety requirements for internal separation may be overly conservative. The tunnel separation to prevent tunnel damage can be safely reduced from the current $1.0Q^{1/3}$ to $0.6Q^{1/3}$ where Q is the net explosive quantity (NEQ) of storage.

Technological breakthrough: Design of debris mitigating features

For underground ammunition storage in rock caverns, the safety distances for debris resulting from an accidental explosion are generally very large. This is because most existing safety codes have been developed based on storage or tests sites where the exploding chamber is connected by a relatively short tunnel to the exit (Zhou and Kummer, 2011). In underground ammunition storages, debris hazards resulting from an accidental explosion can be mitigated using one or more mitigation features, such as long tunnels, sharp turns, debris traps, expansion chambers and portal barricade (Zhou and Kummer, 2011). They typically work by reducing the debris density and debris velocity but no quantitative guidelines on the effectiveness of such features exist. There are many factors which affect debris flow and the external hazards such as the explosives quantity NEQ, the ammo profile, chamber and system loading density, tunnel layout and geometry, and the mitigating features such as debris traps and expansion volume. However, there is a lack of work to quantify the effects of these debris mitigation features and how they can be used for the safe siting of an underground facility.

From 2000 to 2001, DSTA conducted several large-scale tests in a rock tunnel facility in Älvdalen, Sweden (Chong et al., 2002; Zhou et al., 2003). Results from these tests validated the effectiveness of some tunnel features such as branch tunnels and orientation relative to the main tunnel, debris traps and sharp tunnel turns, as well as tunnel volumes (Zhou and Kummer, 2011). The tests demonstrated that a suitably designed debris trap, placed at a sharp tunnel turn, can reduce the amount of the debris by approximately an order of magnitude. In addition, a properly designed portal barricade can act as the last barrier against any remaining debris that may exit the tunnel. Based on the tests and analytical results, Zhou and Kummer (2011) developed some quantitative guidelines on the design of debris mitigating features in underground storage. They also developed the following general guidelines for the design of tunnel features to mitigate the debris hazards for an underground ammunition storage facility:

(a) The debris trap directly opposite the chamber should be as deep and as voluminous as possible to account for the expected volume of debris leaving the storage chamber in case of an explosion.

(b) Larger debris traps in other parts of the tunnel system are also important for catching additional debris from technical installations, rock material, concrete etc. in the tunnel system.

(c) The branch tunnel to the storage chamber should be as small as possible in order to prevent as many fragments as possible from exiting the chamber.

(d) Use as many sharp turns as possible combined with debris traps to reduce the momentum of the debris flow and to capture the debris. However, to be effective the debris traps should be separated by at least 5–10 tunnel diameters.

(e) In combination with other functions of the storage facility, large tunnel volumes should be located strategically in order to reduce the debris hazards.

(f) The portal barricade should have sufficient height and width to account for the debris fly angles. There should also be sufficient volume between the tunnel exit and barricade to allow for gas expansion. If possible, a debris trap can be designed into the barricade to capture any debris exiting the tunnel system. This is especially important when there are substantial technical installations after the final debris trap in the tunnel system.

