International Journal of Innovation and Technology Management

MULTIPLE PERSPECTIVES ON APPRAISSAL TECHNIQUES FOR NEW TECHNOLOGIES; EXAMPLES FROM THE AEROSPACE INDUSTRY

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Received ( )

Appraising the benefits of new technologies is a commonly accepted challenge for any organization and is a prime area for technology management research. A wide variety of methods are available that intend to service this need, such as discounted cash-flow, real options, portfolio methods, road-mapping, etc. However, little evidence exists on who applies these techniques and how they are used in practice. This paper will evaluate the techniques from literature and compare the results with cases from the Aerospace industry. The paper will show that there are two distinct perspectives that can be taken when looking at the valuation process and these perspectives change in the course of the technology's life cycle.

Keywords: Valuation techniques, Technology Appraisals, Decision Making.

1. Introduction

Whether or not to invest in technology is a fundamental question for most technology based firms. Many techniques that are available for appraising technologies are quantitative techniques and stem from financial management. Mostly these are based on traditional capital budgeting techniques such as Discounted Cash-Flow methods [Accola, (1994); Boer, (1998)], decision trees and real options e.g. [Bowman & Moskowitz, (2001), Faulkner, (1996); McGrath, (1997)].
These techniques have been widely adopted for valuing new technologies. Yet research shows that these techniques have limitations as a considerable extent of new technology investments is affected by non-quantifiable benefits [Kaplan, (1986)] such as strategic considerations. Research on advanced manufacturing technologies stressed the importance of alignment of strategic and financial considerations when dealing with technology investment appraisals [Abdel-Kader and Dugdale, (1998); Ordoobadi and Mulvaney, (2001); Slagmulder, *et al.,* (1995)]. Additionally Heidenberger & Stummer [1999] provide a review of quantitative modeling in R&D project selection and warn of the risk of developing "mathematically sophisticated but contextually naïve" R&D models by ensuring early involvement of practitioners in the modeling process.
"Soft" or non-quantitative techniques do exist and focus more on the qualitative aspects of valuation. These techniques generally attempt to structure reasoning and serve as an

aid to decision makers in shaping their judgment, such as the use of scoring [Cooper, *et al.,* (2001)] and roadmaps [Hunt, *et al.,* (2004)]. Heidenberger & Stummer [1999] stress the importance of "soft" approaches to supplement quantitative techniques, especially in these early stages of an analysis.

Despite the availability of these valuation techniques little empirical evidence exists about the role these techniques play on technology investment decisions [Nixon, (1995)]. From an industrial perspective, techniques are in most cases customized or hybrid approaches [Abdel-Kader and Dugdale, (1998); Cooper, *et al.,* (2001)] if any techniques are indeed being used. Akula [2003] provides 10 case studies in the UK and the Netherlands and finds that although research in capital budgeting suggest the use of quantitative models for R&D, their application is not found in practice. This also limits the establishment of best practices and calls for efforts to integrate the various areas of technology valuation techniques.

The aim of the paper is to explore the practical implications of the use of valuation techniques for new technologies. This paper explores these implications by providing an overview of prevailing approaches in literature from various disciplines and elaborates on the advantages and shortcomings. Furthermore the literature study is corroborated with the findings of four cases in the Aerospace industry that shows how different functions (commercial and technical) within the valuation process perceive and use the arsenal of methods and tools. Finally future requirements are explored from an industrial point of view.

For this study two distinct perspectives have been taken on the use of valuation techniques; the technological and commercial perspectives. The findings show that whereas from a commercial view the preference towards quantitative tools is apparent, the technical view seems to rely more on expert engineering judgment. Furthermore, the different stages of technology development also play a significant role in the selection of the technique. It is argue that in selecting techniques for technology valuation it is important to link these perspectives in order to construct and convey technology investment decisions.

The theoretical contribution of this paper is an evaluation on the gaps and limitations of prevailing valuation techniques for new technologies backed up with empirical evidence from one technology driven industry. These results can be used towards the preparation of a research agenda for the development of new tools and techniques for technology valuation.

To industry the results of the study can be used as a guideline to select the most appropriate set of tools in order to bridge the gap between the commercial and technical perspective. Acknowledging the different points of view on good valuation practice can enhance the acceptance and understanding within the decision making process and ultimately lead to better decisions.

