Appraising a Portfolio of Interdependent Physical and Digital Urban Infrastructure Investments: A Real Options Approach

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Abstract

Massive capital investment is required into both existing and new urban infrastructures in order to address the historically unprecedented challenges faced by many cities around the world. However, traditional methods of appraisal and evaluation are widely regarded as inadequate since they do not correctly take into account the various sources of uncertainty nor the multiple interdependencies among investment projects. In this paper we develop a new portfolio-based appraisal framework that combines a real options approach to investment under uncertainty with a mathematical modelling approach of infrastructure interdependencies. In particular, we apply the least square Monte Carlo approach to option valuation and model interdependencies among infrastructure investments to be physical, cyber, geographical, or logical. The application of the framework is illustrated through the appraisal and evaluation of a hypothetical investment into a portfolio consisting of a number of physical and digital urban infrastructure investments. We show that such an approach has enormous potential to enhance investment decisions, particularly with regard to timing, scale, and project selection, thus potentially creating significant value for investors. Future work will comprehensively evaluate the comparative performance of the conventional and new approach under a wide range of real-world case studies.

Keywords: Real options analysis, Urban infrastructure systems, Capital budgeting, Least Squares Monte-Carlo, Infrastructure interdependency

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1. Extended abstract

1.1. Background

Today’s cities face historically unprecedented challenges in managing their transition towards a sustainable, low-carbon future. In order to address present and future urban challenges, massive capital investment is required in both existing and new infrastructure systems in the so-called “urban silos” comprising energy, transport, water, waste, ICT, real estate, and others (Della Croce, 2012). It has been estimated that cumulative investments of at least USD 40 trillion will be required globally during the period 2005-2030 (Doshi et al., 2007; Ottesen, 2011) to modernise existing and build new urban infrastructures. These include investments in electricity systems (generation, transmission, and distribution), sewage treatment plants, public transportation systems, district heating networks, telecommunication systems, and others.

Besides investing in such traditional technologies, significant investments are expected towards new technologies and services collectively known as “smart city technologies”, such as wireless sensor networks, smart meters (e.g. for electricity, water, gas, etc.), and intelligent transport systems. Pike Research (2011) forecast global investment into smart city technologies – comprising the utilities, transport, building, and government sector – to total USD 108 billion between 2010 and 2020, with annual spending forecast to reach almost USD 16 billion by 2020. In another report, BIS (2013a,b) present a market assessment of smart city solutions in water, waste, energy, transport, and assisted living, and estimate the global market for such solutions including the services required for their deployment at USD 408 billion by 2020. Yet another study (MarketsandMarkets, 2014), considering an even wider area of application additionally including building automation, healthcare, education, and security, expects the global smart cities market to grow to some USD 1,266 billion by 2019.

Regardless of the actual amount to be invested, further investments in both smart and traditional urban infrastructures will have to be made in the context of enormous uncertainties. This includes the rather “typical” investment risks related to construction, operation, as well as costs and benefits, but also a number increased risks for investors since: technologies are often new, complex and unproven; the technologies’ potential market success is generally difficult to predict; and the business case is often difficult to assess. In addition to these uncertainties and given the increasing vertical and horizontal integration of urban systems, the correct appraisal of investments into both physical and digital infrastructure will need to take into account multiple interdependencies and inter-linkages that potentially exist among systemic urban infrastructures.
1.2. Literature review

When compared with many other areas of applications, Real Options Analysis (ROA) has not been widely applied yet in the area of infrastructure investment appraisal (Garvin and Ford, 2012) and, as Gil and Beckman (2009) pointed out, applying ROA to infrastructure design “is still in its infancy”. With regard to infrastructure design, Zhao and Tseng (2003) appraised flexible design alternatives for the construction of public parking garages. Arguing with the inappropriateness of complex option valuation techniques, De Neufville et al. (2006) proposed a simple spreadsheet approach for the valuation of the flexibility incorporated in the design of a parking garage. Another early study (Gil, 2007) on infrastructure design investigated the effects of modularization – i.e. product design modularity – when assessing safeguarding investments as part of airport expansions programmes. Garvin and Cheah (2004) applied options pricing on a case study of a toll road project to comparatively evaluate the project’s economic viability under the NPV and options approach, thereby demonstrating the superiority of the latter by being able to capture strategic considerations (deferment option). A few years earlier but still considering a toll road infrastructure project, Rose (1998) valued complex interacting real options that represent contractual agreements using Monte Carlo simulation. With regard to urban systems, investments into urban transportation infrastructure have been considered by Saphores and Boarnet (2004), whose modelling approach took into account the impact of the variation of a city’s population on land rents and prices as well as on transportation costs.

