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Deferring to improve evidence: The real options approach to value of information.

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Abstract

Real option analysis uses financial option pricing techniques to value 'real' opportunities, highlighting the similarities between exercising financial options and making choices in non-financial sectors. Real options analysis is appropriate when decisions are characterised by uncertainty, some degree of irreversibility and an ability to defer. Subsumed within this is the idea that deferral may reveal information relevant to the decision, that is valuable. The expected value of perfect information (EVPI) places an upper bound on the benefit to instantaneously possessing complete information. Option premium measures the value of evidence obtained through deferral and forms a subset of EVPI. This paper considers the National Institute for Clinical Excellence's opportunity to defer making an approval decision subject to improved information becoming available. The decision is modelled as an American call option to defer approval. A combined Brownian motion and Poisson arrival process is developed to illustrate the evolution of information through time and the value of the option is calculated for a range of expected benefits. Implications of using real options analysis for the current adoption decision and for the related decision to collect additional information are discussed.

The option to wait for more information: Option value and the value of information.

1 Introduction

Methods of incorporating uncertainty into economic evaluation of health technologies have been debated for some time. Techniques to help understand, present and evaluate uncertainty have included single, multi-way and probabilistic sensitivity analysis, scenario and threshold analysis, and the use of confidence intervals and cost-effectiveness acceptability curves (Briggs and Gray, 1999). Value of information analysis has developed as a tool that places a value on uncertainties within a model and has been proposed as a way to prioritise efforts to reduce uncertainty. The expected value of perfect information (EVPI) defines a maximum willingness to pay for research efforts that provide information relevant to the decision.

Real option theories consider decisions under conditions of uncertainty and are relevant when choices can be deferred, and deferral is associated with learning more about uncertain variables(Dixit and Pindyck, 1994). Analysing the opportunity to wait for information as an option to defer, allows option premium (the incremental value of deferral) to be estimated. This places a numerical estimate on the value of waiting for additional information. Option premium is therefore a form of value of information that may have implications both for the way uncertainty is perceived and the way research budgets, aimed at reducing uncertainty, are allocated.

This paper explores the relationship between measures of value of information. Section 2 considers existing work on value of information in economic evaluation and develops a stylised example illustrating information gained from a clinical trial. Section 3 discusses deferral as a way of gaining information and estimates the incremental value of deferral. Section 4 makes the distinction between actively seeking and independently observing information and identifies a relationship between option premium and the expected value of perfect information. A combined Brownian motion / Poisson information arrival function is created in section 5 to

model the option to wait for additional information. Applications to health care and implications for decision-making are examined. Section 6 concludes.

2 Value of information in economic evaluation

When a decision is made in the presence of uncertainty there is some possibility that an alternative, other than that with the greatest expected net benefit, offers a greater payoff retrospectively. Information collected prior to the decision being made can improve the probability of making an ex-post optimal decision. Uncertainty is therefore costly and information is valuable for this reason. In the extreme, perfect information on the parameters of interest may be sought.

The expected value of perfect information (EVPI)[1], measures the value of information by considering the probability of making a sub-optimal decision (based on prior information) and the implications of doing so. EVPI is estimated by calculating the difference in expected payoff between a decision made with perfect information and one made in the presence of uncertainty. Discussion of the concept of EVPI and its usefulness within health care have developed from statistical decision theory (Pratt et al., 1995; Raiffa and Schlaifer, 1959). In practice value of information analysis has been applied to a variety of areas including engineering (Howard, 1966) and food safety (Hammitt and Cave, 1991).

Clinical trials are designed to improve current evidence concerning effectiveness, providing greater information for clinicians, GP's and policy makers. Whilst gathering information is beneficial, it is also costly; trials and research and development consume large proportions of research budgets. EVPI defines the maximum potential improvement in payoff available as a result of improved information and therefore places a bound on the achievable benefit from collecting evidence (Felli and Hazen, 1998). As a result EVPI has been used to identify an upper boundary on the willingness to pay for research activities within health care (Claxton and Posnett, 1996). EVSI (Expected value of sample information) has likewise been

[1] EVPI is mathematically equivalent to, and is sometimes referred to, as expected opportunity loss.

used to define the potential benefits from clinical trials that sample effectiveness for a subset of the population (Claxton and Posnett, 1996).

The classical concept of EVPI can be illustrated through a hypothetical example. Suppose a new technology has been submitted for approval to the National Institute for Clinical Excellence (NICE). The approval / rejection decision is assumed to be made immediately and is fully irreversible. Once approved the technology confers uncertain monetary benefits each period in perpetuity. For simplicity the decision is characterised by first order uncertainty over the cost-effectiveness of the technology, which is resolved by a trial. If an improvement in cost-effectiveness is demonstrated expected benefits per period are £1000. If a reduction is shown benefits per period are £40. The prior belief is a 0.5 probability that the trial will improve (or deteriorate) periodic monetary benefit. Upfront irreversible costs of approval are assumed to be £2000 (figure 1) encompassing the costs of generating and disseminating guidelines.

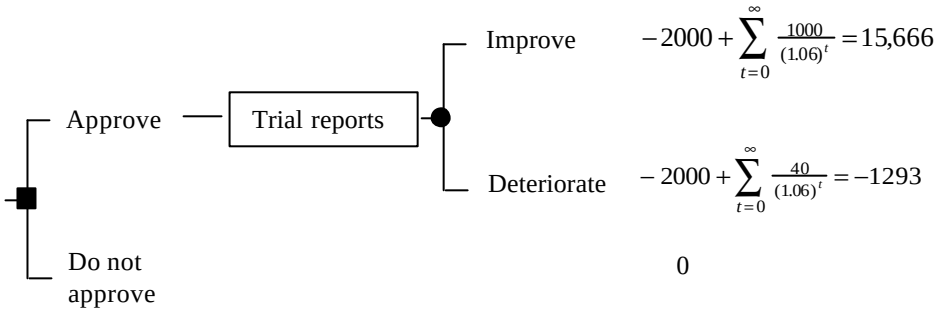

Figure 1. The decision to approve a technology

With a discount rate of 6% the optimal decision is to adopt the technology with a net benefit of £7187 (Equation 1).

$$\text{Net benefit} = -2000+\sum_{t=0}^{\infty}\frac{0.5*1000+0.5*40}{(1.06)^t} \qquad \textbf{(EQN. 1)}$$

-2000+9187

7187

EVPI is calculated by considering immediately, the best retrospective decision. In this case approval should only be granted in the event that an improvement in cost-effectiveness occurs. The difference in payment between this and expected net benefit

is EVPI. The classical approach to value of information assumes no delay in receiving information, and in this example additional information would improve expected payoff by £646 (Equation 2). This represents the decision-makers maximum willingness to pay to obtain the research results immediately.

