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A real options approach to satellite mission planning

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Abstract

Satellite missions are one instrument of Earth observation targeted at obtaining information for improved decision making in sustainable development. But satellite missions are expensive undertakings involving large sunk costs and facing uncertain benefit streams. In the area of avoiding damages through, for example, better weather forecasts or better-informed rescue missions, the benefits are high, but also difficult to quantify. Using real options to optimize the timing of the launch of a satellite enables us not only to optimize the timing of the mission, but also to derive the value that such information conveys when it can be used to reduce the extent of the damage from disasters and their consequences: with low benefit expectations or large uncertainty, launching will be postponed, so ex ante Earth observation benefit assessment is an important task.

1. Introduction

Recent political efforts such as the Group on Earth Observations (GEO),[1] in which 72 governments and the European Commission participate, acknowledge and emphasize the need to make better scientific information available. This implies that more comprehensive and timely data about the planet's physical, chemical and biological systems should be collected.[2] One means for such data gathering is through satellite missions. However, satellite missions are costly and public officials might be reluctant to commit resources to the launch of another satellite if the ensuing benefit streams are not certain ex ante. In economic terms, once the satellite mission has been started, all resources committed are largely sunk and the situation is, thus, characterized by irreversible investment. On the other hand, future benefits are potentially very high if we think of the environmental and economic damage that could be avoided or at least better forecast and alleviated if unavoidable. Better weather forecasts, for example, could lead to improvements in early warning systems in case of disasters, and thus to great reductions in economic losses as well as in losses of human life. Yet such benefits are difficult to estimate and quantify ex ante and this reduces the incentive for satellite launches—both from the point of view of private investors and of government budgets.

What we are essentially facing is an investment problem in terms of launching a new satellite under uncertainty about future benefit streams[3] in a context of irreversibility associated with the large sunk costs connected to satellite missions. Such problems can be addressed in a real options framework [2], which takes into account investment irreversibility, uncertainty and the flexibility to time the satellite launch differently as new information arrives. We adopt such a framework here, and apply it to a satellite mission considered to bring about new scientific information potentially leading to lower damage from disasters. However, these benefits will be very volatile and difficult to predict: if there is no disaster, then the benefits are low,

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[1]See http://www.earthobservations.org.

[2]In addition, Harris and Browning [1] point to the need for coherency in existing databases and information sources, since differences in legal protection, data formats, metadata, distribution, pricing and archiving make the information that already exists difficult to use.

[3]It is important to emphasize at this point that modelling the timing of a satellite launch as a function of these benefit streams is a simplification, which abstracts from other factors influencing the launching decision in practice. Such factors include the extent to which the development phase is successful, for example, because unforeseen technical problems and organizational shortcomings can lead to delays. Another example is uncertainty about political issues that might arise, e.g. in connection with the place of launch and other associated decisions.

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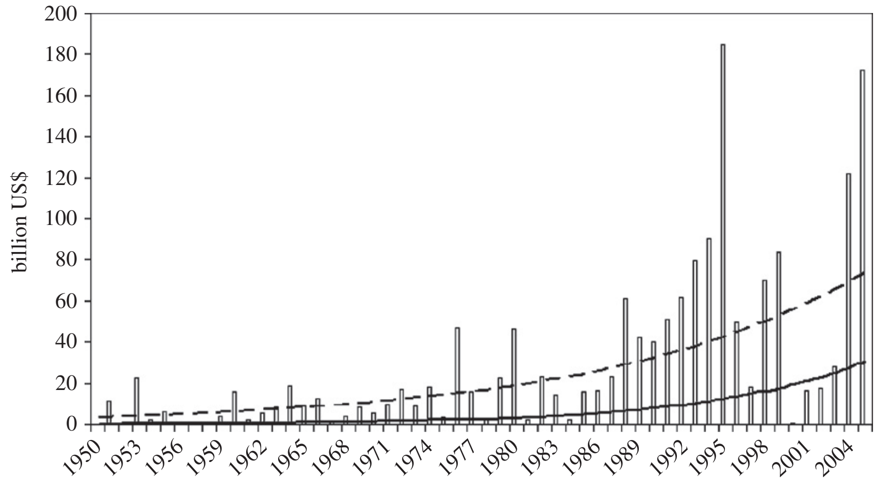

Fig. 1. *Economic losses from disaster incidents*. The bars show the total economic losses from disasters in 2005 US$ billion. The dashed line is the trend in uninsured, the solid line the trend in insured losses. Source: OECD Information Technology Outlook 2006 [3].

but if the new information helps to preserve people and equipment from such a disaster, the benefits can be immense.