In addition to the above, a number of papers have dealt with issues related to the provision and ownership of infrastructure systems. In the light of different forms of private sector participation arrangements such as PPPs, PFIs, and BOTs, Cheah and Garvin (2009) discussed the potential application of ROA in infrastructure projects, noting that such projects are (naturally or intentionally) “ripe with flexibility” with typical options being call, put, switching, timing, compound, and learning options. Ho and Liu (2002) proposed a quantitative model based on real options theory – considering both construction cost and cash flow risks – to evaluate the economic viability of privatised (BOT) infrastructure projects from the perspective of both the government and the project promoter. Having stressed the dominance of private over market risks in most infrastructure projects, Cheah and Liu (2006) investigated the case of the Malaysia-Singapore Second Crossing and therefore developed a methodology to value governmental support in BOT infrastructure projects by modelling the government guarantee as a put option and the potential repayment (i.e. a cap on the return of the private sponsor) from the private sector participant to the government as a call option. More general, Chiara et al. (2007) argued that a revenue guarantee in
a BOT infrastructure project can be modelled as a discrete-exercise real option (e.g. European, Bermudan, or Australian), while noting that currently applied valuation approaches, such as the one used by Cheah and Liu (2006), represent the government guarantee as a European styled option, thus modelling a rather “static contract”. In order to provide a more flexible way to deal with the associated revenue risk, the authors developed a novel methodology that allows the valuation of “dynamic contracts” based on Australian-style options (i.e. discrete-time American-type option) and solved by the LSMC approach. Alonso-Conde et al. (2007) applied ROA to analyse the contractual terms associated with the case of the PPP of the Melbourne CityLink Project. Krüger (2012) analysed the implications of PPP agreements on the execution of expansion options in road infrastructure.

Besides appraising investments in physical infrastructures, ROA has also been applied in the context of digital infrastructures like information technology (IT) infrastructures. One of the first attempts to link ROA and more broadly options thinking with information systems investments has been presented by Kambil et al. (1991), who recognised the growth options often embedded in such investments. Panayi and Trigeorgis (1998) applied a multi-stage (compound) real options on the case of an IT infrastructure investment faced by CYTA, the state telecommunications authority of Cyprus. Another ROA application on IT investments has been presented by Benaroch and Kaufman (1999), who argued that investments in IT infrastructures generally do not result in immediate expected paybacks, but rather can provide the basis for profitable future investment opportunities. Miller et al. (2004) applied ROA to evaluate the “Korean Information superhighway infrastructure” investment project. Benaroch (2002) stated that real options generally must be intentionally planned in an IT investment project, instead of being “inherently” embedded, and mainly focused on how ROA may be applied to manage the risks involved – particularly functionality and organisational ones – in an IT investment project. Furthermore, the author claimed that there currently exists a number of gaps between real options theory and what is required to adequately model and appraise real-world IT investments. One of these, the need to formulate and model a “custom-tailored analytical valuation model” in situations with more than two sources of risk involved concurrently, has been tackled by Kumar (2004). The author developed a novel general framework based on the “asset valuation” literature to evaluate IT infrastructure investments in the light of multiple sources of uncertainty.

Several attempts have been made in the last two decades to introduce the notion of “interdependency” into real options models, with approaches focusing on either single projects or portfolios of projects. With regard to single projects, Trigeorgis (1995) reviewed the literature and noted that the recent recognition of real options
interdependencies (i.e. when values of multiple real options interact), has the potential to widen the applicability of ROA to many practical situations. Wang and De Neufville (2005) stated that real options “on” projects do usually not feature interdependencies, whereas real option “in” projects are complex and interdependent, often even highly interdependent/path-dependent, which rapidly increases the associated computational costs; see the earlier paper (Wang and De Neufville, 2004) by the same authors. One of the first attempts to overcome the restriction to single investments was presented by Childs et al. (1998), who considered a firm that has the opportunity to invest in two (mutually exclusive) projects, more precisely in their development stage, but then only select a single project for implementation.

