Valuing strategic interactions in systemic urban infrastructure investments using option games: A portfolio-based approximate dynamic programming approach

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Abstract

The performance of investments in systemic urban infrastructures such as in energy, transport, water, waste and ICT is frequently affected by enormous uncertainty surrounding intrinsic technical and other risks, exogenous volatility in supply and demand conditions and by the strategic interactions of multiple decision makers with often competing interests. As such, the application of option games, which combine real option analysis to investment under uncertainty and game theory to study decision makers competing behaviours, appears to be a promising avenue for the analysis of such complex investment problems. However, existing option game models generally take a corporate perspective, use continuous-time models and aim at the provision of analytical solutions, which makes them both impractical and inadequate. This paper presents a new discrete-time, option games-based appraisal framework for selecting a portfolio of interdependent urban infrastructure investments. Representing the decision makers flexibilities through influence diagrams and mathematically modelling their strategic interactions, we have used this framework to formulate a multi-stage stochastic optimisation model that combines Monte Carlo simulation for scenario generation with the approximation of the value functions through simple least-squares. Using the real-case of district heating network investments in London, we investigate the sensitivity of the optimal portfolio value to changes in both decision makers' strategic behaviour and demand and supply patterns. The numerical results demonstrate that our approach has substantial potential to enhance and support long-term, strategic investment decisions, particularly with regard to timing and scale, but also short-term, operational decisions, for example to switch between different

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modes of operation.

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1. Introduction

It is widely acknowledged that Real Options Analysis (ROA) has substantial potential as a framework for the adequate appraisal and risk-management of systemic low-carbon urban infrastructure investments given that these investments are not only being made in the context of both significant uncertainty and highly volatile conditions, but also (naturally or intentionally) "ripe with flexibility" (Cheah and Garvin, 2009). Even some governments recently realised these benefits. For example, appraisal guidelines of the United Kingdom's Treasury Department state that "it is important to incorporate the value of exibility" (HM Treasury, 2015) and that ROA may be appropriate "if an activity has uncertainty, flexibility and learning potential" (HM Treasury, 2009). However, despite its great potential and evidence (Martins et al., 2015) of the large growth in the past 15 years in the number of publications advocating the use of ROA in infrastructure projects, the absolute number is still comparatively low when compared with most other areas of applications. Indeed, (Garvin and Ford, 2012) noted that it is not widely applied in practice and, as Gil and Beckman (2009) pointed out, applying ROA to infrastructure design "is still in its infancy".

Most of the recent infrastructure-related applications of ROA fall into one of two categories: physical and digital infrastructure investment projects. With regard to the former, ROA has been used to inform decision making in the case of parking garages and their design (Zhao and Tseng, 2003; De Neufville et al., 2006); to investigate the effects of product design modularity as part of airport expansions programmes Gil (2007); for the appraisal of toll road projects (Rose, 1998; Garvin and Cheah, 2004); as well as to investigate important issues related to the provision and ownership of infrastructure systems including different forms of private sector participation arrangements such as public-private Partnerships and private finance initiatives, for example see Ho and Liu (2002); Cheah and Liu (2006); Chiara et al. (2007); Alonso-Conde et al. (2007); Krüger (2012). On the other hand, ROA has also been applied in the context of digital infrastructures like information technology (IT) infrastructure investments (Panayi and Trigeorgis, 1998; Benaroch and Kauffman, 1999; Miller et al., 2004). In contrast to physical infrastructures, Benaroch (2002) mentioned that real options generally must be intentionally planned in an IT investment project, instead of being "inherently" embedded.

Widening its applicability and allowing the study of the influence of competition, significant research in recent decades has been conducted towards the integration of strategic (game theoretic) interactions into real option models. Most of the earlier literature on (real) options games, which is the combination of ROA with game theory (Ferreira et al., 2009), has focused on strategic considerations from a corporate perspective and continuous-time models (Grenadier, 2000b). One of the very first studies in this area was published by Smit and Ankum (1993), who applied basic game theory principles and a simple numerical example of two companies to study the influence of competition (monopoly, oligopoly, duopoly) on investment project value and corporate strategies like investment timing. A few years later, and calling it a "burgeoning area of research", Grenadier (2000a) published a book containing a collection of papers that deal with the integration of game theoretic approaches into the ROA framework, thus illustrating how the consideration of strategic considerations such as having multiple competing economic decision makers can provide valuable insights into their behaviour. While aiming at bridging the gap between real options (capital investment) and game theory (strategic interactions), Smit and Trigeorgis (2004) explicitly recognise the added value obtained when incorporating both flexibility and strategic considerations into the valuation process. Another book on this topic is (Chevalier-Roignant and Trigeorgis, 2011).