Disasters can be of a climatic nature, involving floods, wild fires or extreme temperature episodes, or they may be lithosphere disasters, including earthquakes and landslides. Finally, epidemics can be related to the previous two categories, but have a dynamic impact structure as well. Fig. 1 shows that there has been a clear upward trend in the economic losses from disasters over the past few decades, which might be associated with the increased rate of global warming leading to more extreme weather situations, more intense storms, the melting of icecaps, glaciers and permafrost, etc.[4]

The development of the losses in Fig. 1 can be considered as a stochastic process, where the spikes can be interpreted as the occurrences of high-impact disasters on top of those disasters, which lead to an increasing average amount of losses denoted by the trend line. The value of additional information from a satellite mission for disaster mitigation is then represented by the ability to reduce this average amount of losses. Note that, in contrast to models where the value of information is derived by comparing the decisions taken in the face of stochastic processes to those taken in a deterministic setting, the framework in this paper follows a different approach, since we do not think that the occurrence of high-impact disasters can be avoided most of the time. However, better warning systems and also damage mitigation through improved and better informed rescue operations *after* the event of a disaster can significantly reduce the average losses depicted in Fig. 1.

In the following, we will first present an overview of the literature on expected value of information and show how our approach differs from this. Then the model is outlined and solved. This can be done analytically for the simple case considered, but it is also possible to extend the model, for example to include more than one stochastic benefit stream.[5] Such extensions complicate the computations, but it is no problem to solve the model numerically with stochastic backward dynamic programming methods. We will include two extensions that can be solved in the analytical framework and present the numerical results for another extension with two stochastic benefit streams, before concluding with a summary and some ideas for further research.

2. The value of information—existing literature and applications

As pointed out by Macauley [4], most information models find that the value of information largely depends on four important factors: (1) the extent of uncertainty on the part of decision makers; (2) the cost of making a decision, which is not optimal in the light of better information; (3) the cost of making use of the information and incorporating it into decisions; and (4) the price of the next-best substitute for the information. In other words, the value of information can be interpreted as the willingness to pay of the decision makers concerned.

With a simple example Macauley shows that the value of information is zero when the decision maker attaches a probability of zero or one to the events that are thus no longer uncertain in his or her view [4]. The other cases (where information has no value) occur when there are no alternative actions available, even if information can be

[4]Another factor is the increase in the amount of physical wealth, materials and equipment that can be damaged as economies expand. In this way, there is just *more* that can be damaged.

[5]Private investors can include research equipment on their satellites that are otherwise used to deliver communication and location services, for instance, to receive payments from agencies or institutes that then use the collected data. This is generally known as ‘‘hosted payload’’ and can make the launch of a satellite more attractive when it is probable that additional income can be secured. We show a simple case considering a hosted payload, which can be solved analytically.

obtained, or when a wrong decision will not result in any costs. In the same vein information is most valuable when the costs associated with a wrong action are high, when many alternative actions are available and when the decision maker has no extreme preference for one or more of the alternatives.

She then goes on to categorize the methods by which the expected value of information has previously been measured into two subsets. First, studies that use wage and/or housing prices to infer the value of, say, weather information because the latter can be expected to be capitalized in these prices and so it makes sense to deduce the value from existing time series; this is what Macauley calls "hedonic pricing studies" [4]. The second subset includes all studies that measure the value of information by gains in output or productivity, even though the value of information is generally found to be rather small in most of the studies. Macauley attributes this to the fact that people are obviously only willing to pay for information ex ante and are often not aware of the severe consequences that the lack of information in the case of an uncertain event can have. Similarly people often only attribute a very low probability to catastrophic events and then choose not to pay for information that might itself be rather costly.

In the end, she deems the computation of expected values of information a very suitable tool for the valuation of Earth observation benefits, where the availability of information can save costs, lives and alleviate misery in the face of disasters. In economics—and more specifically in the area of climate change policies—the expected value of information has been a well-known tool for years. Peck and Teisberg [5] and Nordhaus and Popp [6] are examples adopting a cost–benefit approach to finding the optimal policy response to climate change damage and to estimating how much the world would be better off economically, if climate sensitivity and the level of economic damage were known. In general, these studies use multi-stage optimization where all information about the correct level of the uncertain parameters arrives in one time instance. Others, like Fuss et al. use stochastic dynamic programming, allowing for a rich description of the evolution of the uncertain parameters but with the disadvantage of having less scope in terms of controls and states [7]. They derive the value of information by comparing profits and emissions when optimizing with stochastic prices to the case where prices are deterministic (and therefore the optimal decisions are different).