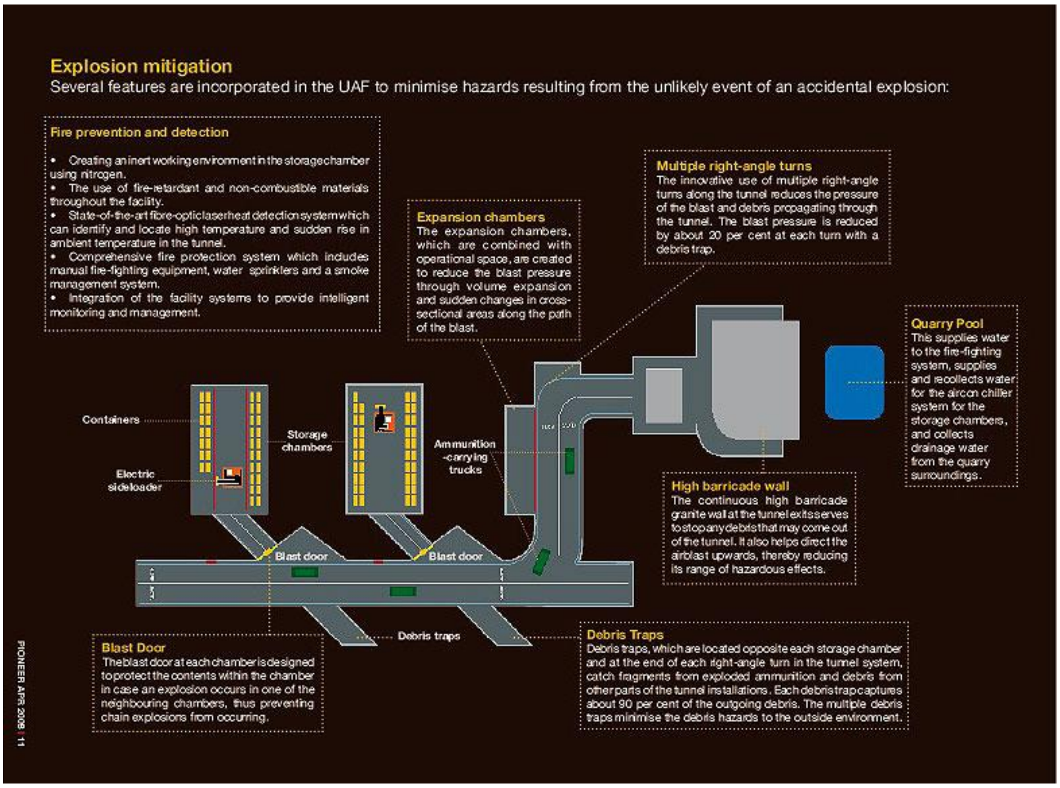


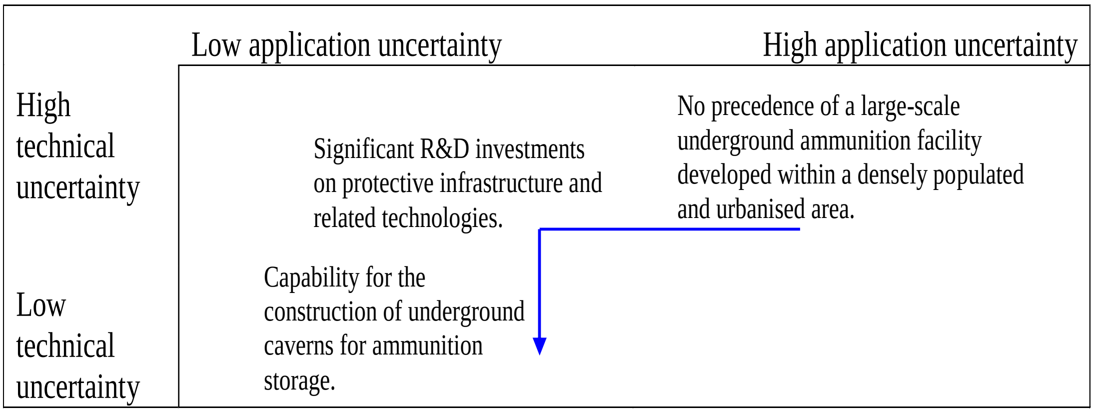
Fig B-1. Technologies developed to mitigate an explosion in the Underground Ammunition Facility. (Source: Web site of Cyberpioneer, http://www.mindef.gov.sg/imindef/publications/cyberpioneer/features/2008/apr08_fs.html)

Many of these technologies were subsequently transitioned into the UAF. The innovations incorporated include the debris trap, expansion chambers and multiple right-angle turns (please see Fig B1). The debris trap are located opposite each storage chamber and at the end of each right-angle turn in the each tunnel system, and catch fragments from exploded ammunition and debris from other parts of the tunnel installations. Each debris trap captures about 90% of the outgoing debris. The multiple debris traps minimise the debris hazards to the outside environment. Expansion chambers, which are combined with operational space, are created to reduce the blast pressure through volume expansion and sudden changes in cross-sectional areas along the path of the blast. The innovative use of multiple right-angle turns along the tunnel reduces the blast and debris propagating through the tunnel. The blast pressure is reduced by about 20% at each turn with debris trap.

Development

The rock excavation phase of the project commenced at the Mandai Quarry site in August 1999, using the drill and blast technique. The granite found in the quarry is about six times as strong as normal concrete, and provides natural fortification to contain the risks associated with ammunition storage. As a result, the UAF required 90 per cent less land to be 'sterilised', compared to a traditional above-ground ammunition depot of similar capabilities. This translates to about 300 hectares of land (equivalent to 400 football fields or half of Pasir Ris New Town) freed up for other use. Another benefit is the natural insulation provided by the granite caverns, resulting in a 50 per cent reduction in the energy required for cooling compared to a conventional depot (MINDEF, 2008).