2. Review of technology valuation techniques

2.1. *Discounted cash-flow*

A technique commonly used for valuing technologies is the discounted cash-flow. The concept of discounted cash flow (DCF) is central to the valuation of any asset when any part of its return is captured in the future. The roots of these techniques are mainly derived from finance and capital budgeting techniques. DCF techniques are easy-to-use, intuitive, widely applicable, credible, and accepted [Hunt, *et al.*(2004)].
However technology valuation is often associated with high levels of uncertainty. Myopic use of the technique in these situations can lead to poor decision making [Boer, (1998); Faulkner, (1996)] by manipulating the valuation process and raising cash-flows to unlikely levels [Hunt, *et al.,* (2004)]. Megantz [1996] argued that by sticking to the correct use of traditional valuation tools, many US firms missed significant growth opportunities in their industry. These methods used have been adapted from those applied to value more tangible assets i.e. not such assets as "managerial flexibility". DCF methods tend to penalise uncertainty by using higher discount rates, even when there is flexibility in a project to profit from this uncertainty. There is sometimes value to be obtained through waiting for more complete information, and this value is also not incorporated in the DCF [Dixit and Pindyck, (1994)].

2.2. *Real options*

Real Option (RO) theory has received increasing attention in recent years, and its application areas are widespread. Real options provide an essential framework for sequential decision making, extending current practices in decision theory. Options provide access to opportunities at lower costs, and create additional decision options such as waiting [McGrath, (1996)] and abandonment of investments [Adner and Levinthal, (2004)]. Applied at the strategic level, various authors classify the types of options e.g. options enabling future growth, options to defer investments, options to stage investments; options to expand or contract operations [Dixit and Pindyck, (1994); Trigeorgis, (1996)].
In recent years, scholars have drawn attention to the parallels of financial options and investing in a technology and R&D [Angelis, (2000); Benninga and Tolkowsky, (2002); Faulkner, (1996)]. Option contracts represent small investments which yield the opportunity to purchase an underlying security at a later date [McGrath, (1996)]. When an investor holds an option, the investor can exercise the option and buy the underlying security. In essence the investor only carries a limited downward risk (the price paid for the option – which is a fraction of the price of the underlying security), without losing access to the opportunity [McGrath & MacMillan, (2000)].
A fundamental idea behind so-called options thinking is that uncertainty can be good. RO valuation can justify investments strategically even if the DCF analysis suggests otherwise by incorporating managerial flexibility and thus minimizing the downward risk and taking advantage of the upward risk. DCF is an input to the RO valuation analysis so DCF and RO could be thought of as being complementary rather than competing. Slater et al. [1998], Moyen et al. [1996] and Olafsson [2003] thoroughly discuss the

disadvantages of DCF analysis, the advantages of options thinking. Slater et al. propose an integrated DCF/Options analysis model for the investment decision making problem.

A major limitation to utilising RO for technologies is that, unlike financial options, with technologies there are no underlying assets. One way of dealing with this is to create more sophisticated stochastic models, but the question of whether it is valid still remains. Arbitrage pricing analysts need to be able to form a risk free portfolio. With technology projects though, the date on which the project/option will mature and its cost are not guaranteed as they are in the financial world. In fact, the project might fail and not provide an option at all, again unlike the guaranteed options contract in the financial world. If the project does complete successfully, then the payoff is typically the option to launch another project to commercially exploit the technology i.e. typically real options are compound options [Hunt, *et al.,* (2004)].

A further pragmatic point to consider is the limit of accessibility for the users under consideration: venture capitalists and management teams. The "lumpy" nature of information release in technology might make decision trees a better model than commonly used random walk processes [Loch and Bode-Greuel, (2001)]. Hunt et al. [2003] point out that the loss of intuitive understanding of the model may significantly undermine the value of the technique for non-expert users.

2.3. *Decision trees*

Decision trees are another way of dealing with sequential decision options. Decision trees are closely aligned with RO. These originated from decision theory [Markland and Sweigart, (1987); Raiffa, (1968)] which essentially helps decision makers to structure problems to the extent that statistical calculations can be performed to work out the expected value of particular decisions. Decision tree analysis classifies possible future outcomes e.g. a research project failing, producing a reasonable result or producing an exceptionally good result. It then ascribes probabilities to these outcomes, by some means e.g. past data on similar projects or expert opinions. This can be done for a series of events e.g. the research project then the market launch, and from these a tree of outcomes can be constructed. Next decision points need to be inserted and the optimal decisions chosen to maximize the expected value. This approach can be extended into one of Monte Carlo modeling where probability distributions are assigned to variables such as "market size" and simulations of the project created by sampling from the probability distributions.

