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Optimal seismic upgrade timing of seaports in high-capital cost and high-throughput growth environments using a real options approach[1]

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1 INTRODUCTION & SCOPE OF WORK

Container seaports are critical nodes in most of the contemporary globalized supply chains (e.g. *Zhang and Lam 2016*) as well as important drivers of regional economies (e.g. *Lam and Su 2015*) since more than 80% of world-wide trade is seaborne. Further, they constitute critical lifelines supporting the resiliency of local communities in the aftermath of natural disasters such as earthquakes (e.g., *Chang 2010*). Therefore, structural upgrading of the most seismically vulnerable seaport infrastructure facilities such as cranes, wharves, and quay walls (e.g. *Pachakis and Kiremidjian 2004*) is a necessary step to increase the resilience of local communities to the earthquake hazard in seismically prone areas and to minimize the risk of earthquake-induced downtime to seaport operations (e.g. *Burden et al, 2016*) which may impact large-scale maritime transportation networks. Seaport demands for increasing resilience is concurrent with demands to accommodate the continuously increasing seaborne trade throughput. The latter are particularly intense in seaports of developing countries as they are vital in supporting national economic growth as well as the ever-expanding global supply chains.

In view of the above demands, there is a clear practical benefit to delay undertaking seismic upgrading of seaport facilities until the next capacity expansion investment, typically involving strengthening, deepening, and/or extending berth quay walls and wharf foundations, in order to save on mobilization costs and to minimize on operational disruptions. On the other hand, postponing these investments increases the potential revenue loss due to downtime after a future earthquake which is known to be much more significant in seaports compared to the repair cost (*Burden et al, 2016*). In developing countries, operating in a high growth and high cost of capital financial environment (*e.g. Canada et al, 2004*), potential seismic loss due to downtime becomes more significant in time as cargo-related revenues may increase significant annually. In this context, port stakeholders are faced with the question of when is the most opportune time to seismically upgrade an existing seaport facility exposed to some regional seismic hazard so that the loss (due to structural damage and downtime) for a pre-defined seismic hazard is below a material significance threshold. Existing approaches in the relevant literature addressing this question are only applicable to the case of structures and infrastructure that do not accrue time-dependent revenues, i.e. loss of revenue due to business interruption is time-invariant, which typically leads to a trivial answer to the question at hand: either invest on seismic upgrading now or never (see e.g., *Nuti and Vanzi 2003*). Recently, the authors (*Savvidis et al, 2019*) developed a novel real options (RO) based approach treating the opportunity to invest on seaport seismic upgrade every year as an

[1] This is an extended abstract of the work reported in *Savvidis et al. (2019).*
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option associated with a profit/payoff, while also accounting for changes in business interruption loss in line with increasing cargo throughput demand. The approach is only briefly presented in this extended abstract. For technical details the interested reader is referred to *Savvidis et al. (2019)*. Major research outcomes and conclusions, partially supported by selective numerical results pertaining to a case-study of a seaport authority operating in a developing country, are herein summarized.

2 METHODOLOGY

In stock markets, an option is the right, but not the obligation, to buy or to sell a number of stocks at a certain pre-defined price anytime in between present time and an expiration date (*Luenberger 1998*). In this setting, rigorous mathematical approaches have been developed in the past four decades to price options in an uncertain market environment to facilitate investors on decision making about the timing to exercise (or not) a financial option. Consequently, the concept of the financial option migrated to decision-making under uncertainty in engineering problems where an option involves taking (or postponing) a decision on a "real" action which yields a certain payoff (e.g., *Trigeorgis and Reuer 2017*).