The UAF completed in 2008 is the world's most modern underground ammunition facility and the first large-scale underground containerised facility to be designed and developed within a densely developed and urbanised area. The new safety standards developed by the team have since been incorporated into the North Atlantic Treaty Organisation (NATO) safety manual, and Singapore is now recognised internationally for its knowledge in underground storage safety. Through good systems engineering, the UAF has also achieved efficiencies beyond land use. The UAF requires 20% less manpower to operate than a conventional facility by leveraging on IT and automation. Equipped with the latest ammunition storage technology and systems, the UAF "created more space for our defence, while freeing up more precious land for Singapore" because the team "dared to pursue a bold new solution to overcome one of our perennial constraints," said Minister for Defence Teo Chee Hean, who officiated at the UAF commissioning ceremony on 7 Mar 2008 (MINDEF, 2008).



Evaluation of the real options developed

Ho et al (2009) from DSTA described the creation and valuation of the flexibility in the systems architecture for the Underground Ammunition Facility. The following types of real options were identified:

- Option to Grow
- Option to Utilize
- Option to Expand
- Option to Switch
- Option to Stop/Defer

- Option to Sustain

In particular, in view of the uncertainty in the technology gap and lack of information on safety standards, design guidelines and blast effects, an Option to Grow was purchased through over a decade of R&D investment in ammunition storage safety and rock engineering. The intended Option Value was the ability to make decision with confidence that the UAF is feasible, safe, and secure. The emergent Option Value was greater savings in land than expected, contribution to the NATO safety codes, and the venture into other underground developments in Singapore.

An Option to Sustain was purchased by investing into research program in Underground Technologies & Rock in Nanyang Technological University and, hence, sustaining our capabilities. This investment was made under uncertainty in the value of sustaining local capabilities after completion of the UAF. The intended Option Value is enabling DSTA to tap on local capabilities and contribute when there is a new demand. The emergent Option Value is enabling DSTA to advise JTC Corporation on the Jurong Rock Cavern Project and the National Inter-Agency initiative for Underground Planning which charts the Masterplan for Long-Term Underground Development for Singapore (Ho et al, 2009).

APPENDIX B-2: INFRARED FEVER SCANNER SYSTEM (IFSS).

Defence Science & Technology Agency capability in thermal imaging sensors

Thermal imaging sensors are used commonly by the military forces, especially those in the developed countries. Basically, the thermal imagers sense heat that is generated by an object. As long as heat is generated, the sensor will be able to pick up the heat and map the image of the subject. The Defence Science & Technology Agency (DSTA) had worked with the Singapore Armed Forces (SAF) planners to jointly develop the operational and technical requirements, and contracted Singapore Technologies (ST) Electronics to develop and manufacture thermal imaging sensors to meet SAF's unique operational requirements (Tan, 2003). The sensors are fielded with the operational weapon systems to enable the systems to operate at night.

Severe Acute Respiratory Syndrome

When the Severe Acute Respiratory Syndrome (SARS) hit Singapore in 2003, one key factor in containing its spread was the early detection of probable SARS cases. One of the earliest detectable symptoms was fever but identifying subjects who have higher than normal body temperature of 38°C through the conventional method of taking oral/ear temperatures was tedious and time consuming. At the Singapore Changi Airport and Singapore Cruise Centre, where more than 100 nurses and paramedics were stationed to spot incoming passengers who were unwell and check their temperature using oral or ear thermometers, it took six to eight nurses more than 15 minutes to screen one flight of some 150 passengers (Tan, 2003). Passengers also had to pass through a phalanx of inquisitive nurses in their protective gowns and masks upon their arrival. The need to deploy nurses to these checkpoints added more strain on the demand for nurses, who were already stretched coping with their work at the various hospitals.

The Ministry of Health (MOH) approached DSTA to help provide possible fever screening devices that could be deployed to identify possible SARS cases (Tan, 2003). With a focus on tapping existing resources so as to quickly deliver a device to meet the urgent need, the DSTA team identified the thermal imager as a highly possible device for such temperature screening, and proceeded to find out more about body and skin temperatures and explore how feverish persons could be diagnosed more accurately with the use of sensors.

