TOWARDS AN ASSESSMENT OF RESILIENCE IN TELECOM INFRASTRUCTURE PROJECTS USING REAL OPTIONS

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Abstract

This paper employs the concept of real options to quantitatively assess resilience. First, the definitions of resilience are distilled from literature in the fields of engineering, management and ecology to give requirements for further assessment. From this, it was found that resilience requires a system to be robust, adaptable and flexible in the face of uncertainty. The main contribution of the paper is to connect these requirements to real options valuation and demonstrate the evaluation of the robust and flexible cases through real options methods. Specifically, Least Squares Monte Carlo method is used to value each option with the robust case being the benchmark and flexibility representing upgrades to the system. This is applied to an illustrative telecommunications case and the properties of the model assessed. The results show that uncertainties on the system can be captured and valued through this method so that it can aid a decision maker to assess which technology option or investment to select for future planning.

Keywords: Large-scale engineering systems, Uncertainty, Design management, Resilience

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1 INTRODUCTION

Infrastructure systems such as telecommunications, power and transport networks form the backbone of most societies. Failure in these services can bring major disruption to a community and recovery can incur substantial time and cost. Furthermore, infrastructure systems characteristically have relatively long life cycles, typically more than 10 years, and also involve major investments. As such, these systems are subject to uncertainties through a range of time-scales: from uncertainty in immediate, day-to-day operations to strategies for the far future. How these engineered systems are designed to accommodate this range of uncertainty is therefore paramount to ensure the success of such projects.

The concept of "resilience" has emerged in literature and has been found to address these concepts in a number of fields. The term "resilience" was first popularised by Holling (1973) within the field of ecology to assess the stability and resilience of interacting populations and the environment. In their work, the term is defined as the "persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist". This concept of a system's interaction with the environment and surviving disturbances is similar to the foundations for resilience in many other fields including supply chain management (Sheffi and Rice, 2005), crisis management (McManus et al., 2007), psychology (Rutter, 1987) and resilience engineering (Hollnagel et al., 2007). Thus, resilience has traditionally been associated with negative connotations: the ability to recover from adversity or trauma. However, there is now growing recognition that resilience not just allows for recovery from disruption, but also to allows for the ability to thrive and prosper despite difficult times (Hamel and Valikangas, 2003).

While there has been, substantial literature describing the concept of resilience, there is much less work on quantitatively assessing resilience. To this end, the method of real options is used here to assess resilience so that the design of infrastructure systems can be evaluated and the best design option can be chosen moving forward. This is applied to a telecommunications infrastructure example where different infrastructure investment options are evaluated.

The remainder of this paper is structured as follows: Section 2 briefly describes the requirements of resilience, based on the author's previous work and is linked to Section 3 which introduces how real options can be used to meet these requirements and be further used to assess resilience. Section 4 describes the Least Square Monte Carlo simulation approach taken to value different infrastructure real options and Section 5 presents the results from the simulations of a telecommunications example for robust and flexible options.

2 REQUIREMENTS FOR RESILIENCE

Previous work by the author involved distilling requirements for resilience from engineering, management and ecological literature to gain a broad perspective of the term. It was found that the system lifecycle properties robustness, adaptability and flexibility were required for resilience. It should be noted, however, that there is significant overlap in the definitions of adaptability and flexibility in literature. These lifecycle properties are briefly defined in this section to give requirements for the quantitative assessment of resilience.

2.1 Robustness

Formally, robustness may be defined as the ability to be "insensitive towards changing environments" (Fricke and Schulz, 2005) and gained attention through Taguchi's seminal work in controlling quality in product manufacture (Taguchi, 1985). Essentially, the system does not respond to variation in the environment, nor changes any processes or properties when faced with disturbances, yet maintains a desired output. For example, a bridge may be designed with some tolerance to be robust enough to withstand extra loading from increased traffic or wind.

