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Optimal seismic upgrade timing in seaports with increasing throughput demand via real options

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ABSTRACT

A real options (RO) formulation is proposed for decision-making on the timing to upgrade the seismic performance of existing seaports with increasing throughput demand in earthquake prone areas. The pay-off of the seismic upgrade investment option is estimated based on projected net earnings, repair cost, and downtime for a damaging reference seismic event having a pre-specified annual probability of occurrence. These projections inform a discrete-time RO binomial tree, following the American option valuation framework, which propagates the probability of the reference seismic event assuming Poisson temporal distribution of earthquake occurrence. The net present value of the expected annual payoff of the considered investment is used as an index supporting risk-informed decision-making discounted by the weighted average cost of capital (WACC). Numerical examples pertaining to decision makers with different capital cost, namely port authorities and terminal operators, operating in different economic environments typical of developed and developing countries are furnished to illustrate the applicability of the proposed RO formulation. It is found that high WACC and/or low throughput growth bring the optimal seismic upgrade timing forward, while earthquake consequences and upgrade cost have almost no influence on this timing.

Keywords: real options; seaport terminals; seismic hazard; binomial tree; seismic upgrade.

Introduction and motivation

Maritime transport is the dominant mode of cross-border trade that many countries rely on worldwide, since more than 80% of the World trade volume is seaborne (UN, 2015). In this regard, seaports are critical nodes not only in marine transportation networks (MTNs) but in most of the contemporary globalized supply chains serving as gateways of MTNs to in-land transportation networks (e.g., Flynn *et al* 2011, Zhang and Lam 2016). Therefore, even a partial loss of cargo throughput capacity in a single seaport due to a (local) natural disaster can cause disproportionally high disruptions to global MTNs and local supply chains (e.g., Berle *et al* 2011, Omer *et al* 2012). At the same time, seaports are also important drivers of regional/National economies (e.g., Lam and Su 2015) while they constitute important lifelines supporting the resilience (i.e. ability to recover after a disaster) of local communities (e.g., Chang 2010, Stevenson *et al* 2011).

All the above aspects are particularly pertinent to seaports exposed to seismic hazard. Indeed, major seismic events can cause significant damage to seaport engineered structures such as cranes, wharves, and quay walls, which enable cargo handling and vessel docking (see e.g., Pachakis and Kiremidjian 2004, Na and Shinozuka 2009, Shafieezadeh and Burden 2014). These structures have particularly high replacement costs and require considerable repair downtime in the aftermath of destructive earthquakes. For example, the Seventh Street Terminal in the Port of Oakland remained closed for 6 months following the Loma Prieta earthquake in North California (1989), while repairing the 922m-long damaged wharf costed $14 million and took almost 23 months to complete as reported by Fotinos *et al* (1992). Importantly, such appreciable downtime entails significant revenue losses to the seaport and to the local economy, on top of the direct seismic repair costs, since they result to reduced, if not complete loss of, cargo throughput capacity. For instance, the estimated repair cost of the Port of Kobe in the aftermath of the Hyogoken Nanbu (Kobe) earthquake (1995) was amounted to about $5.5 billion while reported losses to the local port-related businesses due to loss/reduced operations were estimated to $6 billion in the first 9 months after the earthquake as reported by Werner *et al* (1997). Moreover, in the case of large high-throughput seaports, several of which are located in medium-to-high seismicity regions along the West coast of US (Scharks *et al* 2014) and in East Asia (Lam and Su 2015), throughput capacity reductions due to earthquakes can result to further financial losses due to disruption to various National and International/global MTNs and supply chains, while the unavoidable post-earthquake vessel re-routing can eventually have long-term/ permanent consequences to the seismically damaged seaport and to the local/National economy (Peng *et al* 2016). As an illustration, the Port of Kobe was ranked 6th in the World at the time of the Hyogoken Nanbu (1995) earthquake in terms of cargo throughput, and never recovered this position post-earthquake as discussed by Chang (2000). Lastly, even the relatively low throughput capacity seaports, whose loss of functionality may not be detrimental to global supply chains, are still critical for the resilience of the local communities in the aftermath of seismic events. Recent examples, are the Lyttelton, Port of Christchurch, which remained operational to a large extend following the Christchurch (2011) earthquake and significantly facilitated recovery efforts as reported by Stevenson *et al* (2011), whereas, on the antipode, both terminals of the Port-Au-Prince seaport suffered significant damaged during the Haiti (2010) earthquake rendering an important lifeline of the country non-functional at the time when it was mostly needed as discussed by Bono and Gutierrez (2011).

In this respect, undertaking local seismic upgrades of the most vulnerable and least resilient infrastructure identified in a seaport, that is quay walls and foundations of wharves and cranes, is a necessary step to increase the resilience of local communities to the earthquake hazard and to minimize earthquake-induced losses to seaport operations (see e.g., Werner *et al* 1997, Na and Shinozuka 2009, Shafieezadeh and Burden 2014), while being a robust strategy to achieve resilience of MTNs to the earthquake hazard (Peng *et al* 2016). The latter consideration is particularly pertinent in an environment of continuously increasing seaborne trading demand in which MTNs become more important every year for global supply chains (UN 2015, Lam and Su 2015). More importantly, within such an environment there is an opportunity to combine seismic structural upgrades with investments to increase the seaport capacity to meet increased throughput demands. In typical medium-to-large capacity seaports, the latter investments are commonly undertaken every 20 years or so and involve strengthening, deepening, and/or extending berth quay walls and wharf foundations, that is, the same key infrastructure at container terminals that are known to be the most seismically vulnerable (see e.g., Na and Shinozuka 2009, Scharks *et al* 2014, Shafieezadeh and Burden 2014, Burden *et al* 2016). Such investments involve high capital costs and can cause partial temporary operational disruption in the terminal operation. In this respect, there is a clear practical benefit to delay undertaking seismic upgrades/retrofits until the next throughput capacity expansion. On the other hand, postponing these investments increases the anticipated revenue losses due to downtime caused by a future strong earthquake as trade traffic increases yearly (UN 2015).