A criticism commonly leveled at decision tree analyses is the reliability (and meaning) of the probabilities. In cases of uncertainty, such as the future value of technology potentials, decision theory uses "subjective probabilities" or "best guesses" [Dobbs, (1991); Raiffa, (1968); Spencer, (1962)], on which risk-like calculations can be applied. The success of such decisions thus depends on the accuracy of the assumptions of the decision maker. Decision trees only are useful when the outcome of a new technology is relatively predictable. However if the outcome of the new technology is not yet known, and a so-called wide judgmental gap [Raiffa, (1968)] exists, decision trees are no longer adequate.

2.4. *Portfolio management methods*

Portfolio management is a decision process where a business's list of active new products and R&D projects is constantly updated, reviewed and revised. In this process, new products are evaluated, selected and prioritized; existing products may be accelerated, killed or de-prioritized [Cooper, *et al.*, (2001)].

Selecting a portfolio is in theory merely a question of optimizing profitability within constraints of resources and timing. Mathematical techniques, such as the ones described in our previous section, are available for doing this but, as Cooper *et al.* [2001] and Tritle, *et al,* [2000] have observed they are seldom used in practice. Financial analysis suffers from the fundamental problem that the data required may be unavailable, or of dubious quality, especially in the critical early stages.

For this reason many companies prefer to replace, or at least supplement quantitative models with techniques that incorporate qualitative assessments. An example is scoring models. With scoring models projects are assessed and rated according to a range of criteria regarded as predictors of success. For example scores may be given for unique product features, size of market, the ability to leverage the company's core competences etc, as well as the planned cost and profit. The criteria may be very generic, reflecting what is known in general about success criteria for new products [Cooper et al., (2001)], or they may be industry- or company-specific. The sum of the scores against all the criteria represents the overall merit, or potential value, of the project. A simple selection of projects can be done by ranking them according to value for money or for effective use of critical resources.

Another example of portfolio management is the use of strategic approaches [Cooper et al., (2001)]. The portfolio must also reflect the company's general strategic intent, ensuring that sufficient resources are allocated to strategically important businesses, markets or technologies. This may be achieved by simply allocating a certain proportion of innovation spend (known as 'strategic buckets') to particular businesses or types of project [Cooper et al., (2001)].

A further example is the so-called "bubble diagram". Managers can use them as an aid to ensure that the portfolio is not inappropriately biased in one direction or the other. Many authors advocate the use of checklists to ensure that all relevant aspects of value and risk are captured [Tritle, *et al.,* (2000)]. The bubble diagram is merely an aid to understanding the portfolio, not a decision-making tool in itself. Generally a mix of low risk projects will be desired, balancing a few higher-risk and higher benefit opportunities but it is left to management judgment how they are to be balanced.

These portfolio management approaches all contribute to technology valuation in that they provide various ways of depicting a set of assumptions across a variety of dimensions. Albeit widely used in industry [Cooper et al., (2001)] these approaches fail to address where the data actually comes from, what are the techniques used to collect the data that fills the diagrams and scorecards. Furthermore, it is unclear how useful portfolio tools are for relatively small portfolios.

2.5. *Roadmapping for technology valuation*

A recent addition to the arsenal of technology valuation tools and techniques is the use of roadmapping. Roadmapping is a way to explore and improve the value of technology projects at a very early stage [Hunt, *et al.,* (2004)]. As well as supporting communication within the project team, roadmaps can be post-processed to emphasize key messages and can then be used as a tool for communication with senior management. A roadmap is typically used to collect and digest qualitative information and stretches over several years. It is particularly suited to ensure that the longer-term orientation of the business is adequately served by the selected projects.

Technology road-mapping was originally developed by Motorola in the late 1970s to support integrated product-technology strategic planning [Willyard and MacClees, (1987)], using a simple graphical representation. The roadmapping approach has subsequently been adopted (and adapted) widely in industry, both at the company and sector levels, to support a variety of strategic goals e.g. [Kappel, (2001); Kostof and Schaller, (2001)]. Roadmaps take a variety of forms, although perhaps the most generic and flexible is based on a time-based multi-layered architecture [Phaal, *et al.,* 2001; 2004].

Roadmapping, in a customized format, can be used as a framework for supporting technology evaluation and valuation (to explore, communicate, calculate, maximize and manage value) – a value roadmap. The approach can be used (supported by a workshop) at the early stages of a project to explore the value proposition, and to improve the design of the project (risk reduction). In principle, the approach can also be used to support the business case for technology development, qualitatively and quantitatively (in financial terms), when the technology reaches a higher maturity level (assessed in term of technology readiness level). Such value roadmaps are based on the premise that, although it may not be possible to predict the exploitation path for early stage research with any degree of precision, the 'richer' the picture that can be created in terms of potential future revenues, the more likely it is that value will be created.