This design may be more cost efficient when the disturbances are predictable, but the system may still fail if pushed outside the system tolerances by some unexpected event. As such, robust designs suit situations where the uncertainties are relatively more understood, typically in the near future. That said, a system might also be designed to be robust into the far future if uncertainties on the system are unlikely to change throughout the system lifecycle.

For infrastructure projects with relatively long lifecycles, there will be a range of uncertainties throughout the system lifecycle and it is difficult, perhaps impossible, to foresee all future scenarios. Coupled with the fact that infrastructure systems are often complex and involving interactions with multiple stakeholders, a robust design is usually not sufficient nor cost efficient to protect against all eventualities. Resilience, therefore, not only requires the system to be able to accommodate predictable uncertainties in the near future through robust design, but also allow for change and evolution of the system. This is addressed through adaptability and flexibility as follows.

2.2 Adaptability

For most infrastructure projects, due to the long lifecycles involved, it is inevitable that the system needs to change at some point. This can be addressed by designing the system to be adaptable or flexible. There is, however, a lack of consensus concerning the definitions of "adaptability" and "flexibility" in engineering design literature and the terms are often used synonymously. While both properties refer broadly to a change in the system, a slight subtlety may be distinguished in literature and the terms are defined here to give requirements for resilience assessment.

Here, adaptability is used to denote where the system changes through an internal change agent (Ross, 2006). An internal change agent is where change is instigated within the system automatically without the need for external action and serves to move the system to a predefined performance level. This could be in the form of internal control systems and feedback loops where the system changes automatically to maintain system performance. For example, an aircraft can automatically maintain stability and adapt to changes in flight conditions through a lookup table of stability derivatives. In this case, actuator positions are automatically adjusted as a function of flight conditions. These responses are also useful in high-risk situations where immediate responses are needed instead of waiting for human intervention (Neches and Madni, 2013).

In this sense, the system automatically changes to accommodate for a range of uncertainties. However, since the changes occur automatically, the system is still designed at the conceptual stage to operate within certain boundaries and requirements. That is, although an aircraft autopilot can be designed to handle a range of conditions, some unforeseen event could still push the aircraft outside designed performance limits that cannot be automatically corrected by the system, leading to failure. As such, an adaptable design may be useful where it is impractical to make the system excessively robust through large redundancies and instead allows the system to change automatically. This requires some foresight into the environment in which the system is deployed and therefore may be useful, as similarly for robust designs, where uncertainties are relatively more understood in the near future or where the demands on the system is unlikely to change throughout the lifecycle.

2.3 Flexibility

Research in ecology was also included in the literature search since it revealed another perspective to resilience which contrasted with much of the literature in engineering and management. In ecological literature, resilience became a concept that allows systems to adopt new system states. For example, an introduction of a species could cause some species to become extinct, but more importantly on the other hand, it could also allow others to thrive. This concept gave rise to the idea that resilience is not only about adversity, but also the ability of the system to evolve for new opportunities and requirements (Walker et al., 2004). This can be seen to be similar to the concept of flexibility in engineering design.

Flexibility, in engineering design literature, refers to a system that is designed such that the requirements and performance can be changed at a future date (Fricke and Schulz, 2005). This is typically designed through modularity or platform designs which make it easy to change the design when necessary. Contrasting this with an internal change agent for adaptability, flexibility allows for an external change agent or decision maker to change the requirements of the system when appropriate (Ross, 2006). Furthermore, while robustness and adaptability serves to recover the system to some normal or desired state, flexibility allows for a change in the "normal" state and requirements through upgrades to the system. By designing a system to be flexible, and thus having multiple choices for the decision maker, it allows a system to evolve and potentially thrive when faced with significant changes in demand.