Development of the Infrared Fever Scanner System

The DSTA team worked on the hypothesis that infrared radiation from the skin could be used to estimate the skin temperature and an elevated skin temperature is a proxy indication of core body temperature under some controlled temperature and physiological condition. They consulted with their colleagues in DSTA's Defence Medical Research Institute (DMRI) and the medical literature to complement their knowledge accumulated over years of work in military sensor development (Tan et al, 2004). Previous research has shown that human beings have a core body temperature within the range of 36-38°C. The skin radiates heat and the skin temperature of a person with a fever is expected to rise. Skin temperature can thus be used as an indirect indicator of the core body temperature. Skin temperature of a normal person ranges between 32-36°C. Skin temperature, unlike the core body temperature, varied at different parts of the body. It is also subjected to both internal environment (such as after an exercise) and external environment (such as ambient temperature). And skin temperature on the face (i.e. forehead, face and neck) differs significantly between normal and feverish individuals. This temperature change and distribution is observable externally to deduce that a person is running a higher-than-normal temperature. Hence the thermal imager can be used to detect such differences in temperature.

The DSTA team then worked with several assumptions based on the initial requirements of screening air passengers (Tan, 2003). Research on human body thermography has shown that skin infrared radiation of a normal population, at resting metabolic rate and with normal clothing in a room temperature of 15-20°C, corresponds to a mean skin temperature of 32-35°C. As movement on board a plane is restricted and the environment is controlled through air-conditioning, the body metabolic rate of the arriving passengers will generally be close to that of the resting metabolic rate. Passengers with a fever would likely demonstrate a similar distribution of their skin temperature, but with a higher mean temperature. The team also decided to focus the reading of the skin temperature on the forehead and neck, as these selected facial regions have a narrow layer of tissue and reading temperature could be made readily.

The thermal imager has to be calibrated to ensure unbiased sensing of the true skin infrared energy (Tan et al, 2004). According to Planck's Law, all objects with temperatures above absolute zero emit infrared radiation, and there is a correlation between infrared radiation energy and temperature - the higher the temperature, the higher the energy radiated by an object at a particular electromagnetic wavelength. The human body temperature is about 300K and the skin will have a maximum infrared energy radiation at a wavelength of about 10-micrometer. A thermal imager can capture this energy as it is made up of many small detectors (infrared radiation sensitive materials bonded on electronic read-out chip). The proposed sensing system would use a thermal imager to sample the infrared energy radiated from a scene at a very high refresh rate and generates a video image to map and display the energy. A thermal reference source (TRS) serving as a constant and stable thermal energy source is another key component. Infrared energy radiated from all objects in the sensor's field of view can be compared with the infrared energy radiated from the TRS. When the infrared energy radiated by the object is higher than the TRS, the image of the object will display red. The temperature of the TRS thus allows more accurate temperature threshold setting.

Based on their expertise and experience in military surveillance radar, the DSTA team drew an analogy between screening the massive passengers arriving at the aerobridge in Changi Airport and a radar detection environment (Tan, 2003). In general, air defence radar will scan its radar beam continuously and search a large surveillance space for potential targets. There are actually very few real targets of interest in the huge air space, and the radar processor is able to efficiently search for them, and detect and track the real targets. The overall design of the radar system will determine its effectiveness and efficiency. A proven technique in the radar signal detection and processing, commonly known as double-threshold detection approach, was adopted in the fever screening. The two levels of thresholds identified were:

- First tier – to use a system including thermal imager to rapidly scan and screen a large pool of passengers efficiently as they pass through the device. Passengers detected to have a higher-than-normal facial skin temperature are assumed to have a higher body core temperature. These passengers will be led to undergo a second stage of screening to assess if they were indeed running a fever.
- Second tier – experienced nurses equipped with the oral thermometer will further assess if the passengers are running fever and note if they have other SARS symptoms.

The team quickly adapted the matured thermal imager, with additional software and hardware, to work as a temperature device to screen masses for fever. The prototype for this system, which was named Infrared Fever Scanner System (IFss), was developed within 36 hours to help investigate the effectiveness of the proposed system (Tan, 2003). The performance of the IFss is highly dependent on some key parameters including the settings of the thermal imager, the threshold settings of the TRS and consistency in the surrounding environment. Technical parameters of a thermal imager include uniformity, drift, minimum detectable temperature difference (affected by number of quantisation levels, uniformity, max drift between self-corrections), distance effect, as well as accuracy and stability of the TRS must be specified accurately so as to ensure the robustness of the system. Hence, more R&D and trials were conducted to ensure that the technology was sufficiently matured to be deployed for temperature screening under different operating conditions, with an acceptable false alarm rate. It was found, for example, that the IFss had to be installed in an environment which demonstrated consistency in temperature, preferably in an air-con environment. In addition, the IFss should not be set up facing glass panels, or directly under air-con ducts or halogen lamps. These could affect accurate reading of the temperature.