In this context, pertinent stakeholders and decision makers (i.e., port authorities, terminal operators, government agencies, etc.) are faced with the practical question of *when is the most opportune time to seismically upgrade an existing seaport exposed to some regional seismic hazard* such that earthquake loss (due to structural damage and downtime) for a nominal seismic shaking intensity or, similarly, the risk of sustaining earthquake loss having a nominal mean annual probability of exceedance are below a material significance threshold. This work aims to facilitate an informed response to the above question by casting the problem at hand within the so-called “American option” valuation framework (see e.g., Luenberger 1998, Herder *et al* 2011). In a nutshell, the proposed real option (RO) formulation treats the opportunity to invest on seaport seismic upgrade every year as an *option* associated with a particular *value*. It then uses a series of simplification assumptions to evaluate this option, accounting for earthquake loss due to a reference seismic event having a specific annual probability of occurrence. Notably, the developed RO formulation accounts for changes in earthquake loss in line with increasing cargo throughput demand: this is an important consideration for the problem at hand, since the largest portion of earthquake loss in seaports is due to downtime (i.e., business interruption) rather than to repair cost (see e.g., Na and Shinozuka 2009, Shafieezadeh and Burden 2014, Burden *et al* 2016). The conceived RO formulation is solved in discrete-time by considering a simple lattice (tree)-based approach. Conveniently, by relying on the widely-used in seismic hazard and risk analysis memoryless Poisson process assumption to model the temporal occurrence of the reference seismic event (e.g., McGuire 2004, Pachakis and Kiremidjian 2005), a simple discrete-time binomial tree, which is almost exclusively assumed in (real) options pricing (e.g., Cox *et al* 1979, Brandao *et al* 2005, De Neufville *et al* 2006) suffices to solve the RO problem at hand.

Previous related studies and novel considerations

Whilst various RO-based approaches have been proposed in the literature to facilitate decision-making for critical infrastructure investments under uncertainty in the energy sector (Thomas and Chrysanthou 2012), in road transportation networks (Power *et al* 2015), and in seaports (not in earthquake prone areas) (Taneja *et al* 2010), to the best of the authors' knowledge, it is the first time that RO analysis is considered to inform decisions on seismic upgrade of infrastructure exposed to the earthquake hazard. Indeed, standard cost-benefit analysis (CBA), sometimes supported by lifecycle cost considerations, is most often used financial analysis tool to address the questions of whether to undertake seismic retrofit, replace, or do nothing for a given structure (or a specific class of structures), and which type and/or target performance of retrofitting strategy should be adopted in doing so, out of a number of possible choices (e.g., Smyth *et al* 2004, Kappos and Dimitrakopoulos 2008, Chiu *et al* 2013, Liel and Deierlein 2013). This is typically achieved by first integrating local seismic hazard curves with pertinent fragility curves of the current/existing and of the seismically upgraded structure upon application of different retrofitting methods. Next, the most economically viable, if any, retrofitting strategy is chosen as the one that maximizes the net present value (NPV) of benefits over costs, as considered by Kappos and Dimitrakopoulos (2008), or the one that minimizes the NPV net costs over the lifetime of the structure as taken by Chiu *et al* (2013). In this context, a recent application of CBA on seismic retrofit decisions for the Port of Portland is reported by McMahon *et al* (2016) and Graf *et al* (2016), which compares seaport reduction in annual losses (annual benefit) with and without seismic retrofit for various seismic intensity levels. The sum of the annualized benefits for all hazard levels is then discounted and divided by the retrofit or replacement cost for each option to form the benefit-cost ratio. Further, Taylor *et al* (2016) lists a number of actual seaport-related seismic risk evaluation and mitigation studies in which various mean-variance criterion based approaches have been considered in conjunction with CBA to account for the statistical variability of net costs and/or benefits in the decision-making process. Moreover, Caterino *et al* (2008) used multi-criteria decision making tools to appraise the optimal retrofitting strategy for a given structure in cases of conflicting cost-benefit criteria representing trade-offs.

Despite their appropriateness to inform decisions on economically viable seismic upgrade solutions and prioritization of funding allocation to undertake seismic upgrading, none of the above financial tools and approaches aimed to provide for the optimal timing of undertaking a pre-specified seismic upgrading to bring an existing (seaport) structured facility to a particular/target level of seismic performance. The latter aim has been addressed by Nuti and Vanzi (2003) based on an analytical expression derived for the equivalent annual cost (EAC) of seismic upgrading as a function of the future time that retrofit takes place. In theory, a local minimum of the EAC in time provides an optimal timing for seismic upgrading under the various assumptions made in deriving the EAC including memoryless (Poisson) process to model the temporal distribution of exceedances of a given limit state of the structure. However, it is found that the EAC is either monotonically increasing or decreasing, which leads to the trivial timing solutions of either retrofit at present time or never (Nuti and Vanzi 2003). More recently, Bradley et al. (2009) defined analytically the point (year) in time that a particular seismic upgrade solution becomes economically neutral and proposed this timing to be a criterion to decide on competitive retrofitting solutions to be undertaken at present time. This critical time is defined as the year when the NPVs of the expected annual loss, computed through probabilistic seismic loss analyses (see e.g., Porter *et al* 2004), of the upgraded structure and the existing structure become equal. Clearly, this critical time is not the optimal (future) time for a given seismic upgrade to be undertaken such that potential benefits are maximized.