Another area is the estimation of the abovementioned merits of early warning systems. Lave and Apt employ a stochastic cost–benefit framework to the valuation of control structures (e.g. dams and levees), of mitigation policies (e.g. construction standards in the face of natural disasters), and of the benefits of information for early warning and evacuation in the USA [8]. Especially for the latter they find large scope for improvement through better information. In addition, the availability of information ex ante should lead people to make better decisions about matters like the areas that they choose to live in. The authors emphasize that economically much could be saved by informing people that they will have to bear the consequences when they move to high-risk areas because the lack of opportunity for moral hazard will lead them to refrain from decisions they would have made when they expected government and insurance to alleviate their losses.

A similar conclusion is found by Khabarov et al., who conduct simulation studies to estimate the benefits of a finer grid of weather stations and more frequent patrols in forest areas, so that wild fires can be detected earlier and—if not prevented—at least limited or extinguished before they can spread to a larger area, and thus cause economic damage and endanger the life of humans and animals [9]. They find that the addition of more weather stations does indeed reduce the fraction of the area burnt by wild fires.

Other studies show that not only are the ex ante prophylactic actions facilitated by better observation information, but also the losses that can be expected after a catastrophe has struck may be significantly reduced if rescue teams can be better informed and coordinated. Let us consider the example of an earthquake: while there is definitely no possibility of stopping an earthquake occurring in the first place, and the scope for early warning systems is limited by the lack of understanding of the deep underground geophysical processes involved, it is important to note that a high percentage of the deaths caused in an earthquake actually occur after the event, because long response times jeopardize the success of rescue operations. These response times could be significantly shortened by obtaining better information that can then serve to accelerate the assignment of rescue brigades to specifically damaged areas. Moltchanova et al. use a stochastic framework to model the dependence of an earthquake rapid response system (in a virtual city of standard size) on available information and resources [10]. They find that, for any level of available (rescue) resources, the efficiency of saving lives is higher when those involved are better informed and can thus coordinate operations much more effectively.

In Macauley's terms [4], our work falls into her second subset because we assume that, through better information provided by Earth observation, a portion of the damage can be mitigated, which can also be interpreted as a gain in economic output that would otherwise have been lost. The framework used in this paper is different from those developed by Nordhaus and Popp [6] and others, where multi-stage optimization is employed and the gains from having information that arrives in a certain time period are measured. In contrast, we develop a real options model where the uncertainty about the occurrence of disasters and their economic impact persist throughout the planning period. The approach is also different from Fuss et al.'s real options model mentioned above [7], since the latter derives the value of information by comparing decisions and the resulting profits (and emissions) under uncertainty with those derived under certainty, while here the spikes in the stochastic process of economic losses cannot be removed by the availability of better information: the level of economic losses can only be dampened through mitigation and prevention but the event of the disaster itself cannot be avoided.

3. A real options framework for optimal timing of a satellite launch

The decision maker in a satellite mission planning procedure does not necessarily have to be a private person or entity. Most probably it will be government officials or agencies deciding about the allocation of the budget to such a project, especially where the collection of policy-relevant data is concerned. In this model, we just consider the costs and benefits of the satellite mission over time and neglect the problem of raising funds for the mission. Instead, we assume that potential benefits net of the costs incurred to obtain these benefits should be maximized. This will be referred to as "net benefits".

The model determines the optimal timing of the satellite mission for a single decision maker. The latter faces an uncertain net benefit stream in terms of reduced economic losses, but these are hard to estimate ex ante. In addition, such a mission is very costly and most of these costs will be sunk as well. The planner can exercise the option to launch immediately or wait until s/he learns more about the development of the net benefits, i.e. the economic losses that can be avoided. On the other hand, waiting also implies that these benefits cannot be enjoyed in the meantime, yet these might be very high in terms of avoided economic, environmental and even human losses.

The planner's decision problem is to maximize expected net benefits under uncertainty. Let us denote the benefits by B,

$$B_t = \theta L_t \tag{1}$$

where L_t represents the economic losses, which correspond to the height of the bars in Fig. 1 in Section 1. θ is the fraction of L that can be saved thanks to improved information from Earth observation and is constant over time, as damage can never be reduced beyond a certain minimum impact. As an example consider the loss reduction in the case of better-informed rescue missions after an earthquake: even though more people might be saved, most buildings will be irreversibly damaged, as will large parts of the infrastructure. In other words, the risks involved in the occurrence of natural disasters might not be completely avoidable, but the vulnerability represented by low values of θ can be decreased by obtaining better information through Earth observation.