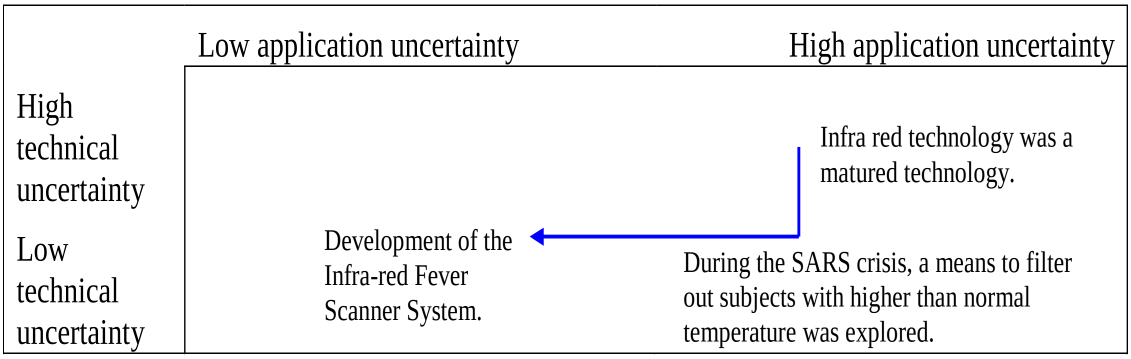
A series of trial tests were subsequently conducted to verify the effectiveness of the IFss and to obtain a suitable set of threshold settings. Data collected were validated to verify if there were any misses and those detected by the IFss had indeed higher-than-normal body temperature. With positive results, the IFss was subsequently deployed at Changi Airport making it practicable to screen large groups of people coming into as well as going out of Singapore, and to do this efficiently, effectively and unobtrusively.

Fig 1. The Infrared Fever Screening System
(Source: http://www.mindef.gov.sg/cyberpioneer/backissues_jun03_1.htm)

Improving the performance of the Infrared Fever Scanner System

When the IFss was first conceptualised, there was an operational need to produce and deploy these systems quickly. Cooled military thermal imagers operating in the 3-5 μm waveband were used as they could be made available by the SAF (Tan et al, 2004). Optimised for military scenarios, they have very high gain and the advantages of better spatial resolution and sensitivity. However, compared to commercial uncooled thermal imagers, they have a smaller field of view, higher power consumption, longer start-up time and higher cost. The peak wave length for human body temperatures, which is around 10 μm falls outside the cooled thermal imager waveband. As such, uncooled thermal imagers were chosen to replace these military thermal imagers for long-term operation. Developed by ST Electronics, the 8-12 μm waveband uncooled thermal imagers in use now are based on microbiometer technology. Microbiometers are thermoelectric in nature, which means that when the detector senses IR energy, it reacts by changing resistance. Changes in resistance are converted to electrical signals to form a video image. Furthermore, the initial IFss categorised the subject's temperature based on shades of colour as a proxy (Ang et al, 2011). This was subsequently improved to the "numeric" tagging of temperature to the subject's forehead as they appeared on the sensor computer screen. The technology for numeric tagging was already well developed in other applications. The use of this technology provided more resolution and accuracy than based on the proxy of shades of colour. This has proven to be useful in assisting the temperature filtering processes as part of the H1N1 screening.

DSTA also helped to produce a technical reference that specifies the technical and implementation requirements for thermal-based systems used for human temperature screening (Tan et al, 2004). The important technical parameters including uniformity, drift, minimum detectable temperature difference (affected by number of quantisation levels, uniformity, and maximum drift between self-corrections), distance effect, and accuracy and stability of TRS. These key parameters will affect the performance of all thermal-imager-based screening systems. Besides emitting infrared radiation, objects can also reflect infrared radiation. As such, ambient lighting condition becomes an important consideration when situating the IFss for reliable results. Stray light and reflections, which may change throughout the day (such as sunlight from a nearby window), must thus be minimised when operating the IFss. The performance of the IFss is dependent on the stability and accuracy of the TRS, since it is used as a reference to which objects are compared. Besides using a high performance TRS, the external environment, namely the ambient temperature and air flow, also has to be stable. Trials were conducted to see if the IFss was suitable for use in uncontrolled ambient conditions, but the performance was found to be inconsistent in such environments.


Low application uncertainty
High application uncertainty
High technical uncertainty
Low technical uncertainty
Infra red technology was a matured technology.
Development of the Infra-red Fever Scanner System.
During the SARS crisis, a means to filter out subjects with higher than normal temperature was explored.