Roadmapping differs from the other techniques mentioned here as it does not only considers the external (technology and market) factors in order to determine value, but also provides space for an internal assessment of the firm capabilities. The previous perspectives on technology valuation predominantly take an external focus on either the technological aspects or the market aspects of technology valuation.

The roadmapping approach is aimed at individual projects or programs, and is not directly applicable to a portfolio of disparate projects, although the output from the value roadmap could be an input to a portfolio management approach. The value roadmap is an example of a technique that essentially is based on a structured data collection technique that gathers a collective set of expert opinions in a workshop setting. These opinions are populated in a predefined architecture, as to draw conclusions on likely future scenarios for technologies. The value roadmap does not prescribe decisions or outcomes, yet it can be used to fuel the imagination and shape the judgment of the decision maker with the aim of increasing the quality of their assumptions.

2.6. *Analysis of some prevailing business appraisals techniques for new technologies*

The methods described above have advantages and limitations in their usage for appraising technology potentials. In table 1 we have provided an overview of the techniques discussed. Although not necessarily conclusive, the list gives an indication of the implications of the various techniques. Furthermore, each of the studied techniques can be attributed to a distinct reference discipline from which the techniques have been adapted for the purpose of valuing technologies. These reference disciplines can be used to explain the multiple perspectives from literature on technology valuation.

Technique	***Reference Disciplines***	***Advantages***	***Limitations***
Discounted Cash flow	Finance Management	Accepted, intuitive, credible, easy-to-use, transparent, suitable for stable predictable environments	Accuracy and reliability – especially for early stage technologies, no managerial flexibility
Real Options	Finance Management	Managerial flexibility, sequential decision making, suitable for more dynamic environments	Validity, limits to analogy with financial options, accessibility (black-box), has limits to applicability for early stage technology
Decision trees	Decision theory, Statistics	Sequential decision making, more accessible then RO	Reliability and meaning of probabilities, judgmental gap for early stage technology.
Portfolio methods	Strategic Management	Supplementary qualitative assessment, graphical representations	Do not address how to get the required data, can be time consuming
Road-mapping	Strategic Management	Construction of mental model, applicable for early stage technologies, internal assessment of capabilities, shapes judgment	Not directly applicable for portfolio of disparate projects

Table 1. Overview of Techniques for Business Appraisal of Technology Potentials

Firstly, from a financial management perspective techniques such as discounted cash-flow and real options have been applied to value new technologies. The literature study shows discounted cash-flow techniques can be useful, but only in cases where the uncertainty arising from the new technology is relatively stable. This is typically the case when the technology is in the more mature stages of the technology life cycle. In the early stages of technology life cycle, uncertainty is inherent and thus DCF techniques alone are not sufficient. In these cases an alternative approach from a financial management perspective can be the use of real options, as this allows for the sequential decision making and managerial flexibility. Yet, the real options techniques range from simplistic options thinking to complex mathematical approaches. As it is still unclear how financial options can be compared to technology options, the underlying mathematical schemes adapted for the use of the valuation of technologies are still doubtful. Furthermore, the added complexity of these techniques may also hinder the overall process of communicating and, in some cases, convincing the decision makers, as the technique itself can be subject to heavy scrutiny. It seems that the options thinking approach as opposed to singular go/no go decisions, has the most potential in supporting decision making for technology investments. Yet, especially in the early stages of technology development it is doubtful if all the options can be clearly distinguished. Technology valuation is a learning process that benefits from reflections on the methods used and their outcomes.

From a decision theory perspective, visualization techniques such as decision trees can be used to support the clarifications of the various options a decision maker has. Yet, the probabilities assigned in a decision tree can suffer from the judgmental gap of the user of the technique, in cases the probabilities are hard to predict. Nevertheless, decision trees can be used as helpful visualization for the description of the route to market stemming from each decision option.

Finally, adapted from strategic management are the techniques that also incorporate non-quantifiable (or 'soft') factors. Firstly, techniques used to manage investment portfolios of assets have been adapted and applied to manage portfolios investments in technology projects. Techniques such as strategic buckets, and the use of scoring methods allows for the incorporation of the non-quantitative aspects. The limitation of the technique is that it can be time consuming and it does not elaborate on how to get the additional non-quantitative data.