In the light of these challenges, ROA applied on a portfolio of possibly interdependent projects has recently been considered in a number of fields of application including energy (e.g. Wang and Min (2006) for electric power generation planning) and the pharmaceutical industry (e.g. Zapata and Reklaitis (2010) for R&D portfolio). However, it appears that particularly applications to portfolios of IT investment projects have received considerable attention by academics. For example, Bardhan et al. (2004) modelled a portfolio of IT investment projects, each of which embedding a single option, and proposed a real options portfolio optimisation algorithm that can be used to both prioritise projects and make optimal funding decisions for these projects given limited resources. As an extension to Bardhan et al. (2004), Bardhan et al. (2006) took into account time-wise project interdependencies and formulated the portfolio optimisation problem as a mixed integer programming model. Based on the MAD assumption and a binomial lattice approach, Pendharkar (2010) developed a real options model that includes cash flow interdependencies amongst multi-stage IT investment projects. Generalising his own model to enable an application to more than the earlier considered two projects, Pendharkar (2014) proposed a decision-making framework to value an IT project portfolio containing project interdependencies and subsequently solved, as the author claimed, “easily” a project selection problem of 60 dependent projects.

However, all the above cited publications consider only one type of project interdependency (almost always cash flow interdependencies), one type of option available (e.g. a compound call option), and a very limited number of independent uncertainties (e.g. market and technological ones), whilst addressing capital budgeting situations in one specific field (e.g. R&D or IT investments). Yet the correct appraisal of

\[1\] Existence of a traded replicated portfolio is unnecessary (Borison, 2005), since the NPV of the investment project without flexibility “is the best unbiased estimate of the project were it a traded asset” (Copeland and Antikarov, 2001).
a portfolio of interdependent urban infrastructure investments – potentially located in different urban silos, e.g. energy, transport, water, waste, ICT, etc. – necessitates an alternative and more general approach. The approach we have used in this study aims to overcome the limitations of earlier approaches by taking into account four types of interdependencies (physical, cyber, geographical, and logical\(^2\)), many embedded real options, and various sources of uncertainty.

1.3. Methods

There are several limitations inherent to ROA when used in a portfolio context, particularly path-dependency of options, curse of dimensionality, and combinatorial burden (Zapata and Reklaitis, 2010). In order to overcome these limitations, a number of further developments have been proposed in the academic literature. Some of these combine Monte Carlo simulation, introduced to the pricing of European call options by Boyle (1977), with dynamic programming in order to value American (e.g. Barraquand and Martineau, 1995; Broadie and Glasserman, 1997) and Asian (e.g. Broadie and Glasserman, 1996) styled options; Boyle et al. (1997) provided an overview of recent developments. Despite adding computational complexity, Monte Carlo techniques have significant advantages over traditional option pricing techniques such as analytical and lattice-based methods since they allow the consideration of multiple sources of risk and stochastic variables, multiple underlying assets, real options with complex features, etc. (Pringles et al., 2015).

The practical valuation approach for American options called “Least Squares Monte Carlo” (LSM) method, proposed by Longstaff and Schwartz (2001), has gained considerably attention from researchers in the last few years. Combining least-square regression used to approximate the conditional expectation function of the dynamic programming problem with Monte Carlo simulation of random variables’ evolution over time, the LSMC method is a simple and efficient numerical technique that can be applied to value complex and compound options, such as multidimensional American real options (Cortazar et al., 2008; Pringles et al., 2015). Besides being used to efficiently value American options, the LSMC method can also be applied to value complex real capital investments with many, possibly interacting, embedded real options and in situations with multiple uncertain state variables (Abdel Sabour and Poulin, 2006). The method has been recently assessed and analysed in detail by Stentoft (2004a,b), confirming its computational advantages over other existing numerical methods.

\(^2\)See Ouyang (2014) for a recent review of infrastructure interdependencies.
The real option valuation method applied in this study is based on the framework presented by Chiara et al. (2007), who, similar to Meinshausen and Hambly (2004), expanded the LSM method to the valuation of multiple-exercise real options.

With regard to the interdependencies among different investment projects, i.e. underlying assets, we consider the four interdependency types first defined by Rinaldi et al. (2001) and then modelled by Rinaldi (2004). These interdependencies are: physical, cyber, geographic, and logical. The mathematical modelling of these interdependencies is done via both interdependency matrices that affect an investment’s contribution to the objective function and constraints that affect the optimisation problem’s feasible region. In both cases, the actual effect of the modelled interdependencies depends on the state of each investment project.

The approach is illustrated by applying it to a portfolio of several hypothetical urban infrastructure investments.

The results clearly demonstrate that certain investment risks can be mitigated through making use of both a pro-active approach to risk management and the interdependencies among the considered physical and digital urban infrastructure investments. Furthermore, applying such a portfolio approach generally results in a higher optimal value than applying single investment appraisal strategies or portfolio approaches which do not explicitly consider (multiple) infrastructure interdependencies.

References


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