Collectively, all the above reviewed non-RO studies treat the case of structures and infrastructure that do not accrue time-dependent revenues which, in practice, means that loss of revenue due to business interruption are stationary (time-invariant). In this regard, the problem of finding an optimal seismic upgrade time/year, if there is one, in a regime of increasing operational revenues for a certain *a priori* decided (e.g., based on CBA) retrofit strategy has not been addressed. As previously discussed, determining such a point in time in a rational and systematic manner for any (given) seismic retrofitting strategy is of significant practical importance for seaport authorities as well as for terminal operators. To this end, the herein proposed RO formulation contributes a novel tool filling a niche gap in the overall decision-making process for seaport seismic risk mitigation. Notably, this tool facilitates decoupling the type/level of seismic retrofit from the problem of the timing that this retrofit should take place. In this manner, it allows for studying the influence of economic factors which are uncorrelated to seismicity and structural vulnerability, such as throughput traffic growth in cargo seaport facilities and cost of capital (i.e., the NPV discount rate). In fact, in the numerical part of this work, it is shown that such factors influence most the optimal timing of seismic upgrading which, contrary to the case of EAC considered by Nuti and Vanzi (2003), turns out to have a non-trivial solution for certain economic environments and/or decision-makers.

Definitions and assumptions

Seaport revenue and earnings model

Container seaports can be seen as complex engineered systems comprising several different types of infrastructure such as quay walls, wharves, cranes, warehouses, and gates. These components enable various inter-related operations associated with container loading and unloading to and from vessels, storage, and movement within the seaport premises (see e.g. Na and Shinozuka 2009, Burden *et al* 2016 and references therein). Such seaports benefit from numerous types of revenues collected in the form of port dues (e.g., Pachakis and Kiremidjian 2004). For the purposes of this work, the total cargo-related revenues are assumed to be proportional to the wharfage fee collected for every twenty-foot equivalent container unit (TEU) loaded and discharged to and from a vessel. In this manner, throughput capacity in terms of TEUs can be related to seaport revenues in a straightforward manner. It is further assumed that there is an increase in the annual seaport throughput volume T (i.e., in the number of TEUs handled per year) by a throughput growth rate, g, in alignment with the increase to global seaborne trade demands (UN 2015). Therefore, the throughput at a given year t is written as

$$T(t)=T(t-1)\big(1+g(t)\big) \tag{1}$$

where $g(t)$ is in percentage applicable to year t. Further, the total annual seaport revenues $I(t)$ can be expressed in terms of the TEU throughput as

$$I(t)=\frac{T(t)\,f}{q} \tag{2}$$

where f is the fee collected for every TEU handled, and q is the portion of the wharfage contribution to the total cargo-related revenues. The seaport net earnings in year t are computed as

$$E(t)=I(t)-CO(t)-CM(t) \tag{3}$$

where $CO(t)$ and $CM(t)$ are the operational cost and the maintenance cost during the considered year, respectively. Under the above assumptions, Eqs. (1)-(3) can be used to calculate in discrete time (yearly increments) the seaport earnings at any future year t, provided that no earthquake-induced damage takes place.

Consider now the scenario that the seaport sustains earthquake-induced damage in a particular year t. Then reduced earnings ER are accrued in that year given by

$$ER(t)=(1-D)E(t) \tag{4}$$

where D is an equivalent downtime as a portion of the year duration during which no TEU handling occurs (e.g., D=0.5 in case of 6 months of equivalent downtime). On the year of earthquake damage, a reduced throughput volume TR is observed equal to

$$TR(t)=(1-D)T(t)=(1-D)T(t-1)(1+g)\,. \tag{5}$$

Furthermore, the associated net losses L in that year are estimated as the sum of the lost net earnings due to downtime plus the repair/replacement cost CR of the damaged seaport structures and infrastructure, that is,

$$L(t)=E(t)D+CR\,. \tag{6}$$

The RO formulation presented later makes use of Eqs. (4)-(6) to account for the consequences of earthquake damage in year t . These expressions are applicable for any level of damage expressed in terms of repair cost, CR, and downtime,

D values. Consequently, these values depend on the seismic hazard of the seaport site and on the seismic vulnerability of key seaport infrastructure facilities such as the berths and the cranes. The next two sections elaborate on two different approaches supporting practically meaningful determination of CR and D (i.e., earthquake consequences) associated with a *reference seismic event*. Note that risk to life is not accounted for throughout this work since typical quayside port structures have very low occupancy and, therefore, this risk is negligible.

Earthquake consequences using seismic loss curves (top-down approach)

A first viable "top-down" approach to determine earthquake consequences for a given seaport within a probabilistic context is made possible through the availability of physical damage (i.e., repair cost CR) and of business interruption (i.e., downtime D) seaport loss curves. These curves provide the mean annual frequency (MAF) that a particular repair cost value and a particular downtime value are exceeded; they are mathematically expressed as

$$\lambda_{CR}\left(cr\right)=\int_{rr}\int_{dm}\int_{edp}\int_{im}G\left(cr|rr\right)\left|dG\left(rr|dm\right)\right|\left|dG\left(dm|edp\right)\right|\left|dG\left(edp|im\right)\right|\left|d\lambda_{IM}\left(im\right)\right| \qquad (7)$$

and

$$\lambda_{D}\left(d\right)=\int_{rr}\int_{dm}\int_{edp}\int_{im}G\left(d|rr\right)\left|dG\left(rr|dm\right)\right|\left|dG\left(dm|edp\right)\right|\left|dG\left(edp|im\right)\right|\left|d\lambda_{IM}\left(im\right)\right| \ , \qquad (8)$$