The latter has been addressed recently by adapting roadmapping techniques for technology valuation. Using a structured process, expert knowledge can be collected and depicted in a way to ensure a comprehensive picture the potential value streams of a new technology become visible, not just to the individual but also to the group as a whole. This technique is appropriate for the earlier stages of technology development as it helps to get a collected view of the individual expert judgments, both from a commercial as well as technical perspective. Yet, the technique is still relatively new and it still needs to be seen how many new insights can be gained. Furthermore, it does not seem a very appropriate technique when the decision maker has to deal with a portfolio of disparate technologies.

Although it seems that managers have a wealth of options when it comes to choose a technique for technology valuation, in practice this is not always the case. Pavia [1991] already pointed out that in practice "gut feel" is still a dominant factor in the process. In the next section we aim to explore what perspectives and tools are in fact used in order to value technologies in one particular industry. We will use these findings to corroborate the results of the literature analysis.

3. Cases from the aerospace industry

3.1. *Research Methodology*

In order to study the practical implications of the various techniques from different perspectives we follow Nixon (1995) who argued that surveys provide little evidence about the influence of the techniques on the investment decisions. To examine in-depth the various perspective of the techniques we have examined 4 cases in the Aerospace industry in Europe. Due to this exploratory nature of the study we have used a case study approach [Eisenhardt, (1998); Yin, (1989)] in order to further the understanding of the use of business appraisal techniques for technology valuation. Although there are well-known limitations in terms of validity and reliability (Yin, 1989), this method has been selected as it is best suited to deal with the complexity of the variables, relationships and absence of hypotheses on the use of valuation techniques. Such a situation favors an inductive rather then a deductive approach (Yin, 1989).

The cases represented a civil aerospace integrator, avionics system, air systems and a 1st tier supplier in Europe. The aerospace is a relevant industry as technology is one of the major sources for investment.

Various sources of data were accessed for this research: observations/company visits, interviews, workshops and company reports. For each company we have held semi-structured interviews with middle and top management that represented either the commercial and financial side (C&F), or the research and technology side (R&T) involved in valuing new technologies. Some of the interviewees have been approached several times after the initial interview via an additional visit or on the phone to clarify and refine the data. However we have only counted one semi-structured interview per interviewee. Furthermore we have held two dedicated half-day workshops in which some of the interviewees took part. The aim of the workshop was to identify gaps and challenges in technology valuation. Our dataset is complemented by archival records, personal observations and informal discussion collected over a period of 5 years. An overview of the data collection process is provided in table 2.

We have used semi-structured in-depth interviews. The purpose of the interviews was mainly to understand the process of technology valuation and to map what tools and techniques where used within the various stages technology development in the aerospace supply chain. In addition we have made an assessment of their requirements.

Company	Population	Semi-Structured Interviews (*Data Sources*)	Number of Visits	Number of Workshops	Secondary Data Sources
OEM	R&T	3	1	-	Internal documents Publicly available information
System Integrator	R&T C&F	1 1	2	3	Internal documents Publicly available information
Avionics Systems	R&T C&F	1 1	4	1	Internal documents Publicly available information
1st Tier supplier	R&T C&F	2 1	2	2	Internal documents Publicly available information

Table 2: Data collection overview

4. Technology valuation process in the aerospace industry

The aerospace industry is characterized by high entry barriers, long product cycles, regulations and re-qualification of products every time a new technology is introduced. As the technology projects are often cross-border initiatives these projects are hampered by cultural variability and the fact that the technology will be integrated into a larger system.

The conservative nature of the airline industry (and passengers) leads to optimizing round a fairly set situation. Fundamental paradigm changes are often imposed through regulatory changes that give rise to new criteria and thus research. This has a repercussion on the technology development throughout the supply chain.

In the aerospace industry technology development is often a joint effort involving the whole supply chain. This means that close cooperation is required with the suppliers and customers as the research and development activities are platform dependent. The suppliers rely heavily on what the OEM requires. Nevertheless, this should not be seen as a process that happens in isolation, but in partnership. For example, OEM and suppliers operate jointly in EU funded R&D projects to spread the risk whilst maintaining direction. Additionally informal networks appear to exist that ultimately defines the direction.

Three distinct phases have been identified: ad hoc research, 5-10 year timeframe and blue sky research. Technology valuation activities are mostly deployed in the second phase. By far the highest percentage of total investments is dedicated to short term projects. 90%

of technologies used in an aircraft project are not new. The blue sky work is very dependent on the strategy of the overall industry.