APPENDIX B-3: INDIGENOUS UNMANNED AERIAL VEHICLE (UAV)

Early development of Unmanned Aerial Vehicle in Singapore

The DSO National Laboratories (DSO) in Singapore started developing indigenous capability in Unmanned Aerial Vehicle (UAV) in the 1990s (Ang et al, 2010). It commenced R&D in UAV and worked towards developing a man-portable mini tactical UAV called the Skyblade whose primary mission is to support the Singapore Army battalion operations. These UAVs aim to provide the battalion with real-time video images of its area of operations, including those areas on the "other side of the hill", which cannot be seen by direct observation. Development of such mini-UAVs was technically very challenging as all the subsystems had to be small and light-weight yet robust and reliable (Ang et al, 2010). DSO engineers had to work on a design, within a very tight weight budget, that would include optical devices with sufficient resolution, pointing accuracy and stabilisation so that it can deliver clear video imagery. A miniaturised communications data-link had to be incorporated to transmit the video back in real-time to the users. The mini-UAV also needed a good engine and a high-capacity battery pack for meaningful mission time and range, and a non-trivial problem - it had to be robust enough to survive repeated take-offs and landings in the field and in very rough conditions.

It took eight years and three attempts by different teams of engineers before a successful UAV that can be deployed quickly in battle was developed (Straits Times, 2009). The first variant in 2001, the Skyblade I, could fly very well, but did not have enough operational flexibility and did not have a steerable camera. Two years after that, an Advance Production exploration, Skyblade II, addressed these two problems but it was too heavy and needed more upgrades to its computer systems. The Skyblade III, which took a further three years to develop, was the best of the lot - light, portable and easy to fly. The new team which worked on Skyblade III is made up of staff from the Singapore Armed Forces (SAF), DSO, ST Aerospace and the Defence Science and Technology Agency (DSTA).

Skyblade III mini-UAV

After extensive trials and evolution over a decade, the design was refined and transferred to ST Engineering to produce the Skyblade III. ST Engineering then developed the production model successfully, and these mini-UAVs have since been fielded in the Army (Ong, 2011). Skyblade III can be deployed in the following military applications (ST Aerospace, 2011):

- General surveillance of an area or route
- Detailed surveillance of a designated target (including border, river, airfield, ship and building/installation)
- Early warning deployment ahead of an operation
- Monitoring of an ongoing mission or deployment (including assault landing and maritime operation)
- Target designation
- Battle damage assessment

The Skyblade III mini UAV system is designed for rapid mission deployment and fully autonomous flight operations to carry out a broad array of general surveillance roles. It provides tactical commanders in the field with valuable detailed surveillance capability, delivering quick and accurate intelligence in real time, by day and night. Skyblade III is deliberately designed to be portable, allowing for rapid, two-man deployment. Air vehicle operations are completely autonomous. It can be rapidly deployed within 30 minutes by a two-man team with minimal logistics requirements. Communications with the ruggedised ground control station is achieved via a digital radio link. Its ease of operation makes it an ideal vehicle for use in the lower echelon of the military units, as well as from constrained spaces such as on board small patrol craft. Skyblade III harnesses leading edge technologies for maximum versatility and mobility to perform (ST Aerospace, 2011):

- Over-the-hill reconnaissance and surveillance
- Autonomous flight operations with real time video and telemetry feeds
- Man-packable system, designed to be compact and lightweight
- Modular design allows for a variety of payloads
- Ruggedised ground control station

Hauling day-use and night-use cameras skywards, the mini-UAV is used by scout teams to conduct recce operations. Previously, scout teams relied primarily on visual surveillance, which required them to be in close proximity to their targets. But with the Skyblade III, they can be further away, reducing the chance of being spotted by the enemy (Straits Times, 2009). Army units will also be able to respond faster to threats in its area of operations. During an assault, the units are able to see much further afield, and in defence, they can plan counter-manoeuvres earlier because the scout teams are able to detect the presence of opposing forces much earlier. Opposition forces will not have an easy time trying to locate the scout teams operating the Skyblade III, as the operators could be anywhere within its 8km range. The mini-UAV is also difficult to spot visually as its silhouette in flight resembles a bird to the naked eye. The ground control station offers maximum convenience, allowing operators to upload pre-planned routes and the flexibility of altering route commands on the fly if necessary.