Examples of flexible design include the Ponte 25 de Abril suspension bridge over the Tagus River in Lisbon, Portugal. Originally built with a single deck for road traffic, it was designed so that it had the strength to accommodate a secondary railroad deck in the future if necessary. Although adding a second deck involved a retrofit, the decision makers only exercised this option when there was enough demand stimulated by the single deck bridge (Gesner and Jardim, 1998). Essentially, the designers anticipated that the capacity of the bridge could grow which led to mechanisms being designed into the bridge at the conceptual stage so that capacity could be expanded when appropriate. Flexible designs are therefore especially important where the requirements are likely to change in future and there is substantial uncertainty such as in infrastructure projects.

3 REAL OPTIONS FOR RESILIENCE

Although there has been much literature in defining and discussing the concept of resilience, there is much less work on quantitatively assessing resilience. A number of quantitative techniques may be used to assess robustness, adaptability and flexibility respectively. Indeed, each one of these properties are a whole field of engineering design in their own right. Here, real options, which stems from designing for flexibility, is chosen to assess resilience as it may be used understand which technology investments, or options, to implement in a system under uncertainty. Each different available technology investment, such as different telecommunication network line types, can be treated as a real option and allows for alternatives for deployment. Specifically, a real option allows a decision maker the right, but not obligation to undertake some action in the future. In the case of a telecommunications system an organisation may have invested research into different types of network fibres. This research into future technologies allows a decision maker in the organisation the ability, but not obligation, to deploy these different technologies in the system.

From an engineering design point of view, each real option may be seen to form an alternative component or future action of a system. For example, the Ponte 25 de Abril suspension bridge over the Tagus River had the real option to add a secondary railroad deck that was implemented *only* when there was sufficient demand. Furthermore, each component or action also has some associated robustness or adaptability. That is, the railroad deck on the suspension bridge also has some maximum capacity and therefore some associated robustness.

This applies to resilience because each real option not only provides flexibility in allowing requirements to be changed through investments, but also each real option has some associated robustness and/or adaptability. Each real option has to be analysed so that it is sufficiently robust or adaptable to meet current requirements or demands, but also allow for future evolution of the system. Therefore, resilience involves the transition between a number real options (or investments) to ensure the longevity of systems and assessment involves finding the decision strategies which optimise return on the system. By analysing these decision strategies, the system can be better designed to be resilient and thus be better prepared for future uncertainty.

3.1 Background on Real Options

Real options were originally derived from financial options literature and was proposed as a method to account for flexibility when investing under uncertainty. Formally, financial options give the right but not obligation, to invest in some asset for a predefined price at some future date. Real options apply similar concepts for the analysis of real physical assets and evaluating investments under uncertainty. Furthermore, real options provide better assessment of strategic investments compared to discounted cash flow and net present value calculations due to the ability to account for flexibility and assess managerial strategies. This is especially relevant for infrastructure projects due to significant up front costs.

Real options have been applied to a number of problems where investments are made under uncertainty and decision strategies have to be assessed. Some of the early work in applying real options focused on natural resources such as mining (Brennan and Schwartz, 1985) and oil (Lehman, 1989) and risk management (Huchzermeier and Loch, 2001).

For the assessment of real options, the investment strategies can be categorised using the 7S framework by Copeland and Keenan (1998). This defines 7 category types: scale up, scale down, scope up, scope down, switch up, switch down as well as study and wait. The first options, scaling up or scaling down the project, involves expansion or reduction of the project respectively. For a telecommunications networks, this could be to roll out the network further or slow down the rollout phase. In the extreme case, scaling down the project could also be where the entire project is abandoned. Scope up and scope down options allow management to change product portfolio requirements. This change in management requirements can potentially in turn affect how the project is scaled or switched. The switch up and down option allows for a change in technology with switch up giving rise to better products but usually incurring some extra cost.

In terms of resilience, the robust case can be modelled as the benchmark case where no real options or technologies are implemented and there is no change to the system. Both the adaptable case and flexible case can be studied using switch options. The adaptable case would allow for reversible switching between technologies whereas in the flexible case, the switch would be irreversible. That is not to say future options or changes are not available in the flexible case. Compound options deals with situations where more options may be added on top of options. This is summarised in the following table.