Although there is high customer dependency and joint development, there is no formal process by which the supply chain makes technology investment decisions. In fact internally the companies often have few or no explicit standard procedures specified for technology valuation issues. Local formalized processes do exist but these are often kept within the borders of a specific function. In line with the expectations if specific methods are used, then these are often hybrid or in-house customized developments.

Assessment of aerospace technologies is based on 5 drivers. When a new technology contributes to any of these drivers it is assumed that it will result in value creation:

(1) drag/weight ratio,
(2) cost of manufacturing/recurring cost,
(3) safety,
(4) passenger comfort,
(5) environment.

From a process point of view we have been able to identify a number of stage gates or classifications of technology. A typical classification considers the following stages: discovery, understanding, developing (with respect to the technology), validating and deploying. The formal appraisals are often done periodically rather than on an as required basis.

4.1. *The use of Technology Valuation Tools and Techniques in the Aerospace cases*

For our study we have taken two distinct perspectives: a technology and a commercial perspective, in order to explore and understand how valuation techniques are used and by whom. The first perspective is that of the research and technology (R&T) related departments. This perspective is represented mainly by the research and development people, the engineers and technologists of the company. The second perspective relates to the commercial and financial (C&F) related departments such as the finance department, general managers and managing directors.

The first finding from our case studies is that the use of financial valuation tools is widespread but limited to C&F. In R&T, despite their background usually being in science or engineering, a discipline usually associated with mathematical rigor, financial valuation techniques were hardly used. The majority of our R&T respondents did not use any financial methods. The general view on these techniques was that they considered such tools as a "black art" and in some cases as a waste of time. The reason was not so much that they did not understand the mathematical logic but that they felt that such techniques did not capture the non-quantitative aspects of the technology which, especially in the early stages, was seen as crucial and far outweighing the quantitative aspects. For example, in one interview the person responsible for technology decision said that justification on hindsight was enough, and if he got it wrong the measure would correlate to the future of his position in the firm, thus taking full responsibility. These opinions were for a majority of the cases focused on early stage of the technology life cycle.

For R&T the most common method for technology valuation is individual expertise or "gut feel". Especially with respect to technical uncertainties, a heavy reliance is put on the technical expertise of a few "wise men" within the organization. As one interviewee stated "Shed loads of engineering judgment goes into whether it feels right. Someone will take a bold step regardless of the data."

In the cases where R&T did use some form of financial valuation tool, it was specifically requested by the decision makers. In these cases the DCF technique was applied but only to seek justification for their predefined opinions on the technology.

In contrast, the C&F departments are using dedicated financial tools and techniques. For instance one supplier developed and utilized a complex spreadsheet in which both financial analysis (DCF) was applied together with sensitivity analysis (portfolio management), in order to prepare a comprehensive business case. Many financial issues are regarded such as exchange rates fluctuations. These business cases relate mostly to technologies that are in a more advanced stage in their life cycle and often concern development and production projects.

However when technical issues and uncertainties emerged, no explicit methods were available. In this case an expert opinion was requested. During the interviews it appeared that the technical considerations were seen as too complex, and hence they fully relied on the judgment of the R&T opinions in the company.

Portfolio management techniques are used in adaptive formats often integrated with DCF techniques. In one particular example one of the suppliers developed its own portfolio technique [Farrukh, *et al.,* (2000)]. This activity started with a set of workshops considering how to develop a more structured method of making a judgment on the relative value of the R&D programs necessary to meet aircraft project targets. The aim was to allow the company to make robust decisions on where it should focus its own funding on R&D, both long and short term to the benefit of the business. The work resulted in a project portfolio methodology being developed by the company. The technology selection criteria were divided into two main sets: benefit and cost. The 'benefit set' were further defined in terms of four company values: performance, partnership, technology and people. The 'cost set' were defined by risk and price. A fifth company value, the customer, was included to give a portfolio tool with two axes. Customer Focus aims to capture the value of the R&D in meeting the customer requirements. Technology Benefit/Cost aims to capture the value of R&D to the company as a piece of technology. The value of the technology to the company was addressed by combining the Benefit and Cost criteria via a weighting and scoring method.

Although in one instance this approach resulted in a budget increase, it was seen as painful as most uncertainties are non-quantifiable and difficult to comprehend. This was especially the case in the early stage development projects. Also, in one case the company had multiple international sites, which added to the cultural complexity as different interpretations were given to certain valuations and different methods were used in the various countries.