EVPI = Payoff under certainty – Payoff under uncertainty

$$0.5\left[\sum_{t=0}^{\infty}\frac{1000}{(1.06)^{t}}-2000\right]-\left[-2000+\sum_{t=0}^{\infty}\frac{0.5*1000+0.5*40}{(1.06)^{t}}\right] \qquad \textbf{(EQN. 2)}$$

7833-7187

646

Although simple, using a single source of first order uncertainty this stylised example illustrates relevant concepts for comparison with a real options model.

3 Option value as a value of information

Financial options confer the right to perform a specific future stock transaction. For instance a call option permits the holder to buy (exercise the option) a fixed number of units of a given commodity (the underlying asset) at a specific price (exercise price), on or before a stated date (the exercise date). Financial options are characterised by uncertainty, irreversibility and an ability to defer; the uncertain market price prevailing at the time of exercise determines the extent of any profit[2], once exercised they cannot be exercised again, and exercise can be deferred until the contracted exercise date. The owner of an option always has the right with no associated obligation to carryout the transaction, just as a decision maker may choose not to pursue a project if expected net benefit is negative. This similarity between financial options and 'real' investments has been noted by a number of authors (Dixit and Pindyck, 1994; Trigeorgis, 1999) and has developed into an independent discipline. Real options has also previously received some recognition in health care (Mitchell et al., 2000; Palmer and Smith, 2000)

The opportunity to defer approval of a technology is akin to an American[3] call option on a dividend paying stock. Exercising the option to approve is partially irreversible requiring dedicated time costs of generating and disseminating guidance[4], can be deferred for some period of time and involves incurring some upfront expenditure in return for uncertain periodic benefits.

Taking advantage of the ability to defer allows information on sources of uncertainty to be gained during the waiting period. This can be incorporated into assessments about whether irreversible decisions with uncertain outcomes should be pursued. In that VOI and option pricing both examine the impact and value of improved information on current decision-making, they are alike.

Intrinsic value is the benefit associated with immediate optimal action under an option pricing approach. Option value is the benefit associated with a deferred decision made in light of information becoming available during the period of deferral. The difference, option premium, is the incremental value of being able to defer and gather information, and equates to a value of deferred information.

Suppose the National Institute for Clinical Excellence (NICE) face an option to defer approval for one year. In the intervening period a trial will publicly report additional cost-effectiveness evidence revealing all information relevant to the decision. The probability and absolute payoff associated with improved or deteriorated cost-effectiveness remain the same. NICE must estimate intrinsic value and option value in order to make a decision (figure 2).

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[2] When the prevailing market price exceeds the exercise price the underlying asset can be sold immediately on the market for a profit of S-X. If the market price is less than the exercise price the option would expire worthless and the stock bought on the market.

[3] American refers to the fact that the option can be exercised (the stock bought/sold) before the exercise date.

[4] Potential political ramifications, especially if the approval decision is against popular opinion, or turns out to be poor in the light of mounting evidence, provide further sources of irreversibility.

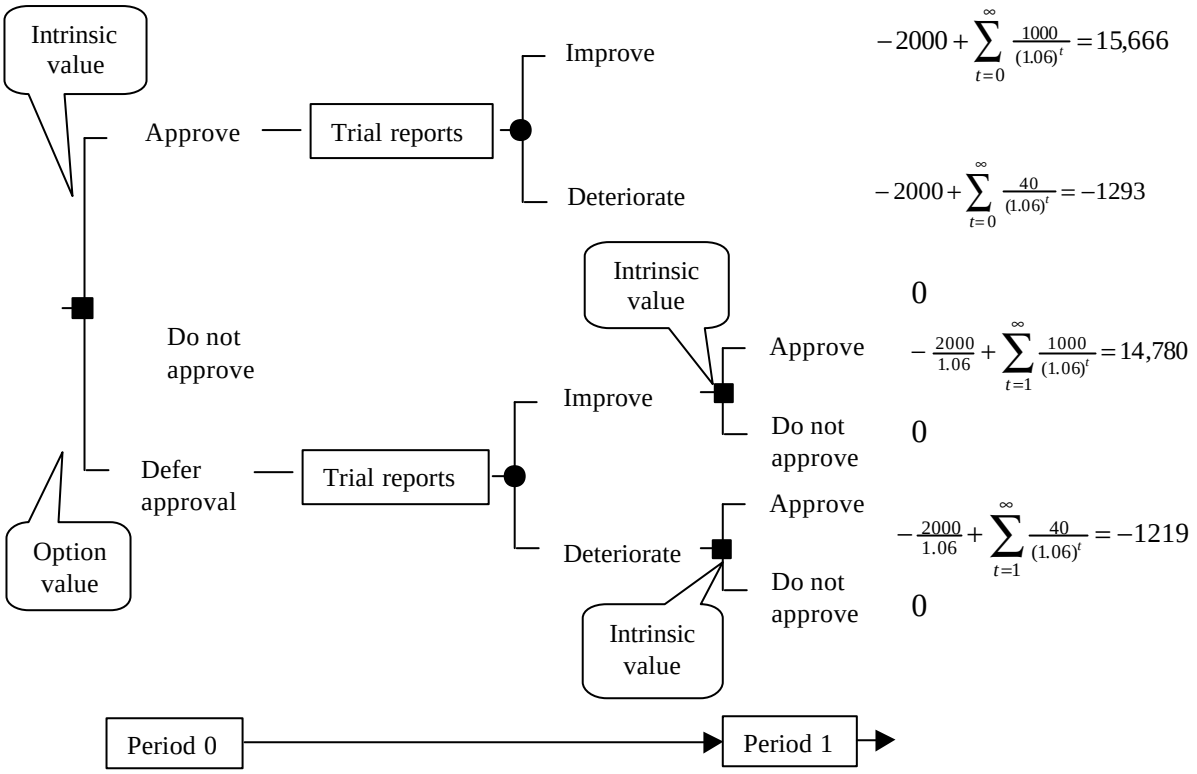

Figure 2. The decision to approve or defer approval of a technology

If immediate approval occurs the irreversible costs are incurred upfront. Combining this with the 0.5 probability of receiving beneficial or detrimental cost-effectiveness evidence gives an intrinsic value estimate equal to net benefit under a traditional approach[5].