Table 1. Addressing lifecycle properties through different option types

System Lifecycle Property	Option Type	Change Type
Robust	None	None
Adaptable	Switch Option	Reversible
Flexibility	Switch Option	Irreversible

For the scope of this paper, the flexible case, where there is an irreversible change of technology, is compared to the robust case to assess the value of improving technology in a telecommunications case. Each option or technology investment is evaluated through real options method with the robust case serving as the benchmark. The flexible case is therefore simulated as upgrades in technology. Furthermore, it is assumed that the flexible options are mutually exclusive so that only one option may be exercised at any one time. The other option types could make for further studies. For example, scale up/down options could be used to explore system architectures and how the options should be used in conjunction. The study and wait option could be useful in understanding when to exercise these options. Here, only the simple flexible and robust cases are illustrated to demonstrate the use of real options to resilience analysis.

3.2 Quantitative Analysis of Real Options

Since real options has stemmed from financial options, the methods to value real options also follow from financial options. These methods include the Black Scholes equation, binomial lattices and Monte Carlo analysis.

The Black Scholes equation is one of the most important models for financial options valuation and was developed in 1973 to price European options (Black and Scholes, 1973). This pioneering formula subsequently earned a Nobel Prize in Economic Sciences in 1997. However, the formula is typically used to price European options which can only be exercised at the specific end date only. This works in finance, but for real options, where investments are on physical assets, there usually is not this restriction where the investment must be made on a specific date. For this reason, American options, in which investments can be made at any date, are more appropriate.

American options are often modelled using dynamic programming techniques such as finite difference methods, lattice methods or Monte Carlo simulations. Finite difference methods where the stock price is modelled using differential equations are difficult to implement for more complex cases and suffer from the curse of dimensionality. Lattice methods, typically binomial or trinomial, comprise a tree structure and assumes, in the binomial case, that the variable can only either increase, with probability p, or decrease with probability, $p - 1$, for some interval of time (Cox et al., 1979). Lattice methods have been used widely for pricing financial options and, by discretising the problem, avoids the costly evaluation of infinite scenarios. These are, however, limited when analysing more than one source of uncertainty. Monte Carlo methods involve random sampling and are commonly used for multi-dimensional problems in a number of domains such as modelling fluids, structures in physical problems as well as business uncertainty and risk. This therefore allows for more comprehensive analysis of uncertainty in further analysis for resilience.

Of the number of Monte Carlo approaches taken to evaluate these options problems, the most promising technique currently available for this problem is presented by Longstaff and Schwartz (2001) using a Least Squares Monte Carlo (LSM) approach. This technique is chosen as a basis to assess resilience and applied to a telecommunications case in the following sections.

3.3 Least Squares Monte Carlo Approach

The LSM approach allows for the valuation of American options through simulation. The contribution of the LSM technique lies in using least squares regression to determine the continuation value of the Bellman equation of the option and therefore allows the optimal execution policy of the investment to be found. This approach is outlined in this subsection before applying to an illustrative telecommunications case in Section 4.

The general problem is formulated by assuming that some stochastic input(s) affects the system and therefore influences the investment decisions of the firm. For a telecommunications network, this could be the demand or usage of the network. The stochastic input of demand, X_{t_n}, on time step, t_n, with N time steps, can be modelled through a geometric Brownian motion given by

$$X_{t_n} = X_{t_0} e^{(r-\sigma^2/2)t + \sigma \mathrm{W(t)}}, \tag{1}$$

where $X_{t_0}$is the initial value of input X at $\mathrm{t} = 0, r$ is the trend of the demand or drift, σ is volatility, and $W(t)$ is standard Brownian motion. This is then used to calculate some payoff, $\pi(X_{t_n})$, which can be understood as the telecoms operator profit from the demand. Let $F(t_n, X_{t_n})$ be the value of the option between time, t and at the option maturity, and the problem then becomes an optimisation of the value of the option, $F(t_n, X_{t_n})$ in the following equation