Real options were not used in the technology valuation process. Although some C&F stated they were currently looking at this method, none of the firms actually applied it.

Nevertheless, some aspects of option thinking could be observed in the informal decision making process, yet they were not explicitly mentioned nor acknowledged.

Finally, although most companies used roadmapping as part of their technology strategy, this technique was not directly linked to technology valuation initiatives. Nevertheless the system integrator was actively exploring opportunities to do this. During this initiative both R&T and C&F were involved to a certain extent, and the experiment led to the ongoing research activity focusing on a value roadmapping approach co-lead by the authors of this paper.

When comparing these results with a typical technology life cycle it becomes apparent who uses what type of technique in which phase of the technology adoption life cycle [Rogers, (1962)]. This life cycle can be depicted as an s-curve with on the x-axis the time and y-axis the sales. We have adapted this by including investment as an adoption factor as this can for example include internal sales. Based on this curve it becomes apparent who plays what role in the development of the technology and what techniques are used to value the technology (see figure 1).

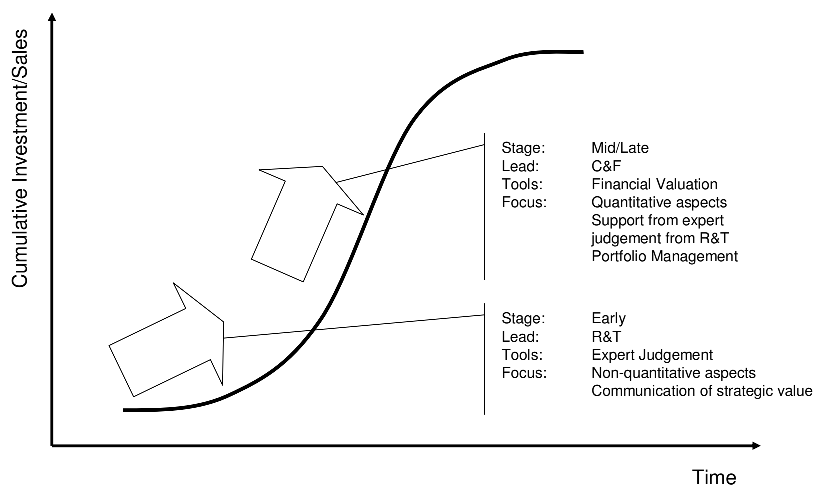

Figure 1: Technology Valuation Techniques vs. the Technology Adoption Life Cycle

Whereas the early stages are characterized by high levels of expert judgment on non-quantitative factors, the later stages are characterized by financial valuation methods on quantitative factors. Interesting is the role change, whereas in the early stages often the R&T has the lead in the valuation process, in the later stages the lead is shifted to C&F. Furthermore, the curve shows that the investments made in the mid/late stage of technology adoption are significantly higher then the level of investment in the earlier stages. Our data confirms this is the case in our examples where the earlier investments are often related to joint research projects supplemented with government funds, whereas the later stages commercialization is key.

5. Discussion

Two gaps and limitations of the current practices could be identified. Firstly the integration of a strategic management approaches during the valuation was predominantly done in informal ways. There was no structured integration between the technology valuation activities and the strategic management approaches applied by the company. Secondly, from a process perspective there was little transparency on the valuation process between R&T and C&F.

Integration with Strategic Management Approaches

From a strategic management point of view very few methods were integrated into the valuation process other then the use of portfolio methods. Especially from the R&T side this gap was identified. One respondent of the 1st tier supplier clearly stated that "…there is a need to have visionaries who can think beyond one aircraft life-cycle". This statement related to the lack of people that could put weight behind identifying the strategic non-quantitative factors in the early stages of the technology life cycle. It was also mentioned that during this early phase the available technology directions were thin and heavily reliant on visionaries due to the long life cycle of aircrafts.

Furthermore, the observed lack of integration with the use of roadmapping and the techniques used to value technologies is another indicator. Most of the interviewees reacted positive on the suggestion to integrate this technique and the system integrator already commenced with a trial based on historical data.