Furthermore, since disasters strike sporadically and not continuously over time, the loss needs to be modelled as a stochastic process. Since the losses depicted in Fig. 1 additionally have a positive trend, we assume that they follow a geometric Brownian motion (GBM):

$$\mathrm{d}L_t = \mu L_t \mathrm{d}t + \sigma L_t \mathrm{d}z_t \tag{2}$$

where μ is the trend, σ the volatility parameter and $\mathrm{d}z_t$ the increment of a standard Wiener process. Referring back to Eq. (1), since the benefit is just a fraction θ of the losses L, B also follows a GBM with the same parameters.

The costs of a satellite mission can be divided into two parts: first, there will be costs for developing and launching the satellite. Later on, there will be costs of operating and maintaining ($O\&M$) it, where the latter are typically much lower than the development and launching ($D\&L$) costs. The net benefits from earth observation are represented by the difference between B_t and these costs,

$$NB_t = B_t - O\&M = \theta L_t - O\&M \tag{3}$$

In real options theory (see [2]), the decision maker holds an investment option and, as long as the option value (of holding on to it) is larger than the value that would be received upon exercising the option, investment does not occur. There is thus a threshold value in the face of uncertain processes and large up-front sunk costs that needs to be reached in order to trigger investment. Applied to the problem at hand, there will be a level of expected mitigated losses that will trigger the launch of the satellite. The value of the satellite mission at the time if launching if the satellite is launched at time t—or the immediate value of (Earth observation) information from 0 to T—is

$$V(B_t) = E\left[\int_0^T \mathrm{e}^{-rt}(B_t - O\&M)\mathrm{d}t\right] \tag{4}$$

where T is the lifetime of the satellite—which will be assumed equal to ∞ for the moment—and r is the discount rate. Integration delivers

$$V(B_t) = \frac{B_t}{r-\mu} - \frac{O\&M}{r} \tag{5}$$

This is the value of the Earth observation benefits if the satellite is launched immediately, which happens only when $V(B_t)$ surpasses the value of the launching *option* or in other words the value of waiting and acting optimally later. The latter will be denoted by $F(B_t)$. In order to determine the point in time when this happens, we have to find the critical level of mitigated losses, B^* that will trigger the launch.

Following the procedure presented in Dixit and Pindyck [2], the following differential equation holds for $B \in [0, B^*]$, where we omit time subscripts for ease of exposition:

$$rF(B) = \mu B F'(B) + \frac{\sigma^2}{2} B^2 F''(B) \tag{6}$$

Eq. (6) is the result of some transformations and the application of Itô's Lemma and basically equates the marginal value of waiting (and earning interest on the unspent money in the meantime) with the value of exercising the option to launch that evolves according to the changes in $F(B)$ over time. Together with the boundary conditions, it can then be used to derive the critical value of B^*.

The first boundary condition states that the option value should be zero as B tends to zero: if nothing can be saved or mitigated, then the investment option is not worth anything.

$$\lim_{B\to 0} F(B) = 0 \tag{7}$$

The other two conditions are called the "value-matching" and the "smooth pasting" conditions (see [2]), such that—at the critical value of B, B^*—the option value and the immediate value of launching (i.e. the net benefits) must be equal; and that there can be no kinks leading to contradictory results around the critical value.

$$\begin{aligned} F(B^*) &= V(B^*) - D\&L = \frac{B^*}{r-\mu} - \frac{O\&M}{r} - D\&L \\ &= \frac{B^*}{r-\mu} - C \end{aligned} \tag{8}$$

$$F'(B^*) = \frac{1}{r-\mu} \tag{9}$$

where C in Eq. (8) comprises all cost items, i.e. the term $((O\&M)/\mathrm{r}) - D\&L$ is replaced by C. Since this is analogous to the problem presented in Dixit and Pindyck [2], we can find the solution in the same way. The solution for the option value $F(B)$ has the form

$$F(B) = K_1 B^{\beta_1} + K_2 B^{\beta_2} \tag{10}$$

where $\beta_{1,2} = ((\sigma^2/2) - \mu \pm \sqrt{(\mu - (\sigma^2/2))^2 + 2r\sigma^2})/\sigma^2$. Since $\beta_2 < 0$, we are only interested in β_1. $K_2 = 0$ and $K_1 = (B^*)^{1-\beta_1}/\beta_1(r-\mu)$, which leads to the final solution for the critical threshold value, beyond which the satellite option is exercised,

$$B^* = \frac{\beta_1}{\beta_1 - 1}(r-\mu)C \tag{11}$$

$$L^* = \frac{\beta_1}{\beta_1 - 1}(r-\mu)C/\theta. \tag{12}$$

This already shows that high expectations about how much damage can be avoided or mitigated (i.e. the magnitude of the vulnerability parameter θ) will lead to an earlier timing of the satellite mission: the larger θ, the lower will be the level of losses, and thus also potential benefits that will trigger the launch of the Earth observation satellite.