$$\text{Intrinsic value} = -2000+\sum_{t=0}^{\infty}\frac{0.5*1000+0.5*40}{(1.06)^t} \qquad \textbf{(EQN. 3)}$$

-2000+9187

7187

If deferral is chosen, the trial reports prior to the decision being made. In this case irreversible costs and potential benefits are both delayed for one period. Real options analysis must weigh the relative gain from information against the gains and losses from delayed action. Once the trial has reported the decision maker can assess the relative desirability of approving given the additional trial based information. On the exercise date the option to approve is exercised only if intrinsic value is positive. If the trial reports improved cost-effectiveness the optimal action is to approve

(£14,780). Conversely, if the trial reports poor cost-effectiveness the optimal action is not to approve (£0). Following deferral approval will only be granted if the trial demonstrates positive results. Current option value providing the expected value of deferral is given by:

$$OV = 0.5\left[\sum_{t=1}^{\infty}\frac{1000}{(1.06)^t} - \frac{2000}{1.06}\right] \quad \textbf{(EQN. 4)}$$

$0.5[16667-1886.8]$

7390

The difference between option value and intrinsic value, option premium, gives the incremental value of deferral and places a value on the information revealed during the waiting period;

Option premium = Option value – Intrinsic value

$$0.5\left[\sum_{t=1}^{\infty}\frac{1000}{(1.06)^t} - \frac{2000}{1.06}\right] - \left[-2000 + \sum_{t=0}^{\infty}\frac{0.5*1000 + 0.5*40}{(1.06)^t}\right] \quad \textbf{(EQN. 5)}$$

7390-7187

203

Option premium may be interpreted as the maximum willingness to pay to gain information available during deferral. In this case deferral is optimal while the cost of observing information remains less than £203. When waiting provides perfect information on all sources of uncertainty relevant to the decision, as in this instance, EVPI and option premium both value obtaining perfect information. Since the two VOI estimates are based on the same underlying principles intuition suggests they should equate. This example demonstrates a situation in which a difference exists. Deeper consideration reveals the reasons for this difference.

EVPI is the value associated with having perfect information available instantaneously (at t=0). Option premium differs from EVPI due to timing effects

[5] Recall that IV=max(net benefit, 0). Therefore if net benefit is negative no action would be taken and intrinsic value would be 0. Net benefit and intrinsic value only equate when net benefit is positive.

introduced into the decision tree by considering deferral. The real options framework ensures that option premium accounts for both the way in which, and time at which, information becomes available. In addition the effects of delayed receipt of benefits and spending on sunk costs are incorporated. Since the negative influence (deferred benefits) dominates and receipt of perfect information is delayed, option premium is less than EVPI. Without deferral and discounting influences in option premium the two estimates of value of information coincide. (The same is true if EVPI is adjusted for delayed arrival of information) [6]. Although acknowledging the timing of information arrival is not new (Claxton, 1999), the issue has received little attention and explicit discussion.

Whilst EVPI and option premium can coincide this is not necessarily, or even usually, the case. The example considered above of NICE approving health related technologies defines a special case in which deferral provides perfect information about all sources of uncertainty relevant to the decision. The following section further explores the more general case in which deferral provides only partial information, calculating the expected value of improved rather than perfect information.

4 Actively seeking and independently observing information

Deferral may reveal information on factors such as disease incidence and prevalence, whether competing drugs become available, or on an individual basis, disease progression. Cost-effectiveness analyses include variables such as efficacy, and trial based cost information for which data might only be obtained through positive actions. For instance, NICE may have felt there was insufficient information to make an immediate decision and may not have expected a trial to report further evidence in the near future. In this case deferral alone may not confer sufficient information for a decision to be made. Rather than simply deferring to benefit from exogenously

[6] The difference between EVPI and OP resulting from timing effects raises questions concerning the validity of using EVPI, which assumes information is instantaneously available, to assess the relative benefits of competing research proposals. Evidence from research is often not available for some time. When EVPI or EVSI is used as a willingness to pay for information and there are competing projects that might provide relevant evidence but at different times, presumably our willingness to pay for evidence should be adjusted for the expected timing of information arrival? Whilst relevant to the

available information revealed over time, NICE may consider taking positive steps to actively improve information. For instance they may think about commissioning a trial themselves.

The extent of information revealed over time in practice will depend on the nature of uncertainty impacting on the decision and costs associated with collecting information. Prices of drugs, interest rates, actions of competitors introducing substitute technologies, some costs, and disease progression can be reasonably well observed through time as they are revealed independently of any actions regarding the decision of interest. Evidence on factors such as effectiveness within a given population subset, or side-effects of a novel drug can only be discovered through specific, and usually costly, activities that are endogenous to the decision of interest.

Whilst EVPI refers to complete information on both types of variable, option premium is relevant for valuing information on variables that evolve through time independently of the current decision. Uncertain variables may be categorised according to whether information must be actively sought, or simply observed. Where at least some variables are active, deferral cannot reveal complete information. In these cases option premium is necessarily less than EVPI[7]. More accurately option premium (OP) becomes a subset of EVPI (figure 3). This distinction creates cause to clearly define willingness to pay for information gained from different sources: option premium defines a maximum willingness to pay to observe exogenous information sources such as literature reviews, meta-analyses, or patient observations and tests[8].