$$F\big(t_n, X_{t_n}\big) = \max_{\tau \in \mathcal{T}(t_n, T)} \big\{\mathbb{E}^*_{t_n}\big[e^{-r(\tau - t_n)}\pi(\tau, X_\tau)\big]\big\}, \tag{2}$$

where τ is the optimal stopping time in $[t_n$,T]. That is, the optimisation finds the optimal time, τ, to invest in the appropriate real option and gives the value of the investment.

The LSM uses a backward dynamic programming algorithm for this optimisation and Monte Carlo to approximate the expected value. Dynamic programming solves optimisation problems by dividing the computation into smaller sub-problems. In essence, the algorithm starts at the final time, T, and marches backwards through the time steps until $t = 0$. At each time step, the algorithm compares whether it is better to exercise the option at the current time step, or hold the option on the expectation that the value of the option will increase. This is computed by calculating the continuation value of the function at each time step and comparing with the value at the current time step. The continuation value is found from

$$\Phi\big(t_n, X_{t_n}\big) = \mathbb{E}^*_{t_n}\big[\textstyle\sum_{i=n+1}^{N} e^{-r(t_i - t_n)}\pi(t_n, t_i, \tau, \cdot)\big] \;. \tag{3}$$

This is estimated using least squares regression where the payoff π, is projected onto a set of basis functions. The Laguerre polynomials are used here since other studies (Gustafsson, 2015) have found them to give appropriate results. The first four functions are defined as

$$L_0(x) = 1 \qquad\qquad L_1(x) = 1 - x \tag{4}$$

$$L_2(x) = \tfrac{1}{2}(x^2 - 4x + 2) \qquad\qquad L_3(x) = \tfrac{1}{6}(-x^3 + 9x^2 - 18x + 6)$$

The estimated continuation value can therefore be calculated through least squares,

$$\widehat{\Phi}^J\big(t_n, X_{t_n}\big) = \textstyle\sum_{j=0}^{J} \hat{\phi}^j\,(t_n) L_j\big(t_n, X_{t_n}\big). \tag{5}$$

This is applied recursively to the following decision rule at each time step

$$if \qquad \Phi\big(t_n, X_{t_n}\big) \leq \pi\big(t_n, X_{t_n}\big) \qquad then \qquad \tau = t_n, \tag{6}$$

so that the optimisation of the value function, $F\big(t_n, X_{t_n}\big)$, can be written as

$$F\big(t_n, X_{t_n}\big) = \max\big\{\pi\big(t_n, X_{t_n}\big), \Phi\big(t_n, X_{t_n}\big)\big\}. \tag{7}$$

The optimal stopping time is found by recursive application of the decision rule (6) from final time T. If the expression is true, the stopping time is updated so that $\tau = t_n$. When the computation reaches $t_n = 0$ and all the optimal stopping times are determined, the value of the American option is estimated by averaging the values for each simulated path, ω

$$F(0, x) = \tfrac{1}{K}\textstyle\sum_{\omega=1}^{K} e^{-r\,\tau(\omega)}\pi(\,\tau(\omega), X_{\tau(\omega)}(\omega)) \;. \tag{8}$$

This form the basic LSM method for American options valuation. In applying this for resilience, each option (or available investment) is valued using the LSM method with the robust case being the baseline case where there is no upgrade in technology. The other options are also evaluated similarly and represent flexible options or technology upgrades.

4 APPLICATION TO TELECOMMUNICATIONS NETWORK

The LSM method as outlined previously is now applied for a telecommunications case. The parameters used for the equations and simulations presented in this section are for illustrative purposes only and do not represent actual data from the telecommunications company.