Using data and estimates from a PricewaterhouseCoopers report on the Galileo Programme[6] (prepared at the request of the European Community) [11], we can then verify at which level of losses (or more precisely benefits in terms of mitigated damages, B^*) the satellite launch will optimally occur. Since the study assumes that there is also a relatively certain amount of commercial income from selling communications and location services, the term C in Eq. (11) changes to $C = ((-\pi + O\&M)/r) + D\&L$, where π is the (deterministic) income from commercial uses of satellite services.

The study estimates that €3.406 billion will be needed for $D\&L$. For the revenues the estimates vary considerable with respect to the underlying assumptions (between €300 and €600 million).[7] $O\&M$ cost estimations amount to €220 million.

In addition, the OECD *Information Technology Outlook 2006* estimates the trend of the economic losses (see Fig. 1) to be 5.145%. σ is at 10%, even though it can be seen from Eq. (11) and the composition of β that a larger volatility parameter will lead to an increase in the option value and therefore a larger threshold value, B^* or L^*. In other words, the satellite will be launched only when a higher level of damages has been reached.

With these estimates B^* is equal to €173.351 million. Note that, while we think it defensible to deduce a general trend from the losses presented in Fig. 1, it is not admissible to compare the results from our theoretical exercise with the levels of the losses shown there. In fact, Fig. 1 is about the losses in the whole of the OECD and the satellite system analyzed would probably only be capable of saving a tiny fraction of those losses. In other words, θ would be very small.[8]

Nevertheless, we can derive some important conclusions from this analytical solution by conducting some sensitivity experiments. Fig. 2 displays the option value (dashed line) and the net present value (solid line) of the satellite mission. In the beginning, the option value exceeds the immediate value of launching, so it is worth waiting. The critical value triggering the launch of the Earth observation mission occurs at the intersection of the two lines. Increasing the volatility parameter will shift the option value line upwards, so that this point of intersection moves to a higher level of B. For $\sigma = 0.2$, for example, B^* becomes 214.69. In other words, an increase in the volatility of losses (and the associated value of earth observation) leads to a postponement of launching, as previously concluded from Eq. (11) and the composition of β. An increase in the trend shifts both lines upwards and makes them a bit steeper, so that the launch will occur somewhat earlier.

4. Extensions

4.1. Economies of scale

Instead of launching a satellite or a satellite system for the sake of collecting and using Earth observation data, governments can also take another route: it is not unusual that companies offer so-called "hosted payloads" to

[6] The Galileo System is of course not just based on a single satellite. In fact, it comprises 30 Medium Earth Orbit satellites and a "ground segment to control the satellites, distribute information and provide service centers for interface with users." (page 6 [11]).

[7] The study takes into account revenues from personal communications and location applications, commercial aviation, oil and gas rig positioning and land and transition zone seismic exploration and other sources.

[8] In addition, the graph is in 2005 US dollars, while the numbers used in our calculations are in 2001 euros.

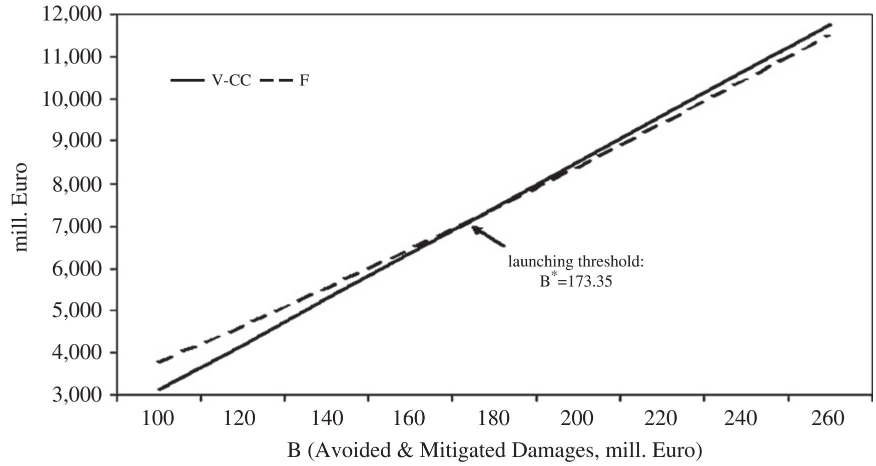

Fig. 2. Net present value (solid line) of launching satellite mission vs. option value (dashed line).

governments on their commercial satellites. The clear advantages of this are that cost risks can be distributed and the unit cost of these additional services are typically lower than in the case where two independent projects are launched for each purpose separately. In other words, adding hosted payloads can rightly be expected to benefit from economies of scale.