Similar observations with regard to value of information and option value have been made previously outside of the health economics arena. For instance Hanemann (Hanemann, 1989) has talked about option premium being “distinct from but bounded

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research priorities debate, and raising serious issues concerning the methodological interpretation and usefulness of VOI, this is a topic for future study and such questions are not the primary concern here.

[7] This distinction of value of information for different types of variable is similar to calculating partial EVPI for individual variables of interest (See (Fenwick et al., 2000)), although with option premium variables are purposefully categorized according to whether information on them becomes available though time.

[8] When there are no synergies or correlations between active and ‘passive’ variables, the difference EVPI-OP, or active value of information (AVOI), gives a willingness to pay for positive actions including commissioning generic research, specific safety and efficacy trials, and cost-effectiveness analyses.

by value of information in the overall problem" and Gersbach (Gershbach, 1997) has made the distinction between actively sought information and uncertainty that is resolved only by the passage of time.

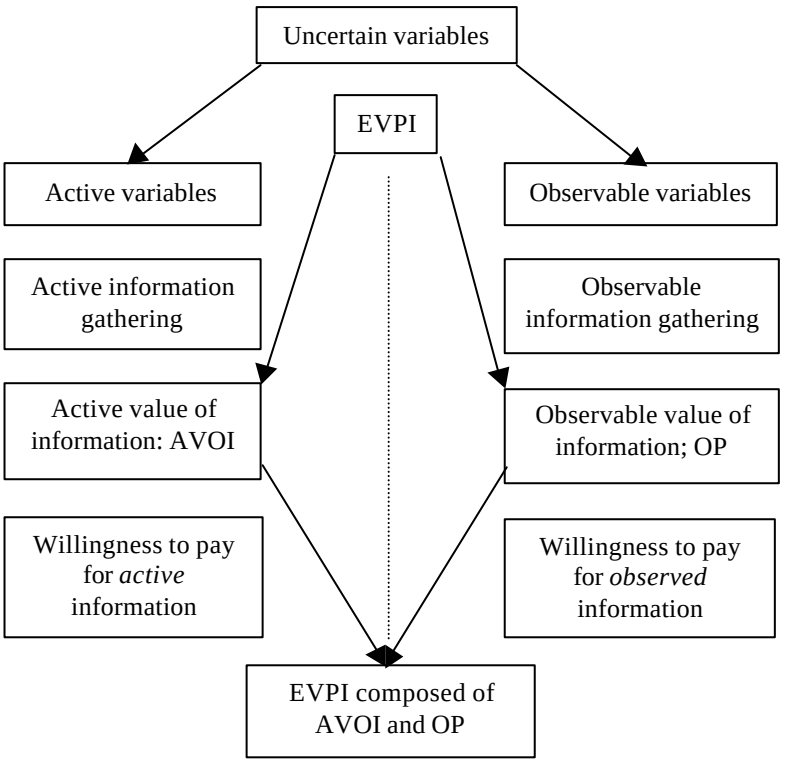

Figure 3. Distinguishing actively sought and independently observable information

For any given decision if immediate action is optimal option premium will equal zero and EVPI will comprise active value of information only; there is no incentive to wait. When waiting is preferable option premium is positive and affects our attitudes towards data collection. In this instance option premium should be explicitly estimated to help inform both the initial adoption decision and the complementary decision of whether to gain additional information. The following section derives a model of stochastic information arrival.

5 A model of information arrival

5.1 The model

Whilst information on uncertain variables may evolve continuously, such as with prices or disease progression, sporadic events may occur that generate one off, discrete shocks in the information set. These events result in discontinuous changes in expected payoff. Shocks may include interim results of a trial becoming available, a patient becoming unfit for surgery, infections following surgery, or launch of a novel drug that affects cost-effectiveness of an existing compound. Combining a Brownian motion process with a Poisson arrival process enables information to evolve in this manner.

Suppose NICE is considering approval of a new drug used to treat a specific disease. Periodic expected benefit from immediate treatment (V) evolves continuously due to changing incidence and prevalence with drift α and variance σ^2. The possibility of a trial reporting means there is some probability λdt that V will change as a result of this Poisson arrival causing an increment of dq. The value of the investment opportunity, or option value is given as a function of V, F(V).

$$\frac{dV}{V} = a\,dt + s\,dz + dq \qquad \textbf{(EQN. 6)}$$

The mean arrival rate, λ, varies between 0, representing no event or trial, and 1 representing a trial reporting each time period. $1/\lambda$ indicates the mean time between arrivals. If a trial is expected once every three years ($1/\lambda = 3$) the mean arrival rate is 1/3. When an event occurs q changes by some proportion ϕ[9] ($0 \leq \phi \leq 1$) (equation 7). If $\phi > 0$ stochastically arriving trial results have a positive influence on V, the opposite occurs if $\phi < 0$. If $\phi = 0$ events have no impact and the combined process reverts to Brownian motion. Following an event V resumes the Brownian motion evolutionary process, until another occurs.

$$dq = \begin{cases} 0 \text{ with probability: } (1 - l)dt \\ f \text{ with probability: } l\,dt \end{cases} \qquad \textbf{(EQN. 7)}$$

[9] In the following model ϕ is assumed to be a fixed proportion of expected benefit although in reality ϕ may be a random variable.

Given this specification the expected rate of change in benefit for any time period is $\alpha+\lambda\phi$. Increasing either the likelihood or impact of an event alters the rate of change in V. Incorporating the Poisson element also has an impact on the variance of V. Although variation is mostly due to the continuous evolution, when an event occurs it has a large impact. Dixit and Pindyck (Dixit and Pindyck, 1994) show that variance consists of two parts; one resulting from the Brownian motion influence when no event occurs and the other from the Poisson influence.

$$\text{Variance(V)} = s^2 V^2 dt + l f^2 V^2 dt$$

When considering this formulation Dixit and Pindyck (Dixit and Pindyck, 1994) used a version of Ito's lemma[10] to derive a second order partial differential equation (PDE) that must be satisfied by the value of the investment opportunity, F(V)[11]:

$$\tfrac{1}{2} s^2 V^2 F''V + (r-d)VF'(V) - (r+l)F(V) + l F[(1-f)V] = 0 \qquad \textbf{(EQN. 8)}$$

For action to occur at a finite point in time the growth rate of uncertain benefits α, must be less than the rate r at which they are discounted. The difference r-α is given by δ and represents dividend type payments. F'(V) and F''(V) represent the first and second derivatives of F(V) with respect to V. By satisfying the PDE, F(V) conforms to the intuitive constraint that the value of the investment opportunity must equal the maximum of the continuation (value from deferring) or stopping value (value from exercising). A set of Boundary conditions must also be satisfied in order to limit F(V) and identify the solution V*.