Fig B-3. An SAF scout trooper preparing to launch the Skyblade III mini-UAV

(Source: Web site of Cyberpioneer, http://www.mindef.gov.sg/imindef/publications/cyberpioneer/features/2011/jan11_fs2.html)

All active Army battalions are expected to be equipped with the Skyblade III by 2012. Following the success of Skyblade III, R&D on UAVs continued with the development of a 60 kg class of tactical UAV called Skyblade IV, for use at the higher echelon of the army. The knowledge and experience gained from the previous R&D effort was channelled into development of the larger

Skyblade IV (Ang et al, 2011).

Skyblade IV tactical UAV

The Skyblade IV UAV is a command and control enabler developed to provide real time situational awareness of the battlefield through autonomous flight operations in an effective, highly mobile reconnaissance force (ST Aerospace, 2011). It can be deployed on the following types of missions:

- Reconnaissance
- Battlefield surveillance
- Search and rescue
- Artillery fire support
- Target tracking
- Maritime and coastal patrol

Fig B3-2. Skyblade IV

(Source of picture: Web-site of ST Aerospace http://www.staero.aero/www/keyoffering.asp?serkeyid=ODAwMDAwMTk)

The Skyblade IV system provides the ground manoeuver commander with situational awareness of the battlefield, allowing him to observe heavily protected areas. This tactical UAV can be operated from small clearings or compounds, designed for ease of use and requiring few dedicated personnel. It is easily integrated and the ground control unit design allows for automatic or mechanical interface with other military systems. Its baseline payload is a very low weight, dual axis gyro stabilised surveillance and observation system, which incorporates high resolution, continuous optical zoom with colour day channel and automatic video tracker. The video mosaic offers superior situation awareness and fast scan mode allows for wide area search (ST Aerospace, 2011). The system can be manually controlled via the ground control station or pre-programmed to fly autonomous missions. It also has the potential to support multi-UAV operations. Launching is automatic catapult-assisted and recovery is assisted by automatic precision parachute, requiring no runway for take-off or landing. Table B3-1 compares some of the specifications of the Skyblade III mini UAV and the Skyblade IV tactical UAV.

	Skyblade III	Skyblade IV
Length	1.4m	2.4m
Wing span	2.6m	3.7m
Maximum Take Off Weight	5.0 kg	70 kg (Maximum Payload Weight is 12 kg)
Endurance	> 60mins	6 – 12 hrs
Operating Altitude	90- 460m	4,572 m
Maximum Speed	35 kts	50 -80 kts
Range	8 km	100 km

Table B3-1. Comparison of the specifications for the Skyblade III mini-UAV and Skyblade IV tactical UAV

Evaluation and design of the flexibility in UAV

Mikaelian et al (2008, 2009, 2012) developed an integrated real options framework and collaborated with DSTA and DSO to apply it in the UAV project. The framework is a structured approach to identify where real options are or can be embedded for uncertainty management, and aims to support holistic decision making under uncertainty in a project involving challenging decisions. Their logic model-based approach identifies real option in terms of 1) patterns of mechanisms that enable flexibility and, 2) the types of flexibility in an enterprise, and uses a Logical- multiple-domain matrix (MDM) to estimate flexibility, optionability, and realizability metrics. The expressivity of the logic combined with the structure of the dependency model allows the effective representation and identification of mechanisms and types of real options across multiple domains and lifecycle phases of a system. The identified options are valued using standard real options valuation methods to support decision making under uncertainty. This approach was demonstrated through a series of UAV scenarios.