respectively, within the performance-based earthquake engineering risk assessment framework for ports developed by Burden *et al* (2016). In the last two equations, $\lambda_X(x)$ denotes the MAF of the event $\{X>x\}$, that is the random variable X exceeds a particular value x, $G(u|v)=Pr(U>u|V=v)$ denotes the conditional complementary cumulative distribution function signifying the probability of the event $\{U>u\}$ given the event $\{V=v\}$, *im* denotes an intensity measure of an earthquake (e.g., peak ground acceleration), *edp* is an engineering demand parameter representing a measurable structural response to an earthquake (e.g., peak deformation of a critical member in a seaport structured facility/component), *dm* is a damage measure converting the *edp* of choice to a quantifiable damage state commonly done through component-specific fragility curves (e.g., Na and Shinozuka 2009, Shafieezadeh and Burden 2014), and *rr* represents component-specific repair requirements due to a sustained *dm*. Equations (7) and (8) make use of the total probability theorem to "propagate" the seismic hazard curve λ_{IM} derived from site-specific probabilistic seismic hazard analysis (PSHA) (e.g, McGuire 2004) to the loss curves λ_{CR} and λ_D. Derivation of loss curves for a given seaport falls beyond the scope of this work (see e.g., Burden *et al* 2016 for illustrative example and discussion). However, it is important to note that the herein developed approach requires loss curves λ_{CR} and λ_D be constructed separately since seaport revenue loss due to downtime is time/year dependent being heavily influenced by the growth rate g of the throughput in Eq.(1). Conveniently, this requirement is facilitated through the concept of the *rr* introduced by Burden *et al* (2016) as duration of repair time for port components based on which cost of repair, *CR*, and downtime, *D*, of the seaport system in Eqs. (6) and (4), respectively, can be estimated individually.

Given loss curves in Eqs. (7) and (8) for an existing seaport, a decision-maker can select the *reference seismic event* that they want to retrofit/upgrade for defined through a pair of minimum unacceptable repair cost and downtime threshold values (cr^*, d^*) having a particular MAF λ_{CRD} to be exceeded. It is acknowledged that this selection depends on the decision maker risk tolerance profile against repair cost and downtime separately, though decision will be mostly dominated by downtime since this is by far most significant contributor to total seismic loss. It is further acknowledged that cr^* and d^* may not correspond to the same seismic event intensity, while $\lambda_{CR}(cr^*)$ may be different from $\lambda_D(d^*)$. To address the above issues in a practical manner, it is herein suggested that a single MAF corresponding to the reference seismic event is conservatively defined as

$$\lambda_{CRD} = \max\left\{\lambda_{CR}\left(cr^*\right), \lambda_D\left(d^*\right)\right\} \ . \tag{9}$$

In this regard, the reference seismic event in the considered top-down approach is defined by the minimum unacceptable earthquake consequences $CR=cr^*$ and $D=d^*$ in Eqs. (6) and (4), respectively, and by the MAF in Eq.(9) based on seismic loss curves in Eqs. (7) and (8).

Earthquake consequences based on a nominal earthquake intensity level (bottom-up approach)

Starting from the site seismic hazard curve, λ_{IM}, an alternative approach can be devised to determine a reference seismic event for seaport seismic upgrade with MAF $\lambda_{IM}(im^*)$ where im^* is as a site-specific seismic intensity threshold having certain probability to be exceeded in a certain time-span. For example, im^* can be taken equal to the peak ground acceleration with 10% probability of exceedance in 50 years. Notably, this “bottom-up” approach to select the reference seismic event may be mostly appealing to practicing engineers since the concept of design verification to specific levels of seismic intensity, as the one defined above, is embedded in seismic design codes for seaport facilities (e.g. PIANC 2001, ASCE 2014). Further, the time-span in the definition of im^* can be adjusted to make it more relevant to the decision maker planning period as discussed by Porter *et al* (2004) for the case of investors in real estate. Accordingly, probability of exceedance can also be adjusted to leverage the intensity of the reference seismic event. In this setting, earthquake consequences in Eqs. (6) and (4) can be mathematically defined through conditional mean values

$$CR = E\left\{cr \middle| IM \geq im^*\right\} = \int_{cr}\int_{rr}\int_{dm}\int_{edp}\int_{im} cr \; dF\left(cr|rr\right)dF\left(rr|dm\right)dF\left(dm|edp\right)dF\left(edp|im\right)dG\left(im\right) \tag{10}$$

and

$$D = E\left\{d \middle| IM \geq im^*\right\} = \int_{d}\int_{rr}\int_{dm}\int_{edp}\int_{im} d \; dF\left(d|rr\right)dF\left(rr|dm\right)dF\left(dm|edp\right)dF\left(edp|im\right)dG\left(im\right) . \tag{11}$$

In the last two equations, $\mathrm{E}\{\cdot\}$ is the mathematical expectation operator, and *F(X)* denotes the cumulative distribution function of random variable *X*. Computation of the conditional loss estimation integrals in Eqs. (10) and (11) is not addressed in this work; the interested reader is referred to McGuire (2004) for pertinent discussion and applications. Suffice it to say that the above integrals are converging and finite since repair cost and downtime are bounded within a materiality threshold (minimum significant losses and downtime) and complete reconstruction/replacement cost and time while the hazard curve is monotonically decreasing and bounded by the regional seismicity.

Temporal occurrence of reference seismic event

For the purposes of this work, *the binomial distribution* is adopted to model the annual probability of occurrence of the reference seismic event, defined by either one of the previously discussed approaches, facilitating the discrete-time RO formulation and solution developed in the following section. Note that the binomial distribution converges to the Poisson distribution, which is widely assumed in the relevant literature in conjunction with outcomes of PSHA to model the temporal occurrence of seismic events, for very low probability events such as the probability that the reference seismic event happens in one year time-span. Therefore, by adopting the Poisson distribution assumption for temporal earthquake occurrence, the reference seismic event has an annual probability of occurrence

$$P = 1 - \exp\left(-\lambda\right), \tag{12}$$

where $\lambda = \lambda_{CRD}$ in Eq.(9) if reference seismic event is defined using seismic loss curves (top-down approach) or $\lambda = \lambda_{IM}(im^*)$ if reference seismic event is defined by means of a nominal earthquake shaking level having a specific probability to be exceeded in a given time-span (bottom-up approach). The use of λ_{CRD} value in Eq.(12) is justified by the fact that any arrival process of a consequence-indicator random variable *X* (such as repair cost, downtime etc.) with MAF λ_x derived from a seismic hazard curve λ_{IM} via a cascade of relationships of the type $\lambda_x = \Pr(x|im)\,\lambda_{IM}$, are Poisson. This property follows from combining and splitting Poisson processes as discussed in the standard texts of Parzen (1999) and Ross (2014).