$F(0) = 0$	Absorbing barrier	
$F(V^*) = V^* - I$	Value matching condition	**(EQN. 9)**
$F'(V^*) = 1$	Smooth pasting condition	

[10] A mathematical tool for computing the derivative of non-continuous random functions

[11] In the deterministic case the value of the investment opportunity is maximised over time: $\frac{dF(V)}{dt} = -(r-a)Ve^{-(r-a)t} + r\,Ie^{-rt} = 0$. Where ? is a discount rate and t is the timing of this investment. ? is defined as here and I is the irreversible investment cost. The partial differential equation (equation 8) is the stochastic equivalent.

The absorbing barrier provides a lower boundary on F(V), stating that should project value fall to zero, the investment opportunity will be worth nothing. Both will remain worthless due to the stochastic process governing V. The value matching condition holds at V*, equating the value of the investment opportunity, with the value of immediate action V-I. The free boundary, V*, and the region of V for which the PDE is valid, are endogenous and as yet unknown. They are identified using the smooth-pasting condition; at V* the stopping and continuation value of the option not only equate but meet tangentially. If this were not the case then over some small waiting period, either the stopping payoff or the continuation payoff would rise more rapidly and immediate exercise would not be optimal, an improvement in payoff would be possible by exercising at a different time point.

Finding F(V) requires solving the PDE subject to the boundary conditions. To comply with the absorbing barrier F(V) takes the form:

$$F(V) = AV^{b} \qquad \textbf{(EQN. 10)}$$

Whereas in the stand-alone Brownian motion model b is a known constant, here β is the solution to a non-linear equation:

$$\tfrac{1}{2}s^{2}b(b-1)+(r-d)b-(r+l)+l(1-f)^{b}=0 \qquad \textbf{(EQN. 11)}$$

Numerical methods are required to find β but once achieved the parameter A can be estimated and the immediate action threshold V* identified. Option value and option premium, both at the critical threshold and the current value of V, can also be determined.

5.2 Numerical example

The key uncertainties within the model are whether and/or when a trial reports evidence and the effect this has on cost-effectiveness. Assume that the trial, on

publication of results, demonstrates a fall in the cost-effectiveness of the compound under consideration by NICE, causing a *downward* jump in payoff. The Poisson event then has a negative impact on evolutionary process defining cost-effectiveness.

$$\frac{dV}{V} = a\,dt + s\,dz - dq \qquad \textbf{(EQN. 12)}$$

In particular, assume the abrupt Poisson jump causes expected benefit to fall to zero, reducing payoff by 100% (ϕ=1). Due to zero being an absorbing state in the Brownian motion process monetary benefit remains at zero[12]. This renders the option worthless. In this special case λ defines a maximum ability to defer before the option becomes worthless[13]. In reality the effects form the trial would not be known and there would also be uncertainty on prior parameter estimates and implications for posterior estimates where Bayesian analysis is used.

The assumptions serve to simplify the analysis allowing analytic solutions to be obtained, and although seemly restrictive, numerous health economic applications conform to such a specification. Patients participating in a watchful waiting regime usually have some disease whose progression evolves continuously. One-off adverse events may occur that render immediate treatment less effective. For instance the patient may experience some co-morbidity. In the extreme a patient may become unfit for surgery, making the value of immediate treatment, and thus the option, zero.

Further examples include a firm with an option to market a drug whose price will evolve continuously. The Poisson event 'a competitor releases a dominant drug' may make the payoff from marketing the current drug fall to zero. Coma patients also conform to this model. The uncertain events that a patient either dies naturally or regains consciousness render the option to defer removal of support worthless because this is no longer a relevant alternative.

[12] This is would not necessarily be the case for alternative evolutionary processes.

[13] This formulation effectively allows an exercise date to be incorporated in to the perpetual Brownian motion diffusion process.

In the case where ϕ=1 Dixit and Pindyck show that equation 11 simplifies to a quadratic, from which β can be determined;

$$b = \tfrac{1}{2} - (r-d)/s^2 + \sqrt{\left[(r-d)/s^2 - \tfrac{1}{2}\right]^2 + 2(r+l)/s^2} \qquad \textbf{(EQN. 13)}$$

This differs from models without the combined Poisson element in the addition of λ which serves as a positive influence on β. V* and A are then given by;

$$V^* = \frac{b}{b-1} I \qquad \textbf{(EQN. 14)}$$

$$A = \frac{V^* - I}{V^{*b}} \qquad \textbf{(EQN. 15)}$$

and option value can the be obtained from the functional form, $F(V) = AV^b$.

Assume that the expected benefit from approval is currently 1.1[14] and improves at a rate of 1% per period with associated volatility of 20%. Suppose also that one period is equal to one year, and that on average a trial will report after 6 years (λ=0.167). If these estimates are combined with a discount rate (6%), and an investment cost normalised to 1 for illustrative purposes, option value can be estimated (table 1).

Parameter	Base case parameter value
V	1.1
α	0.01
σ	0.2
ϕ	1
I	1
r	0.06
λ	0.167

Table 1. Base case parameter values for the option to deferral approval in order to improve information

Option premium at the optimal investment threshold V*, at the current level of expected benefit, and at the point where traditional techniques advocate approval (V=I) can then be obtained to illustrate the value of observable information.

[14] Chosen to be 10% larger than the cost of approval for illustrative purposes.

5.3 Results

Given the base case parameter estimates (table 1) the net benefit of immediate approval is 0.1, while the option to defer approval is worth 0.1668 (table 2).