Similarly, governments could expand their own satellites by hosting more equipment, which could further improve the quality and amount of observations, while reducing the unit costs. So their vulnerability could be decreased (i.e. θ could be increased) without incurring the full cost of another satellite launch. In order to investigate this issue more closely, let us consider the profitability of two possible projects: (1) the launch of a satellite for earth observation purposes; and (2) the launch of the satellite combined with a hosted payload.

We assume the lifetime of both the satellite and the hosted payload to be infinite for now. We denote project i's capital costs as CC_i, and its operation and maintenance costs as OM_i. (This means that the capital costs of the hosted payload are $CC_2 - CC_1$ and the operations and maintenance costs are $OM_2 - OM_1$). The damages that can be avoided by having the project launched are considered to be θ_i, where $\theta_2 > \theta_1$. We also assume $CC_1 < CC_2$.

The aim of this exercise is to prove that the optimal decision is to invest in the second project, which will in turn lead to an earlier launch of the satellite, if the costs associated with the project follow economies of scale.

Using the notation introduced earlier, we will prove the following: assuming $(CC_1 + (OM_1/r))/\theta_1 > (CC_2 + (OM_2/r))/\theta_2$, the optimal decision is to invest in the second project, where the optimal time of investment is sooner than in the case of the first project.

This assumption has a very straightforward explanation: $CC_i + (OM_i/r)$ are the costs associated with project i for its whole lifetime. This means that $(CC_i + (OM_i/r))/\theta_i$ represents the costs per unit of benefit achieved. Thus, if we assume economies of scale, we assume that having the satellite combined with hosted payload leads to a decrease in costs needed per unit of profit.

First, we look at a situation where we need to determine the optimal timing of investment into project i. As shown previously, the value of the option is the solution of the differential equation:

$$rF_i = \mu BF'_i + \frac{\sigma^2}{2} B^2 F''_i$$

for $B < B^*_i$ where $F_i(B^*_i) = V_i(B^*_i) - CC_i$, $F'_i(B^*_i) = V'_i(B^*_i)$. The general solution of the differential equation is $F_i(B) = K_{1,i} B^{\beta 1} + K_{2,i} B^{\beta 2}$, where $\beta_{1,2} = ((\sigma^2/2) - \mu \pm \sqrt{(\mu - (\sigma^2/2))^2 + 2r\sigma^2})/\sigma^2$. It can be shown, that $\beta_1 > 1$ and $\beta_2 < 0$. Together with the condition $\lim_{B \to 0} F_i(B) = 0$, we get $K_{2,i} = 0$. $K_{1,i}$ and B^*_i can be derived from the value matching and smooth pasting conditions as

$$B^*_i = \frac{\beta_1}{\beta_1 - 1} C_i (r - \mu)$$

$$K_{1,i} = \frac{B_i^{*1-\beta 1}}{\beta_1 (r - \mu)}$$

where $C_i = CC_i + OM_i/r$. And since we assume $(CC_1/\theta_1) > (CC_2/\theta_2)$, then

$$L^*_1 = \frac{B^*_1}{\theta_1} > \frac{B^*_2}{\theta_2} = L^*_2$$

From this, we can already observe that the optimal timing for project one (when L crosses the threshold L^*_1) is sooner than for project two (when L reaches L^*_2). The option value of the project i at any current state $L \leqslant (B^*_i/\theta_i)$ is

$$F_i(\theta_i L) = K_{1,i} (\theta_i L)^{\beta_1} = \frac{B^*_i}{(\beta_1 - 1)(r - \mu)} \left(\frac{\theta_i L}{B^*_i} \right)^{\beta_1} = \frac{C_i}{(\beta_1 - 1)} \left(\frac{(\beta_1 - 1)\theta_i L}{\beta_1 (r - \mu) C_i} \right)^{\beta_1}$$

This means

$$\frac{F_1(\theta_1 L)}{F_2(\theta_2 L)} = \frac{C_1}{C_2}\left(\frac{C_2/\theta_2}{C_1/\theta_1}\right)^{\beta_1}$$

And since $C_1 < C_2$ and $(C_2/\theta_2) < (C_1/\theta_1)$ then $(F_1(\theta_1 L)/F_2(\theta_2 L)) < 1$. This implies that the value of the option to launch the first project is always less then the value of the option to launch the second one. In other words, the satellite with a hosted payload is not only the more attractive opportunity in terms of costs, but it is also launched earlier, which leads to a longer period of damage mitigation. In other words, hosted payload offers a win-win situation—both in terms of lower per unit costs and in terms of damage avoided.