From an internal point of view the importance of complementary assets was noted. It is important to make decision in the light of the available resources and time. Few valuation techniques support such an internal view. Estimating what the market potential for a certain technology might be in the future, or the likelihood that a certain development will work still does not guarantee that the organization that is assessing the technology will in fact be able to reap value from the technology. When looking at the techniques evaluated in this paper, only a few methods, such as roadmapping, explicitly provide space to review an organization's complementary assets and capabilities. For example, a firm's entrepreneurial capabilities [Schumpeter, (1934)] could provide an additional indicator for the relative value of a specific technology (for example breakthrough technologies). Other indicators for technology valuation could also stem from the literature on the resource based view. For example Barney [1991] argued that (technology) resources (a) must be *valuable*, by either exploiting opportunities or neutralizing threats from the environments, or both, (b) must be *rare* amongst competitors, (c) can only be *imitated imperfectly*, and finally (d) should be *non-substitutable*. These are also known as VRIN resources [Barney, (1991)]. From a technology valuation perspective such resource indicators could enhance the overall understanding of the likelihood of a return on investment in the new technology.

Furthermore, in cases of breakthrough innovation it is argued that organizations need to have capabilities that will enable them to act and respond to unpredictable changes

[Teece, (1997)]. The basic assumption is that whilst a technology can be seen to have a value in the market, this does not necessarily mean that the company has the capabilities to actually capture this value. These capabilities are described as *dynamic capabilities* in that they enable a firm to reconfigure its resource base and adapt to changing market conditions or technological innovations in order to achieve a competitive advantage [Teece *et al.* (1997)].

The integration of additional indicators in technology valuation techniques thus seems a useful extension.

Transparency & Communication

From a valuation techniques perspective it is important for both R&T and C&F to have transparency on the valuation activities and to understand what is done by who in the various stages of the technology life cycle. It emerged that the existing techniques did little to enhance the communication on the confluence between C&F and R&T. Both areas use different toolsets and approaches.

From a process perspective we observed that there was a distinct lack of knowledge with R&T on the actual use of valuation techniques by C&F and vice versa. In the early stages the process is very informal. For example in the case of the 1st tier supplier a consistent process of collecting opinions within R&T from some key experts could be observed. However these ways of working are not transparent and therefore not well understood by C&F. In contrast the methods applied by the C&F departments relate more to the later stage technologies, and often involve the management of a project and/or contract portfolio. The technologists are often not aware of this and are only requested to make a contribution in cases of technical uncertainties.

The cases imply that there is a need for methodologies that allow for more transparency and joint understanding of the important drivers throughout the technology lifecycle and its subsequent decisions.

6. Conclusions

In our exploratory study we have seen that the spectrum of technology valuation techniques is wide and takes various disciplines into account. This paper contributes additional requirement and integration of new perspectives in the development of techniques for technology valuation.

We argued that more enhanced integration of strategic management techniques in the existing arsenal of techniques would benefit the overall valuation process. Especially the integration of a resource based view could be a worthwhile avenue to explore.

Furthermore transparency of the techniques used is as important as validity and reliability. The cases show two distinct perspectives: R&T and C&F. Both have their own preference for a certain type of tool, the former for more gut feel oriented approaches and the latter uses more quantitative approaches. Yet, when testing them on the knowledge of each others methods, it seems that there is little understanding and transparency what happens on the other side. In addition they seem to operate in different phases of the technology lifecycle.

A limitation of the work presented here is the generalizability as the paper builds mainly on four cases in the aerospace industry. More empirical work is required to extend the practical view on the use of technology valuation techniques. Future research can be directed to further understand the implications of technology valuation in various industries, from which typologies could be derived.

To practitioners this paper can be used as a guideline to organize and structure the process of technology valuation consistently over the life cycle of the technology. The findings of the literature review can be used in a selection process for techniques and the empirical evidence revealed new ways of approaching technology investment decisions.

Future research can be directed to develop a rich methodology that incorporates not only interdisciplinary approaches but also takes into account the various stakeholders that will be using the methodology. A methodology could for example focus on the underlying embedded routines that shape the "gut feel" of technologists and make this process more explicit to finance and commercial managers. They would then be able to have a more thorough understanding what the specific considerations are from a technical perspective. Conversely, methodologies could support the awareness and rational behind the structured and objective approaches often used in the commercial and finance departments. The value roadmapping technique seems a good starting point to commence with such a consensus based approach for technology valuation, taking multiple perspectives. Furthermore, few methods are aimed at supporting the valuation for the complete technology life cycle. A framework which incorporates all disciplines and stipulates when to use what could be a step in the right direction to address this challenge.

7. Acknowledgements

This research is an Innovative Manufacturing Research Centre project, "Business Appraisal of Technology Potentials", supported by the UK Engineering and Physical Sciences Research Council. We would also like to thank Rob Phaal, Ken Platts, Emre Kazancioglu and Clive Kerr for their helpful contributions.

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