Parameter	Calculation	Base case result
ß	Equation 13	3.628
A	Equation 15	0.118
Option value F(V)	Equation 10	0.1668
Net benefit	V-I	0.1
Option premium	F(V)-max[max(V-I),0]	0.0668
V*	Equation 14	1.38

Table 2. Base case solutions for the option to deferral approval in order to improve information

When traditional techniques overlook deferral they suggest approval should be granted immediately (NB>0). Real options theory recommends deferral in order to gain observable information on evolving expected benefit (OV>NB). This ability to wait adds 0.0668, or 67% to the value of the approval opportunity. In this case additional information available during the deferral period is worth 67% of the value of approval itself. Figure 4 shows option value and net benefit for a range of expected benefits.

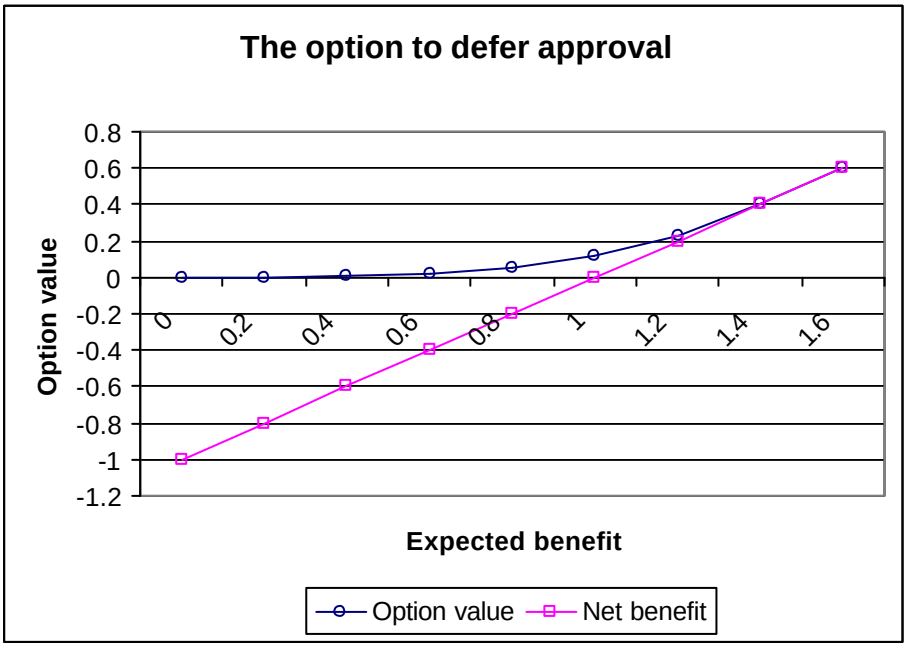

Figure 4. Intrinsic value and option value for a range of net benefits for the option to defer approval in order to improve information.

Option value assumes a minimum of zero when net benefit from immediate action is very negative. Consequently real options analysis would suggest that approval neither be given now nor deferred. Although net benefit remains negative until expected benefit exceeds the investment cost (V=1), option value becomes positive at V=0.4. This indicates positive gains from additional information. Option value becomes equal to net benefit at the real options investment threshold V*=1.38, indicating immediate action. In this case the gains from deferral and information gathering no longer exceed the gains from immediate action. Deferral is therefore recommended once expected benefit exceeds 0.4 but remains less than V*=1.38. Within this range of expected benefit deferral is optimal suggesting that observable information is valuable.

Under traditional techniques a technology is approved when expected benefit equates to the irreversible investment cost (V=1). This threshold is appropriate if deferral is not feasible. A technology with net benefits just smaller would be rejected whilst one with net benefit just greater would be approved; opposing decision rules despite the potentially very small actual difference between technologies[15]. Real options analysis circumvents the perversely polarised treatment of relatively similar projects by placing a high value on observable information, recommending that the adoption decisions for both technologies be deferred. Waiting may reveal differences in cost or effect that enable technologies to be distinguished methodically on cost-effectiveness grounds.

The incremental value of deferral (option premium) can also be used to identify the decision threshold and estimate a maximum willingness to pay for observable information. Option premium is plotted for a range of expected benefits (figure 5). Until option value becomes first becomes positive option premium remains at zero. Net benefit here is so poor that even positive additional information is unlikely to influence the rejection conclusion. This makes exogenously observed information effectively worthless and immediate rejection optimal. At V=V* option value

[15] Confidence intervals surrounding the point estimate may well include 0, suggesting no significant difference between technologies.

becomes equal to intrinsic value and option premium is again zero. The decision is undertaken immediate precisely because the action is sufficiently desirable that additional information holds no further benefits.

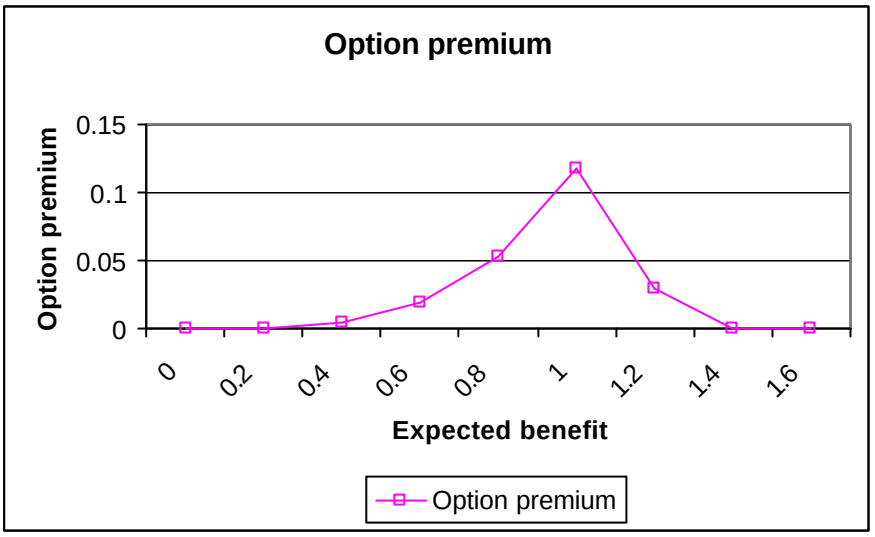

Figure 5. Option premium for a range of expected benefits for the option to defer approval in order to improve information.