4.2. Analytical solution with finite satellite lifetime

It is obvious that the assumption of an infinite satellite lifetime made in Section 3 does not hold in reality. Therefore, we want to relax this assumption here and investigate how the results change, if we take into account that the lifetime of a satellite is not infinite. In this case the integration in Eq. (4) delivers

$$V(B_t) = \frac{B}{r-\mu}(1 - \mathrm{e}^{(\mu-r)T}) + \frac{\pi - O\&M}{r}(1 - \mathrm{e}^{-rT})$$

Following the same procedure as in the previous section, we arrive at the following equation for the critical value of B:

$$B^* = \frac{\beta}{\beta - 1} C(r-\mu)\frac{1}{1 - \mathrm{e}^{(\mu-r)T}}$$

where C is defined as before, and thus composed of the deterministic revenues from selling communications and location service and the costs of launching and maintaining the system. Note from the last equation that B^* is the same as in the case of infinite satellite lifetime multiplied by the term $1/(1-\mathrm{e}^{(\mu-r)T})$. As T approaches infinity, the term will tend to 1 and therefore we will end up with the same B^* as in Eq. (11). In addition, the lower the expected lifetime of the equipment, the larger will this term be and therefore the mission will be postponed beyond the point in time that would have been optimal with an infinite lifetime. This makes intuitive sense, of course, since the mission will only provide benefits for a relatively short period of time in the case of a short lifetime of the equipment.

Adding the concept of economies of scale introduced in Section 4.1, we find our previous conclusions confirmed: following the same steps as for infinite lifetime of the satellite toward the solution of the differential equation for the option value, F, with the value-matching and smooth-pasting conditions for a satellite with the lifetime T we obtain

$$B_i^* = \frac{\beta_1}{\beta_1 - 1} C(r-\mu)\frac{1}{1 - \mathrm{e}^{(\mu-r)T}}$$

$$K_i = \frac{C_i}{\beta_1 - 1}(B_i^*)^{-\beta_1}$$

And so the timing of the satellite without a hosted payload would occur later than with it

$$L_1^* = \left(\frac{(r-\mu)}{1 - \mathrm{e}^{(\mu-r)T}}\right)\left(\frac{\beta_1}{\beta_1 - 1}\right)\frac{C_2}{\theta_2} = L_2^*$$

.

For the values of the options to invest into the projects 1 and 2 we get

$$F_i(\theta_i L) = K_i B^{\beta_1} = \frac{C_i}{\beta_1 - 1}\left(\frac{\theta_i L}{B_i^*}\right)^{\beta_1}$$

for $L < (B^*{}_i/\theta_i)$, and so

$$\frac{F_1(\theta_1 L)}{F_2(\theta_2 L)} = \frac{C_1}{C_2}\left(\frac{C_2/\theta_2}{C_1/\theta_1}\right)^{\beta_1} < 1$$

We can thus conclude that not only would the hosted payload initiate an earlier launch, but it would also increase the value of the investment, which means the investor would always prefer the second project.

4.3. A numerical application with two stochastic benefit streams

For reasons of comparison, we first use the numerical model with a deterministic income stream and a stochastic one, as in the previous subsection. The data are the same as in Section 3, except for the fact that we use a typical lifetime of 15 years for the satellite system.[9] B^* now amounts to €820.669 million, which is obviously substantially higher than in the infinite lifetime case.

Let us now extend the model to include not only stochastically growing benefits from Earth observation information in the form of mitigated or avoided damage, but also stochastic benefits from services sold commercially, as previously mentioned. We assume that the market will eventually reach an equilibrium and that the revenues from selling these services will, therefore, be mean-reverting.

$$\mathrm{d}\pi_t = \alpha(\mu^\pi - \ln \pi_t)\pi_t \mathrm{d}t + \sigma^\pi \pi_t \mathrm{d}z_t^\pi$$

where π will revert to its long-term level e^{μ^π} at a speed of α. $\mathrm{d}z_t^\pi$ is the increment of a standard Wiener process and σ^π is the corresponding volatility parameter.