Based on all above definitions and assumptions, a year-to-year discrete binomial lattice is constructed following the RO formulation detailed in the next section to address the problem of finding the optimal time to invest in a pre-defined structural upgrade achieving operational performance level of an existing seaport system against the reference seismic event (or *full protection* against the reference seismic event as defined by Avramidis *et al* 2016). Further comments and discussion on the selection of the reference seismic event are provided following the RO formulation.

Methodology of the real options (RO) approach

Stock options and real options

In the field of financial investment valuation, an option is the right, but not the obligation, to buy (call option) or to sell (put option) an asset (e.g., a number of stocks or commodities) at a certain price (strike price) either only on a pre-specified expiration date (European option), or anytime in between the commencement and the expiration date (American option) of the contract (Luenberger 1998). On the expiration date, or on any other previous date in case of the American option, the profit (payoff) of exercising (i.e., buying or selling) the option is calculated by subtracting the strike price from the current market value of the asset. For example, suppose that a certain call option on a stock has strike price of K on a particular date before or on the expiration date, and that the value of the underlying stock is S. If S>K the option holder can exercise the option for a profit (payoff) of S-K. On the other hand, if S<K there is no payoff, so exercising the option should be postponed at a later date unless the considered date is the expiration date. In the latter case, the option does not have to be exercised as the stocks can be purchased from the market for the lower price of S; clearly, the investor suffers a loss equal to the acquisition price of the option.

The problem of pricing options (valuation) in an uncertain environment (e.g., the stock market) modelled by judicially chosen randomly distributed variables and its optimum (stochastic) solution has drawn the attention of applied mathematicians and economists for quite some time. Historically, a first breakthrough was accomplished by the formulation and solution of the Black-Scholes-Merton partial stochastic differential equation (Black and Scholes 1973) which estimates, under certain reasonable assumptions applicable to stock markets, the price of European options in continuous time. Later, Cox *et al* (1979) recognized that a discrete-time solution approach may be more advantageous in solving the options pricing problem as it is more intuitive and involves elementary mathematics, while it is better suited to address both the American and the European style options than Monte Carlo simulation (see e.g., Hull 2012). This is because it allows for determining the value of not exercising the option in a straightforward manner. In the discrete-time approach, the analysis of stock pricing can be traced by a binomial lattice (tree) extending until the expiration, where the price of the stock may increase at certain time instants with a probability of P or decrease with a probability of $1–P$.

Following the above developments in stock options analysis, 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 profit/payoff (e.g., Trigeorgis 1996, Trigeorgis and Reuer 2017). Hence, in cases where a manager/decision-maker has a set of operational options on which to decide upon under uncertainty, the financial options mathematical framework can be readily deployed to obtain the value of these real (as opposed to financial) options. Specifically, the pay-off of the real decision is modelled as a derivative on an underlying uncertain asset or parameter. The uncertainty of the asset or parameter is then quantified commonly though a binomial lattice and the decision pay-off is calculated and discounted backwards to find the value of the real option (Luenberger 1998). Since the mathematical framework of option theory can become quite complex, it is often common to adapt the formulation of the RO problem to a financial option pricing problem (e.g. call option pricing via Black-Scholes solution) with known solution (Canada *et al.* 2004). Nevertheless, even in cases that financial option assumptions may not readily fit a particular RO problem, a solution process involving the representation of all possible futures into a lattice/tree and then valuing the decision going backwards from the final outcomes may still be applicable.

Examples of real actions (or options) are the adoption of an alternative engineering design or expansion in a given structured facility (De Neufville *et al* 2006), the retrofit of a critical component within a complex engineering network (Taneja *et al* 2010), the investment on alternative types of energy sources (Thomas and Chrysanthou 2012), and the adoption of different risk mitigation measures to address security risks in transportation systems networks (Power *et al* 2015). The next section casts the problem of seismic upgrading of an existing seaport under the assumptions set in previous sections within a RO framework and solves it in discrete-time such that it accounts for the “flexibility” to postpone the upgrading and its potential benefits. These benefits need to be further weighted by an increasing probability in time of the reference seismic event having a yearly probability P in Eq.(12) to occur.

Proposed RO formulation and solution in discrete-time

Consider an existing seaport experiencing a constant increase of TEU throughput in each future year t and whose earnings are computed under the previously detailed assumptions. It is of interest to examine the case in which decision makers have the (real) option (or the design/managerial flexibility) to upgrade the seismic performance of certain vital engineered facilities in a future year such that negligible structural damage and downtime occurs for the reference seismic event as defined by the previously discussed top-down or the bottom-up approaches. In this context, the question to be answered is when would be the “optimal” time (year) to exercise this option which entails a certain investment to the seaport. Clearly, this can be viewed as a RO problem since the upgrade may not necessarily be carried out at any one year and can be postponed indefinitely within the lifespan of the seaport. In this respect, the total upgrade cost (investment), Cu, can be considered as the strike price of the aforementioned option. Apparently, there is no benefit in upgrading if the total losses (repair cost plus downtime revenue losses) are less than the upgrade cost. On the other hand, if the total losses are greater than the upgrade cost and the cumulative probability of the reference seismic event to occur in the remaining economic horizon is significant, then it would be advisable to undertake the upgrade prior to this point. In this case the benefit from exercising the option, that is the *payoff*, will be the difference between seismic losses (caused by repair costs and downtime revenue losses) and upgrade cost.