Between the two limits (V=0.4 and V=V*=1.38) option premium assumes positive values. In this region observing exogenous information relevant to the decision of interest has some benefit, and so waiting becomes optimal. If current expected benefit is 1.2, option value is 0.23 and option premium is 0.03. The willingness to pay to observe information amounts to 13% (0.03/0.23) of the value of the option. While the costs of observing information do not exceed this level, observational research including literature reviews and meta-analyses, is efficient.

At V=I=1 the difference between option value and intrinsic value is greatest and so option premium is at a maximum (0.118): observational data is at its most valuable and deferral is most strongly supported. This point coincides with the decision-making threshold adopted by traditional methodology so that at the exact point where standard techniques change from rejection to approval, real options analysis most strongly advocates waiting. This represents a significant change in decision-making. If confidence intervals are used to supplement expected values when expected benefit is 1 (V=1) a 90% confidence interval may well include 0 suggesting no positive benefit to immediate approval. This knowledge helps support the recommendation of

deferral. Once V* is reached a confidence interval is less likely to include the possibility of no significant difference.

The shape of the option premium curve emphasises the similarities between option premium and EVPI. Both represent a maximum value to collecting specific types of information. They are based on the same underlying principles and when graphed over a range of expected benefits both assume the same shape. Consistent with classical value of information, observable information is most valuable when the immediate decision is marginal. In both cases information becomes less valuable as the difference in payoff between the optimal decision and the next best alternative increases. Traditional and real options techniques therefore agree that additional information is most valuable when a close call exists between alternatives, although real options analysis then recommends deferral enabling collection and incorporation of additional evidence.

5.4 Sensitivity analysis

Whilst real options analysis is useful for analysing the approval decision of a single technology in isolation, sensitivity analysis helps examine the impact of different characteristics belonging to multiple technologies. Option premium is responsive to the expected arrival rate of the Poisson event λ. If a trial is expected to report in 20 years (perhaps referring to a cancer technology currently undergoing initial research and development) the rate of arrival is 0.05. An increased rate suggests trials are expected to report more frequently (perhaps representing technologies undergoing phase one and two testing). Figure 6 plots the effect on option premium of three arrival rates; 0.05, 0.1, 0.2 equivalent to trials reporting every 20, 10 and 5 years.

Increasing the expected arrival rate of information reduces option premium for each level of expected benefit. As information arrives more frequently uncertainty is resolved quicker reducing the benefit to further deferral. With respect to decision making, option premium first becomes positive at a higher expected benefit, and returns to zero (identifying V*) at a lower expected benefit reducing the range for which deferral is optimal.

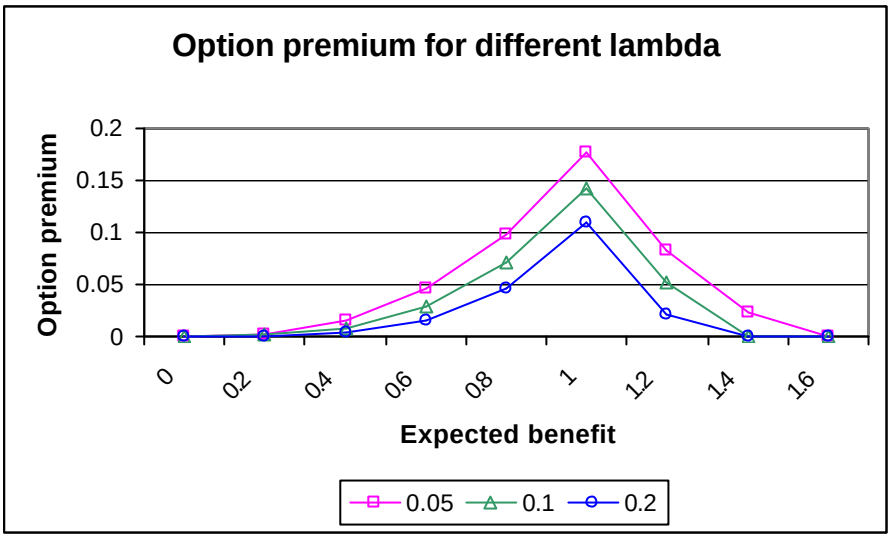

Figure 6. Different Poisson arrival rates over a range of expected benefits.

Comparing two technologies requesting approval with the same underlying characteristics but differing in the expected arrival of information, the technology with a trial reporting sooner will have a lower V* threshold. If the expected benefit of the two technologies starts from the same level and continues to increase at the same rate, approval will occur sooner. This generates a preference towards technologies with results reporting sooner. The alternative technology however, has greater value of observational data suggesting more extensive efforts may be pursued to obtain further information. This may encourage efforts to speed information arrival such as commissioning reviews, or encouraging interim results.

Uncertainty also enters the model through variance in the continuous element of the information evolution function, σ. Greater uncertainty is associated with larger option premium (figure 7) for all values of expected benefit. If changes in disease incidence and prevalence or the costs of using a technology cause increased uncertainty, the value of observing exogenously available information will increase. This reduces the threshold that recommends deferral in preference to rejection and increases the immediate approval threshold. Deferral is therefore optimal over a greater range of expected benefits, allowing information to be collected over a potentially longer period of time prior to an investment commitment being made. For the technology with greatest uncertainty there is a larger maximum willingness to pay for information.