The value function is then composed of benefits immediately received upon launching and the so-called "continuation value" contingent upon all possible future states and benefit and revenue realizations

$$V_t(x_t, B_t, \pi_t) = \max_{a_t(x_t)}\{\psi(x_t, a_t, B_t, \pi_t) + \mathrm{e}^{-r}E(V_{t+1}(x_{t+1}, B_{t+1}, \pi_{t+1})|B_t, \pi_t)\}$$

[9]For a lifetime of 200 years or longer, we get the same result for B^* as before—with the analytical approach and infinite lifetime.

where x_t is the state (i.e. whether the satellite has been launched or not), which is determined by the action taken, a_t. $\psi(\cdot)$ is the immediate net benefit including both the revenues from selling services commercially and the benefits from avoiding or mitigating damage. This can be optimized to find the optimal timing of the launch by using backward dynamic programming.[10]

We set α equal to 0.5 and σ equal to 5% and find that B^* is 820.815 million €, which is not significantly different from B^* with deterministic π. In other words, the uncertainty conveyed by the fluctuations in the market price of communication and location services, for instance, does not seem to have a decisive impact on the critical value of the avoided damage stream triggering the satellite launch.[11]

It is important to note that these results are, of course, sensitive to the underlying parameter values. Sensitivity analysis shows that substantially lower levels for B (e.g. because of a higher than expected vulnerability to disasters, modelled through a lower than expected θ) or π combined with a large volatility of B can even lead to the result that the mission is not launched at all in many cases.[12]

5. Summary and implications

This paper has investigated the applicability of basic real options theory to the timing of a satellite mission in the context of the benefits that can be obtained from Earth observation and the ensuing improvement in the amounts and quality of data that can help to avoid or at least mitigate the damage from disasters. The analysis has shown that even a very simple framework in the style of Dixit and Pindyck [2] can be used to examine issues of uncertainty and optimal timing of launching the satellite (or the satellite system).[13] There are several important conclusions to be drawn from this.

First, large volatility of the benefits from damage avoided or mitigated increases the option value, and therefore leads to a postponement of the satellite mission. While it is completely rational to postpone and wait in the face of larger uncertainty, a higher σ also implies bigger spikes, representing high-impact disasters in our interpretation. This means that it is important to evaluate and assess the economic and social benefits that could be obtained through Earth observation. The same is true for the trend parameter: a larger value of μ has been shown to trigger an earlier launch. So, if ex ante benefit assessment can establish that μ can be expected to be relatively high, an Earth observation system could be installed earlier as well.

In addition, it is fair to assume that governments can expand their equipment on satellite missions at diminishing unit costs and, therefore, benefit from economies of scale. Application of the same analytical framework to this problem has shown that this would not only lead to potential increases in θ, and thus an increase in damage avoided damage (or lower vulnerability) at lower unit costs, but also to an earlier launch of the satellite and thus a prolonged period during which damage can be avoided or mitigated.

Furthermore, the shorter the lifetime of the satellite system, the longer will the option value exceed the net present value, and waiting will be worthwhile. By finding ways to refurbish satellites at relatively low cost or maintain them longer or make them more durable in the first place, this problem could be overcome.

Even though the numerical model in the last subsection did not find a significant impact of the volatility of the "commercial" benefit stream on the timing of the satellite mission, the results will most probably look very different when different price processes are tested for. As can be imagined, communications services, for example, can be subject to substantial network effects and revenues might take off only slowly, then increase more drastically when a critical mass of users has obtained the service, and finally level off as the market reaches saturation.

Similarly, the frameworks presented here are very simple for the sake of transparency and because we want to present a new application of a tool that has previously been applied to other problems in the most straightforward way possible. The parameter θ, for instance, has been treated as a constant here (with the exception of the case where additional equipment on a satellite could lead to an increase in θ), but it is easy to imagine that, as technology progresses, θ can be improved as well, which will decrease the vulnerability of people and economies to disasters. A dynamic version of θ is, therefore, another possible extension that could offer interesting insights.

[10] There are several numerical implementations that all have their specific advantages and disadvantages depending on the application. We have chosen Monte Carlo simulation for reasons of computational efficiency and because we wanted to experiment with different processes, but the results coincide with those obtained when using partial differential equations.

[11] This would be different if we allowed for correlation between the two benefit streams. In the application at hand, however, we did not see a reason why such a correlation should exist.

[12] With "cases" we refer to the number of simulations here.

[13] A more elaborate model should take into account other factors (e.g. associated with the development phase or political issues) influencing the launching decision.

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