Following the above RO interpretation, the problem at hand can be represented and solved by the binomial lattice/tree shown in the left panel of Fig 1. Each column of the adopted tree corresponds to a particular year. The leftmost node (origin) of the tree corresponds to the present year and the lattice expands rightwards in discrete-time with an increment of one year. A downwards step/branch to the right corresponds to the case of a nominal/design (or larger) reference seismic event occurrence at the considered year and is assigned a probability P computed from Eq. (12). An upwards step to the right denotes the case that no reference seismic event occurred at the considered year and is assigned a probability $1-P$. In this context, each node of the tree corresponds to a particular "scenario" with regards to the occurrences of seismic events, equal or above the reference seismic event.

For each scenario (node of the tree), four different quantities (cells) are computed and reported. The upper cell of each node displays the calculated earthquake loss for the corresponding scenario. This value is trivially null for scenarios with no reference seismic events (i.e., top nodes in every column of the tree). At any year t, from the current year (t=0) till the end of the decision horizon H (which could be the end of a concession or the time of pre-determined port expansion), the earthquake loss $L(t)$ is computed using Eq. (6), if only one reference seismic event occurred (regardless of when). For scenarios corresponding to a number of $n \geq 2$ reference seismic events occurred up to and including year t, earthquake loss is determined by using reduced earnings $ER(t)$ corresponding to n-1 number of reference seismic events in Eq.(7) in place of earnings $E(t)$. The second cell of each node reports seaport earnings. These are computed by Eq. (3) if no reference seismic event has occurred, or by Eq.(4) (reduced earnings) corresponding to the reduced throughput volume in Eq.(5). The third cell of each node displays the non-negative payoff (profit) if a seismic upgrade is decided computed as

$$PO(t) = \max\{0; L(t) - Cu\} \tag{13}$$

Lastly, the fourth cell reports the probability of each scenario occurring. This is computed by the sum of the probabilities of all possible paths from the origin to the considered node to occur. For instance, the first node of the third column (t=2) in Fig. 1 corresponds to the overall scenario that no earthquake occurred in the first two years. There is only one possible path to reach that scenario and the cumulative probability is $(1-P)^2$. The middle node of the same column corresponds to the scenario that one reference seismic event occurred in the first two years. There are two different paths leading to this scenario each one having a probability $P(1-P)$ to occur: the earthquake happened in the first year or the earthquake happened in the second year. The aggregate probability for this scenario is $2P(1-P)$.

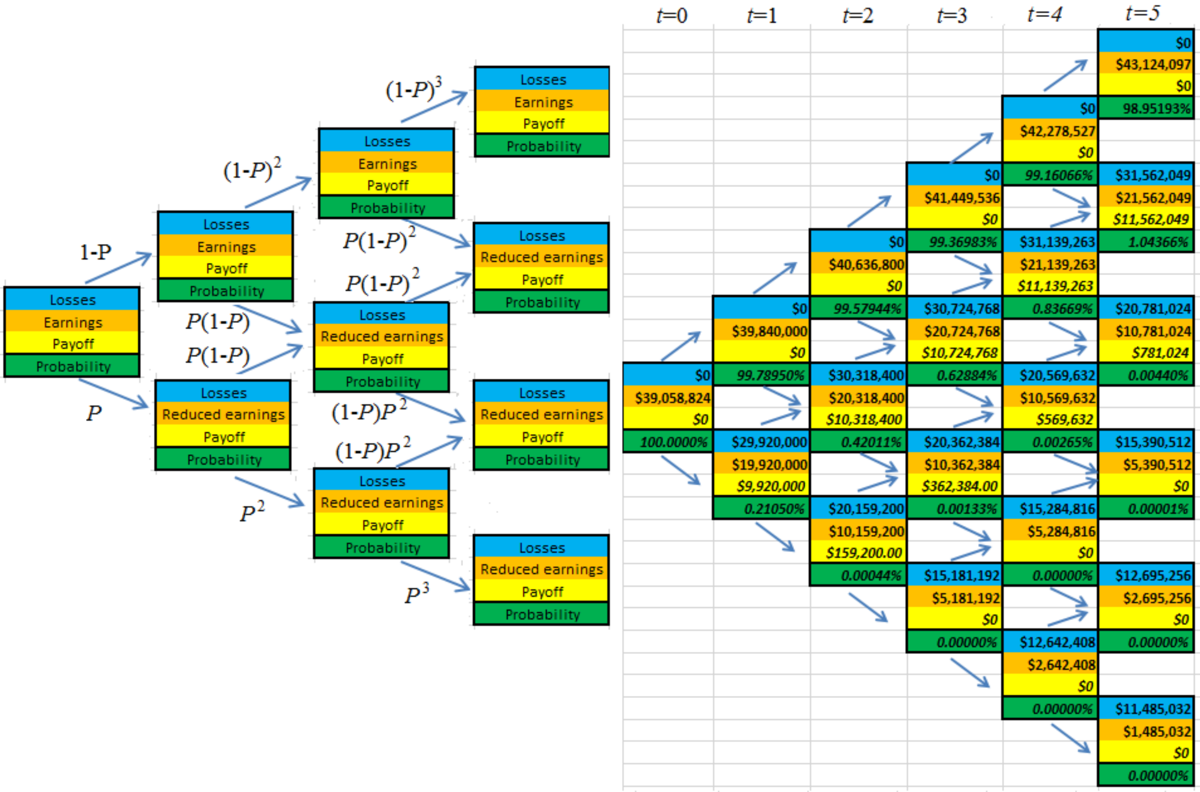

Fig. 1. Construction of real options binomial lattice (left panel) and numerical application (right panel)