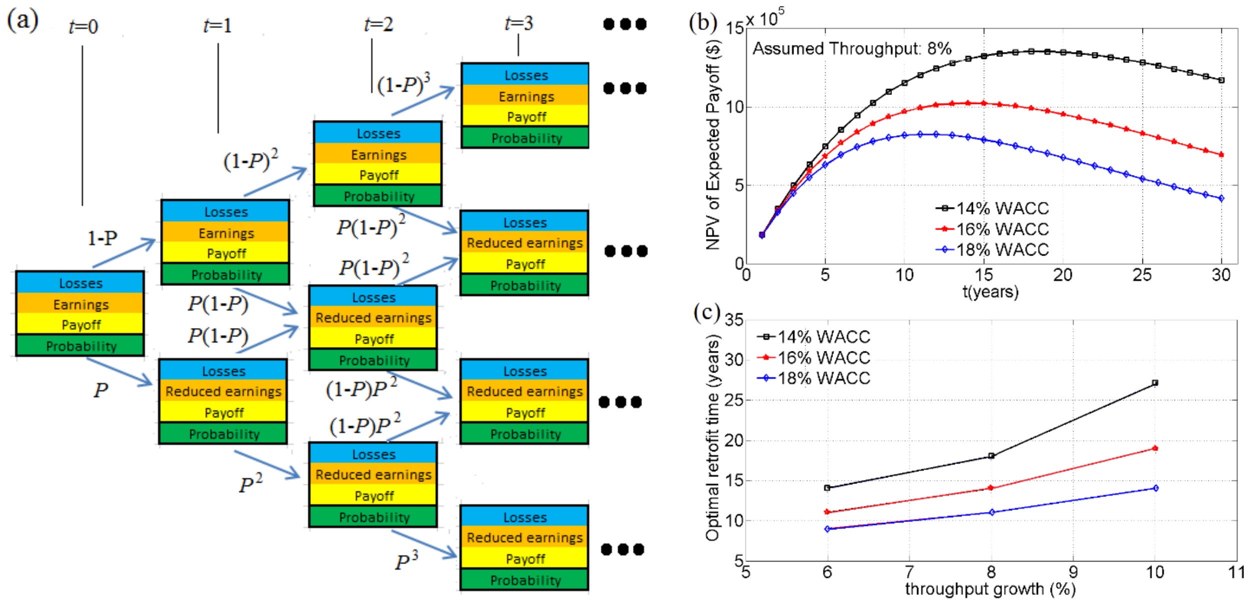

Figure 1. *(a) Considered real options binomial tree; (b) NPV of expected payoff for a seaport authority case-study in developing market with throughput growth rate 8%; (c) Optimal seismic upgrade time for the same case-study as function of throughput growth rate and for various WACC values (Savvidis et al, 2019).*

In this regard, consider an existing seaport experiencing a constant throughput growth in each future year, t, leading to increased annual earnings. It is of interest to examine the case in which decision makers have the option (or the design/managerial flexibility) to upgrade the seismic performance of certain vital engineered facilities in a future year. The problem is formulated in discrete-time by considering a RO binomial lattice (tree) supporting a computationally simple spreadsheet-based solution approach following standard RO solution strategies (*e.g. De Neufville et al, 2006*) as depicted in Figure 1(a). In the proposed RO formulation, the payoff of the option to invest on seismic upgrading in year t is evaluated accounting for earthquake loss separately due to repair cost and downtime caused by one (or more) reference seismic event having a specific annual probability of occurrence, P. This reference seismic event is pre-specified in a rationalized manner either by making use of loss curves derived from full-fledged probabilistic seismic loss analysis (e.g. *Burden et al 2016*) or by adopting a site-specific seismic hazard curve. The memoryless Poisson temporal distribution, commonly adopted in seismic risk analysis (*McGuire 2004*), is adopted to propagate the probability of one or more seismic events to occur every year as shown in Figure 1(a). Further, a series of simplified yet realistic assumptions are adopted to compute yearly seaport earnings, based exclusively on the number of containers handled per year, and reduced earnings in case of a reference seismic event incurring some downtime and, therefore, reduced number of handled containers in the year of the earthquake occurrence. The expected option payoff is computed in year t as the sum of all different possible scenarios (cells in the tree of Figure 1(a) for a given year t) weighted by the probability of each scenario occurring. Lastly, the optimal time for seismic upgrade is defined as the year at which the net present value (NPV) of the expected option payoff is maximized.

Importantly, in computing this NPV, the weighted average cost of capital (WACC) is used as a discounting factor which, for the case of developing countries, is quite high, due to high market risks (*Canada et al, 2004*).

3 RESEARCH OUTCOMES

The herein discussed RO formulation contributes a useful tool in the decision-making process for seaport seismic upgrading by decoupling the type/level of seismic retrofit from the problem of the upgrade timing. Additionally, it allows for quantifying systematically the influence of different factors to the seismic upgrade timing. To this end, *Savvidis et al (2019)* undertook comprehensive sensitivity analyses with respect to the assumed downtime, growth throughput rate, initial seaport asset value and WACC demonstrating that the economic factors (growth rate and cost of capital, WACC), overshadow the engineering-related factors (total asset value, downtime, retrofit and repair costs), in the determination of the optimal seismic upgrade time. The usefulness and applicability of the developed approach is illustrated by application to typical scenario cases of ports and terminals in economic environments ranging from low growth-low cost of capital to high growth, high cost of capital. It is found that in low interest rate regimes, typical of developed economies, the NPV of the expected payoff increases significantly in later years, providing a stronger incentive to postpone the retrofit decision: the "kick the can down the road" strategy of risk mitigation is more appealing. However, in a high growth, high cost of capital economy (reflecting an emerging market economy in a developing country) the optimal time to retrofit appears early on. Figures 1(b) and 1(c) furnish typical results for a most critical case-study of a seaport authority in a developing market assuming various (high) throughput growth values and various (high) WACC values. Consistently, the optimal time to retrofit increases as the throughput growth rate increases and the cost of capital decreases.

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