First, the stochastic input, assumed to follow a geometric Brownian motion, is generated to simulate the demand on the telecommunications network. The drift or trend of demand, r, and volatility, σ, are fixed for the simulated period. Typical simulated paths are illustrated in the following figure.

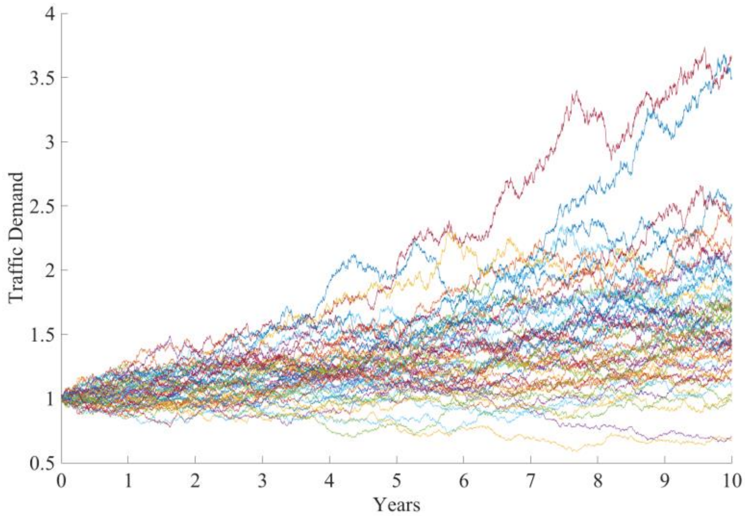

Figure 1. Illustration of demand simulation with $X_{t_0} = 1$, $r = 0.05$, $\sigma = 0.1$

The payoff, $\pi(t)$, for each technology is a function of demand and, for telecommunications models, it is assumed that the payoff or profits generated from demand can be derived from the customer's satisfaction. Here, Enderle and Lagrange's model (2003) for customer satisfaction is employed and is given by

$$H_t(X_t, C) = e^{-\beta/Q_t(X_t,C)}\,, \tag{9}$$

where H_t is customer satisfaction, C is the capacity of a cell of the network, β is chosen such that $\beta = \log(2) \cdot q_{1/2}$, where $q_{1/2}$ is the throughput value ensuring a satisfaction of 50%, and Q_t is the quality of service calculated from $C - X_t$. The customer satisfaction is then multiplied by some transfer price, δ, so that the operator receives some \$/Mbit or \$/Erlang. Following Morlot, Elayoubi and Redon's work (2012), the net profit may therefore be calculated from,

$$\pi(t) = \delta X_t e^{-\beta/(C-X_t)} \quad if\ X_t < \mathrm{C} \tag{10}$$

$$\pi(t) = 0 \qquad otherwise$$

Illustrative parameters used for further analysis are shown in Table 2 and the resulting plots are shown in Figure 2 where each curve represents a different technology or option type.

Table 2. Option parameters

Option	$\boldsymbol{\delta}$	$\boldsymbol{q_{1/2}}$	**C**
1	1	0.5	2
2	3	0.5	2
3	3	5	4
4	1	0.5	4