It is important to note that the above RO modelling and analysis take into account that in all years following a reference earthquake, the seaport throughput is affected (reduced) and so are the net earnings. These effects stem from the assumptions made in setting up the problem at hand, and are in alignment with reported data in the literature demonstrating that in the aftermath of major seismic events, seaports continue to suffer reduced throughput and revenue for several years. In fact, the Port of Kobe never recovered throughput rates and revenues after the Hyogoken Nanbu (Kobe) earthquake in 1995 since cargo traffic was rerouted within regional MTNs in a permanent manner (Change 2000). Furthermore, it is noted that reduced throughput and earnings accrue as more and more reference seismic events occur, however, in a given year *t* their values depend only on the total number of events occurred in all years up to and including year *t*: no discrimination on the times/years that the earthquakes occur is made. For instance, for the scenario that one reference earthquake occurs up to *t*=2, the reduced throughput and earnings at *t*=2 are the same no matter if the earthquake occurred at the first or at the second year from the origin. This attribute stems from the assumption that the maintenance and operational costs in Eq.(2) are proportional to the income which, in turn, is proportional to the throughput through the wharfage fee in Eq.(1). Conveniently, it allows for coupling in pairs the inner nodes of the full binomial lattice, which would normally have 2^t nodes in year *t*, yielding the reduced tree shown in Fig.1 with only *t*+1 nodes in year *t* (see also De Neufville *et al* 2006). Nevertheless, this simplification does not harm the generality of the herein considered RO-based interpretation and formulation of the problem at hand since it would still be valid and applicable in case net earnings and/or revenues were not defined to be throughput-proportional. In such cases, the full binomial tree would be required to solve the RO formulation in discrete-time.

Probabilistic determination of annual payoff and optimal seismic upgrade time

The solution of the previously described RO formulation supports the definition of an *annual expected payoff* which takes into account the probability of occurrence of each of the t+1 possible scenarios (i.e., nodes in the tree of Fig.1) in year t from the present time. Specifically, at each year t, the annual expected payoff, *EPO*, is defined as the sum of the payoffs $PO_k(t)$ of all possible scenarios k=1,2,…,t+1 weighted by the probability, P_k, corresponding to each scenario. That is,

$$EPO(t)=\sum_{k=1}^{t+1} PO_k(t)P_k(t) \tag{14}$$

where $PO_k(t)$ is computed by Eq. (13) and P_k is found by propagating the earthquake occurrence probability through the tree of Fig. 1 as detailed in the previous section accounting for the inner merged binomial lattice nodes. Next, the net present value (NPV) of the expected annual payoff up to year t, defined as

$$\text{NPV}\left\{EPO(t)\right\}=\frac{PO(t)}{(1+r)^t} \tag{15}$$

where the discount factor r is the weighted average cost of capital (WACC) of the decision making stakeholder. Note that WACC reflects the market sector and country risk as it is driven by the expected return on private equity and the government and corporate return on lending (Canada *et al* 2004). Since most capital projects in ports are financed by a mix of own cash, debt and equity, it is considered an appropriate discount factor for evaluating the NPV of such investments (see also further discussion in the practical considerations section below).

The expression in Eq.(15) defines the value of the (real) option to invest in year t for the seismic upgrade of a given seaport such that negligible loss is expected for the reference seismic event accounting for the MAF of the event and its consequences to the existing port (*CR* and *D* in Eq.(6)), the cumulative annual throughput growth (CAGR), denoted as g in Eq.(1), and the cost of capital in terms of WACC. Moreover, being a function of t, the NPV of the annual payoff in Eq.(15) captures the flexibility to postpone the decision for later year. It is, thus, herein proposed to define the optimal time for seismic upgrade to be the year t* at which the NPV of the expected reward, is maximized. That is,

$$t^* \triangleq t\in(0,H]:\text{NPV}\left\{EPO(t^*)\right\}=\max_t\left\{\text{NPV}\left\{EPO(t)\right\}\right\} \tag{16}$$

Notably, the year of maximum expected reward, t^*, may not necessarily be the overall best time for seismic upgrading since practical decision-making on this matter involves several other issues such as the availability of capital for a seismic upgrade investment on the year and the attitude towards low-probability/high-consequence risks of the decision-maker (i.e., risk-averse as opposed to risk-neutral). Nevertheless, these issues are deemed to fall away from the focus of this work; instead, the following section offers discussion on practical aspects related to the definition of the reference seismic event and to the option valuation strategy and cost of capital (WACC) required in practical implementation of the proposed RO approach.

Practical considerations

Reference Seismic Event

In the above presented RO formulation, earthquake consequences with annual probability of occurrence P have been associated with a reference seismic event with small MAF of exceedance. From a theoretical viewpoint, the notion of the reference seismic event has been introduced to ensure that the RO approach is compatible with pertinent seismic code regulations for seaport facilities (e.g., PIANC 2001, ASCE 2014), while being equally well-applicable in conjunction with beyond-codes-of-practice performance-based seismic risk analyses for seaports. In the former case, assessment/verification (and therefore earthquake consequence determination) is required only for certain limit states associated with specific seismic intensity levels anchored on certain probabilities of exceedance in a given time-frame (bottom-up approach), while in the latter case earthquake consequences are defined through loss curves which integrate several seismic intensity levels (top-down approach). Moreover, the fact that MAF λ *in* Eq.(12) is typically very small supports the solution of the RO formulation using a standard binomial tree under the common assumption of Poisson distributed temporal earthquake occurrence at a given site.

Now, from a practical viewpoint, it is foreseen that, whilst the reference seismic event is notionally different from any particular earthquake scenario, it may be taken to coincide with a single seismic intensity level typically specified in seismic codes of practice for routine earthquake resistance design (see e.g., Avramidis *et al* 2016 and references therein). To elaborate further on this matter, it is expected that, in most cases, earthquake consequences in the context of the proposed RO formulation can be defined (with admittedly imperfect information and little rigor) through loss attributed to a single seismic intensity level having some (code-prescribed) probability to be exceeded in a given time-frame along the lines of the bottom-up approach. In this setting, loss is estimated on the level of expected damage after engineering analysis. Interestingly, a pertinent sensitivity analysis undertaken in the following section demonstrates numerically that the optimal timing to upgrade as predicted by the NPV of the expected payoff from the RO analysis in Eq.(16) is significantly less influenced by earthquake consequences (i.e., CR and D) or by the cost of seismic upgrade, Cu, compared to the throughput growth, *g*, and to the discount factor *r*. This finding (further discussed in the following section) suggests that *decision-making on the timing of the upgrade based on a single level of ground shaking may suffice in many practical cases*.