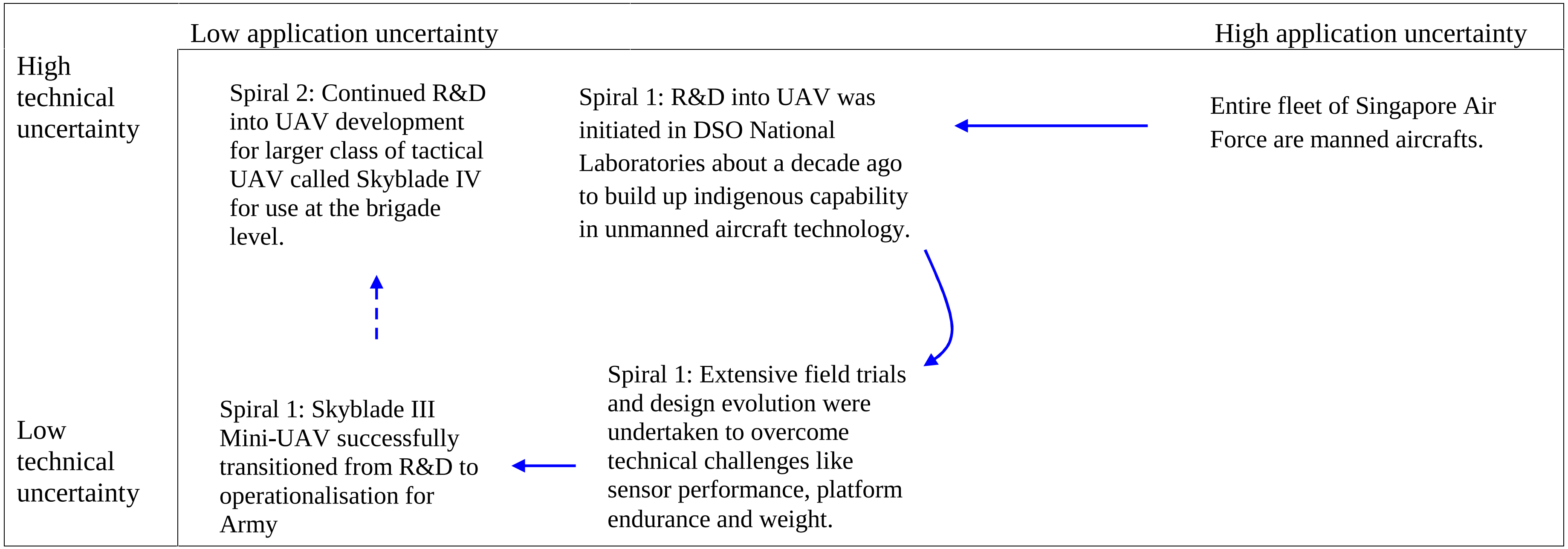


Fig B3-3. Case study of Unmanned Aerial Vehicles development in Singapore

APPENDIX C: TECHNOLOGY READINESS LEVEL

Technology Readiness Level (TRL) is a measure used by the United States government agencies and many of the world's major companies and agencies to assess the maturity of evolving technologies prior to incorporating that technology into a system or subsystem. Generally speaking, when a new technology is first invented or conceptualized, it is not suitable for immediate application. Instead, new technologies are usually subjected to experimentation, refinement, and increasingly realistic testing. Once the technology is sufficiently proven, it can be incorporated into a system/subsystem. Different definitions are used by different agencies, although they are somewhat similar. The most common definitions are those used by the Department of Defense (DoD) and the National Aeronautics and Space Administration (NASA).

Technology Readiness Level	Description
1. Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Example might include paper studies of a technology's basic properties.
2. Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3. Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4. Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is "low fidelity" compared to the eventual system. Examples include integration of 'ad hoc' hardware in a laboratory.
5. Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include 'high fidelity' laboratory integration of components.
6. System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
7. System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft.
8. Actual system completed and 'flight qualified' through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9. Actual system 'flight proven' through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.

Table C.1 DoD definitions for Technology Readiness Levels in the Department of Defense (DoD (2006), Defense Acquisition Guidebook)

Technology Readiness Level	Description
1. Basic principles observed and reported	This is the lowest "level" of technology maturation. At this level, scientific research begins to be translated into applied research and development.
2. Technology concept and/or application formulated	Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be 'invented' or identified. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.
3. Analytical and experimental critical function and/or characteristic proof of concept	At this step in the maturation process, active research and development (R&D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute "proof-of-concept" validation of the applications/concepts formulated at TRL 2.
4. Component and/or breadboard validation in laboratory environment	Following successful "proof-of-concept" work, basic technological elements must be integrated to establish that the "pieces" will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is "low-fidelity" compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory.
5. Component and/or breadboard validation in relevant environment	At this level, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment.

6. System/subsystem model or prototype demonstration in a relevant environment (ground or space)	A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system - which would go well beyond ad hoc, 'patch-cord' or discrete component level breadboarding - would be tested in a relevant environment. At this level, if the only 'relevant environment' is the environment of space, then the model/prototype must be demonstrated in space.
7. System prototype demonstration in a space environment .	TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. The prototype should be near or at the scale of the planned operational system and the demonstration must take place in space
8. Actual system completed and 'flight qualified' through test and demonstration (ground or space)	In almost all cases, this level is the end of true 'system development' for most technology elements. This might include integration of new technology into an existing system.
9. Actual system 'flight proven' through successful mission operations	In almost all cases, the end of last 'bug fixing' aspects of true 'system development'. This might include integration of new technology into an existing system. This TRL does not include planned product improvement of ongoing or reusable systems.

Table C.2 Technology Readiness Levels in the National Aeronautics and Space Administration (NASA)

(Mankins (1995), Technology Readiness Levels: A White Paper)

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