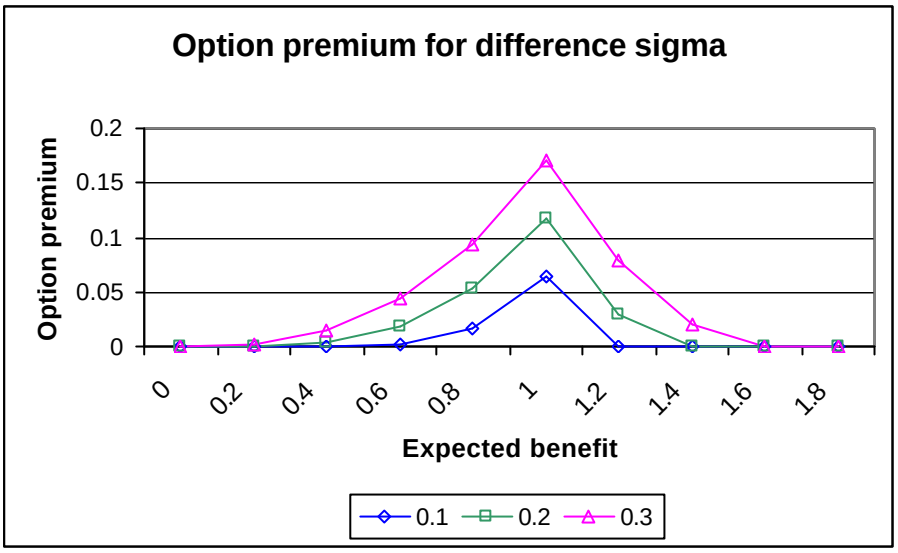

Figure 7. The effect of different sigma over a range of expected benefits

When competing technologies are being assessed, if neither is suitable for immediate approval NICE can consider the benefits from gathering additional information to help inform a future decision. More importantly NICE can combine analysis on continuous and one off sources of uncertainty and information arrival to compare the relative merits of waiting to observe evidence on each of the technologies. This may help when one technology is surrounded by greater uncertainty but additional evidence is expected sooner.

This example has assumed a single source of first order uncertainty that is resolved with the passing of time. It is rare that time alone will provide all the information relevant to a decision of interest and often specially commissioned trials are necessary. Suppose EVPI for this decision problem was 0.55 half the value of expected benefit. For the prior level of expected benefit (V=1.1) deferral was recommended and option premium was 0.067. Willingness to pay for a new trial providing further evidence is 0.483 (0.55-0.067)[16], 12% less than the willingness to pay for complete information on all variables. In addition if this estimate is used to determine whether a particular research proposal should be carried out, the expected timing of information arrival from that proposal should be acknowledged.

Although option premium and EVPI are based on the same underlying principles they refer to opposing types of variable; those revealing information over time and those on which evidence must be actively sought. If the value of observing information is ignored in this example, EVPI overstates the maximum willingness to pay for positive research activities by 13.9% (0.067/0.483)[17]. When thinking in practice about population EVPI and commissioning of trials to improve evidence, 13% represents a large difference in funding. The greater is option premium as a proportion of EVPI the more EVPI potentially overestimates the maximum willingness to pay for active research. If EVPI is used as a means of allocating budgets without accounting for option premium, a misallocation of resources may result, with less money than optimal going towards observational efforts.

6 Conclusions

This paper has reconsidered value of information theory from a real options perspective. Brownian motion and Poisson arrival processes were combined to create an evolution of information function that determined benefits available during a period of deferral. The specification reflects reality by allowing both continuous and discrete changes to influence the arrival of information over time. Whilst used here to describe continuous disease and discrete exogenous trial influences on expected cost-effectiveness, this model is likely to describe many decision-making problems within the field of economic evaluation in health care. Some alternative applications have been discussed. The model has provided insights into the implications of the timing of information arrival for decision-making and suggested a framework for valuing information available independently of the decision of interest.

This work has sought to contribute to value of future information literature in health care. In particular the timing of information arrival has been considered. EVPI estimates the value of perfect information available instantaneously. When comparing potential research projects it is important to acknowledge that information received in

[16] This assumes there are no interactions between exogenously observed information and actively sought information

five or ten years time is not as valuable as information received instantaneously. This should be reflected in our willingness to pay for a given project. In explicitly discussing deferral real options analysis encourages thought on the benefits and costs associated with waiting prior to making an irreversible commitment, and highlights the importance of timing.

In addition, a methodological distinction has been made between option premium and the expected value of perfect information. Where perfect information can be observed over time, and adjustments are made for timing, the two are equal. In the general case where deferral reveals information on a subset of variables option premium is less than EVPI. The distinct yet complementary elements of EVPI leads to a categorisation of variables as being observational or active in nature, depending on how evidence concerning the variable must be sought. Deferral is useful if variables on which information is naturally revealed over time are present within a decision problem.

Variables may at times create conflict in their classification; in particular classification may change over time. Cost-effectiveness estimates may be improved through initiating a trial or by waiting for existing trials to report. The former constitutes positive actions and forms part of active value of information while the latter demonstrates information gained from deferral. When NICE commission a trial to improve evidence they are taking actions motivated by active variables. As the trial begins to report the same uncertainty is revealed by observation. Decision-makers must decide whether active resolution is necessary; this is determined by their assessment of exactly how much, and what quality of evidence may be gained by deferral.

Using a combined information function absolute and relative option premium have been estimated for a hypothetical example. The absolute value gives the maximum willingness to pay for observational evidence. This includes allocating funds to reviewing existing medical evidence such as literature reviews and meta-analyses, and at a patient level, observing progress through means such as clinical observation, MRI, CT and biopsy. Option premium relative to EVPI has broader, policy level

[17] This assumes that EVPI is calculated using perfect information on all variables. In practice EVPI has

implications. In particular relative option premium may be used in conjunction with EVPI to ensure efficient allocation of resources to improving available evidence.

The model used to illustrate these concepts has required some assumptions, particularly those facilitating an analytic solution. This limitation is acknowledged, and can be overcome with the use of numerical techniques and detailed computer programming. Here the emphasis has remained firmly on illustrating the principles behind, and implications of using real options theory to value information. There are several developments that naturally follow from this work. Perhaps most important is calculating option premium in practice. Although fraught with difficulties including estimating volatilities through time, once achieved, observational research efforts can be subject to the same theoretical economic assessment as positive research efforts. Further work may also be carried out on the extent of interaction between observable and actively sought information so that information might be obtained in the most efficient manner.

The timing of information arrival and the distinction between observational and active variables discussed within this paper have been highlighted through the use of real options analysis. These areas may have significant implications for the methodology underlying economic evaluation. In particular the decision to acquire additional information and the way in which budgets are allocated to research projects in future. Real options analysis is an increasingly recognised tool that warrants greater discussion within the field of health care.

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usually been estimated on variables for which information can feasibly be sought.

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