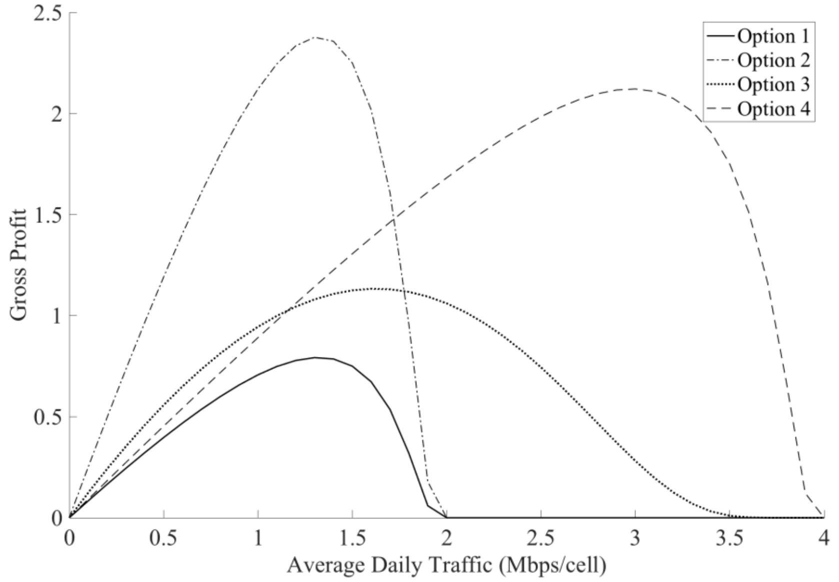

Figure 2. Payoff curve plots

The robust case (Option 1), shown by the solid line, represents the benchmark option. The other options/curves represent other technology investments and therefore flexibility to upgrade the system. All options are valued to obtain $F(t_n, X_{t_n})$ and compared under varying drift and volatilities in the following section.

5 RESULTS

The uncertainty in the model is assumed to be captured using a geometric Brownian motion model and therefore the parameters of drift and volatility can be varied to assess the change in value of different options in response to the change in parameters.
The four options as presented in Table 1 are first assessed for response to varying drift. This is shown in Figure 3 and volatility is fixed to 0.01 $day^{-1/2}$.

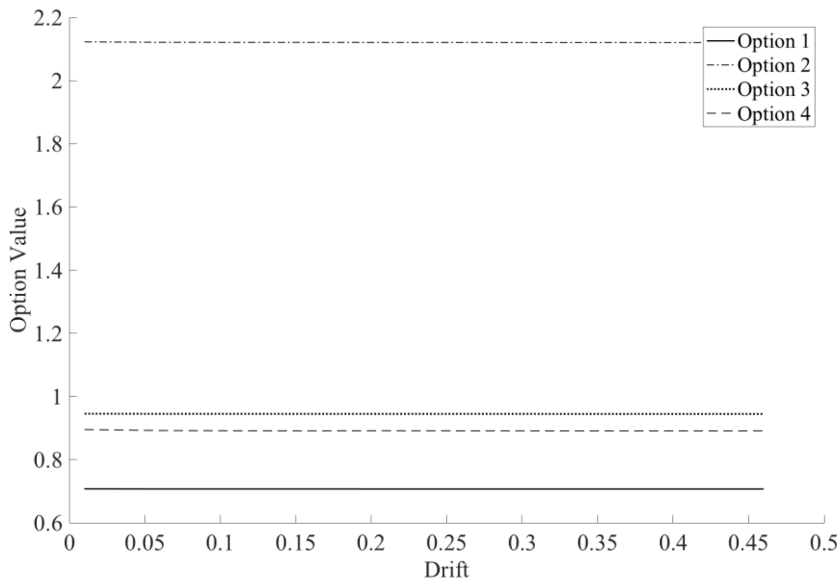

Figure 3. Option response to varying drift

The value of all the options remains fairly constant with standard deviations of 0.001, 0.004, 0.002 and 0.015 for options 1 to 4 respectively. The lowest valued option, Option 1, is as expected, the robust option. This is done similarly for varying volatility and fixing drift to 0.001 per day. The resulting plot is shown in Figure 4.