Despite the potential usefulness of game theory for risk management in infrastructures (Larouche, 2008; Cox Jr, 2009), its combination with real options theory has not been widely used yet to strategically assess and analyse investments into both technology (Smit and Trigeorgis, 2007) and infrastructure systems (Smit and Trigeorgis, 2006). Particularly for the valuation of the growth option value of infrastructure investments – which are often characterised by path-dependencies, lumpy or irreversible investments, considerable requirements for time to build, financial and human capital constraints, and other factors –, option games support strategic capital investments through actively taking account for interactive competitive settings, e.g. multiple decision makers (Smit and Trigeorgis, 2009). Considering the case of European airport expansion, in particular the specific case of the Amsterdam Airport Schiphol in terms of the growth options and restrictions, Smit (2003) applied a real options game approach using a discrete-time binomial tree to value airport expansion (i.e. its growth option). Suttinon et al. (2012) recently applied such a hybrid approach to value investments in industrial water infrastructure projects, illustrating their methodology through a game setting where the public sector (Government of Thailand) may invest in tap and industrial water supply, whereas the private sector firm may invests into recycled-water development.

As a result of all these efforts to combine ROA with game theory, there exists a number of papers reviewing published modelling approaches and studies' findings and contributions. For example, Huisman et al. (2004) reviewed some of the existing literature on options games and showed its potential to extend the existing industrial organisation literature, which, according to the authors, is still underdeveloped. More recently, Azevedo and Paxson (2014) provided a comprehensive review of two decades of real options games to highlight their past achievements, current shortcomings, and potential future applications and avenues of research. Further review papers on option games were presented by Huisman et al. (2005); Chevalier-Roignant et al. (2011); Huberts et al. (2015). In addition, being of great usefulness at a strategic level (Cruz and Marques, 2013), Angelou and Economides (2009) went one step further and developed a framework that merges ROA, game theory and multi-criteria assessment (in particular the Analytic Hierarchy Process) and applied it to analyse an irreversible ICT investment.

Although the above publications have contributed towards advancing the field of option games, they have either only considered the problem of a firm whilst using continuous-time models and providing analytical solutions, or modelled option games with discrete-time approaches using (binomial) trees to analyse investments under both uncertainty and competition. Doing so, however, makes these approaches both impractical and inadequate, particularly in the context of the problem of valuing strategic interactions in a portfolio of potentially interdependent urban infrastructure investments. In contrast, this paper presents a new option games-based appraisal framework in discrete-time which builds upon an earlier portfolio-based real options framework developed by the authors that applies an approximate dynamic programming approach by combining influence diagrams to model decision maker's flexibilities with the least-squares Monte Carlo approach to approximate the value of the corresponding portfolio of interdependent real options. This research shows how the performances of investments in urban district heating systems in the London borough of Islington are being affected not only by changes in demand and supply patterns, but also by decision makers' strategic behaviour.

2. Methods

The option games-based appraisal framework presented in this paper builds upon the earlier work of Maier et al. (2015), which presented two new real options-based appraisal frameworks for selecting a portfolio of physical and digital urban infrastructure investment projects: their first approach considers (strategic) interdependencies between real options within single investment projects but not between projects in the portfolio, whereas their second approach additionally takes into account four types of interdependencies (physical, cyber, geographical, and logical (resource and market, strategic, and budget)) between urban infrastructure investment projects in the portfolio. The new option games-based appraisal framework was then applied to the real-world case of district heating network investments in the London borough of Islington.

3. Results and discussion

Based on the claim that the option games models presented in previous studies are both inadequate and impractical when it comes to valuing strategic interactions in systemic urban infrastructure investments, the aim of this study was to develop a new portfolio-based option games framework in discrete-time and to investigate the sensitivity of the optimal portfolio value to changes in both decision makers' strategic behaviour and demand and supply patterns, whilst using the real-world case of district heating network investments in the London borough of Islington. It is evident from the results that our approach has substantial potential to enhance and support long-term, strategic investment decisions by adequately valuing strategic interactions such as the ones inherent in systemic urban infrastructure investments and can be applied to a wide range of practical situations.

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