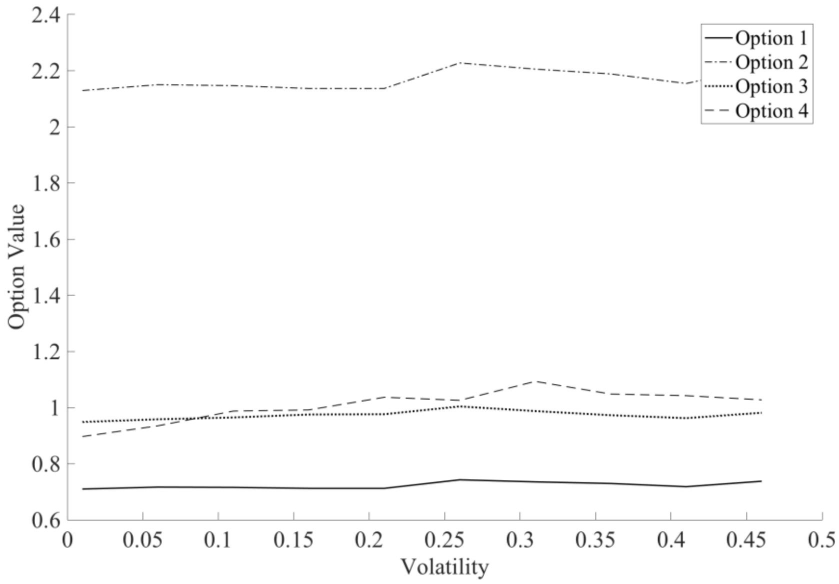

Figure 4. Options response to varying volatility

The standard deviations for options 1 to 4 are 0.008, 0.024, 0.011 and 0.067. The options values give higher standard deviations when changing volatility compared to when varying drift. It can also be seen that there is a slight upward trend particularly for Option 4.

6 DISCUSSION

The results show that the smallest curve, the robust option, has the least value for all drift and volatilities as expected. Option 4, with the highest peak gives the highest values in Figures 3 and 4. However, while Option 4 has the largest integral area under the curve, when comparing drift and at low volatilities, it is not the most valuable. This may be attributed to the demand at $X_{t_0} = 1$ so that for low drift and low volatility, the demand does not change significantly above or below 1. By looking at the payoff curve where the demand or average daily traffic is 1, it is clear that Option 4 returns less than the other options apart from the robust option. For this reason, at demands close to 1, Option 4, while having the largest payoff curve, is not the most valuable.

When volatility is varied, however, the value of Option 4 displays a slight upward trend and is valued higher than Option 3 at higher volatilities. This is due to a larger proportion of the curve being captured and at higher demands Option 4 indeed gives a higher return than Option 3. This also gives reason as to why volatility changes affect the model more than changes in drift. A higher volatility gives a higher spread of demand and as such, more of the curve is covered. The drift would have to be relatively higher to give the same spread in demand.

The results have demonstrated that different options may be valued using the LSM method. The valuation of each option allows uncertainty in the form of volatility and drift to be captured so that a decision maker can assess which option to choose given a projected risk. The further challenge lies in using this model in decision making and understanding how to choose the options such that resilience may be achieved. In reverse, this model could be extended so that for given volatility and drift, bounds for an appropriate option could be derived. Furthermore, this model assumes the volatility and drift remains constant for the whole simulation period which is unrealistic for long time periods. The simulation could therefore be extended to incorporate changing parameters with time.

7 CONCLUSION

This paper connects the ideas of resilience and real options so that resilience can be quantitatively assessed. First, the definitions of resilience are distilled to form requirements for quantitative analysis.

It was found that from literature in engineering, management and ecology, three main lifecycle properties are necessary for resilience: robustness, adaptability and flexibility. In this preliminary analysis, the concept of real options was used to evaluate the robust and flexible case only. Here, the Least Squares Monte Carlo method was used to value each option (or investment) with the robust case being the benchmark and representing no change in the system. Flexibility is where there can be upgrades to the system and thus other options (or investments) are also valued. This is applied to an illustrative telecommunications case and the properties of the model are assessed. The results show that uncertainty, captured as drift and volatility, in the model affects the options value. This allows a decision maker to project uncertainties and assess which technology option or investment to choose to for future planning. The further challenge involves understanding the decision making process in choosing the appropriate option so that resilience may be achieved.

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