Nevertheless, if deemed essential, multi-intensity ground shaking can be accounted for more rigorous decision-making through the definition of the reference seismic event using loss curves. In this setting, full probabilistic loss analysis for the existing port needs to be undertaken involving, apart from a hazard curve obtained from regional PSHA, fragilities for the different infrastructure and simulation-based tools to predict downtime/loss of service (see e.g., Burden *et al* 2016). Nevertheless, such information and analyses may be too costly to obtain and therefore out the reach of most stakeholders. Hence, in the numerical part of this work, the assumption of the bottom-up approach in defining the annual probability of occurrence *P* is made to illustrate the applicability of the RO formulation in most practically appealing settings.

As a final remark, it is pointed out that in the rare case of sites for which seismic hazard is dominated by a single characteristic earthquake (McGuire 2004), earthquake consequences should be estimated by loss analysis using the bottom-up approach, taking the reference seismic event to be the characteristic earthquake. However, in such cases, the memoryless Poisson assumption is not applicable and a temporal-dependent earthquake occurrence model needs to be adopted as reviewed by Cornell and Winterstein (1988). Consequently, probability *P* in the proposed RO formulation becomes function of *t* and is history-dependent, hence the event tree for RO solution needs to be populated with probabilities dependent on *t* and conditional on the number of previous events. Such extensions of the considered RO approach are left for future work given the sparsity of sites for which temporal-dependent earthquake recurrence models is applicable (Cornell and Winterstein, 1988, McGuire 2004).

Options valuation methodology and discounting factor

Looking away from the earthquake engineering aspects of the problem at hand, it is noted that Eq. (15), although derived independently herein, is mathematically similar to the standard valuation expression in RO problems (see e.g., Carmichael 2014) in which the option value at present time is defined as the discounted expected value (present worth) of the net future cash flows from the option (pay-off), conditional on the investment being worthwhile (i.e. have strictly positive pay-off). In this context, the proposed RO formulation follows an option valuation approach analogous to the probabilistic discounted cash flow (DCF) analysis considered to be the most rigorous and conceptually valid corporate valuation method out of numerous alternatives as shown by Fernandez (2017). Nevertheless, practical application of Eq. (15) for deciding on the timing of seismic upgrade in seaports gives rise to two important entities that merit further discussion: (I) the estimation of the probability distribution (measure) of the future cash flows involved in the option pricing and (II) the choice of discounting factor *r*.

In financial options valuation (see e.g., Duffie 2001), under certain reasonable assumptions, it can be shown that there exists a probability distribution (called risk-neutral measure) for which the option value is equal to the expected value (under the risk-neutral measure) of its future cash flow discounted by the risk-free rate of return, usually taken as the US Treasury interest rate. Furthermore, this price is unique (i.e., common to the buyer and seller of the option), and can be replicated by a portfolio of tradeable assets. Overall, in this setting, the existence of commonly observable option prices such as company shares and a risk free asset (e.g. US Treasury bonds) facilitates finding the risk-neutral probability function and therefore the pricing of options, without knowing corporate discounting factors. Nevertheless, in RO the setup is different as extensively discussed by Brandao *et al* (2005). Specifically for the problem at hand, there may not be publicly tradeable assets of a seaport to define a unique risk-neutral probability measure that allows discounting by the risk free interest rate. However, the decision maker knows their cost of capital and can estimate the *actual probabilities* of their future cash flows. To this end, as has been recommended for other RO applications considered by Brandao *et al* (2005) and Carmichael (2014), it is suggested to use the actual probabilities and the corporate WACC for discounting probabilistic future cash flows in Eq. (15). The latter is defined as the average rate of return a company expects to compensate all its different investors and is a weighted average of the return on equity and the interest on debt (minus taxes) that the company has to yield to the investors. The weights come from the proportions of debt and equity in the company's financing structure. For the purposes of this work, WACC is represented as (Canada *et al* 2004)

$$WACC = \left(1 - ETR\right)\sum_{k}\left(DR_k \times i_k\right) + \left(1 - \sum_{k} DR_k\right)e \tag{17}$$

where $\Sigma_k DR_k$ is the debt ratio (sum of the fractions of total capital *DR* obtained by each debt source *k*), *ETR* the effective income tax percentage rate, i_k is the interest on debt financing for source *k*, $(1- \Sigma_k DR_k)$ is the proportion of equity finance, and *e* is the target return on equity. The target return on equity ranges depending on its source, own cost of capital, risk appetite and mandate. In absence of any available information, an indicative return on equity *e* (equity risk premium) can be estimated by the capital asset pricing model (Canada *et al* 2004). For more guidance on selecting *e,* one is referred to [53]. In general, the debt ratio $\Sigma_k DR_k$, effective tax rate *ETR* and return on equity depend on the different industry sectors. If port industry-specific measures are not available, one can consider the transport, energy, marine and shipbuilding, and marine cargo handling industrial sectors or labor classifications as substitutes. The interest on debt, i_k, depends on the borrower credit worthiness, type of debt issued and debt ratio. For an overview of sources of port infrastructure financing, the interested reader is directed to Byrne *et al* (1996).

Illustrative numerical applications and parametric investigations

This section furnishes numerical results demonstrating the applicability and rationality of the proposed approach for a number of practical scenarios involving different decision-makers/stakeholders and economic environments. Specifically, a typical (base) case of port authority in a developed country is first considered and pertinent sensitivity analyses is undertaken to demonstrate the influence of different factors to the optimal year t^* in Eq.(16). Next, the case of a terminal operator as a decision maker is examined and, lastly, the case of port authority in a developing country is also studied focusing attention on the effects of throughput growth and WACC discount factor.

Port authority in a developed country

For a first numerical example of the proposed RO-based approach, a typical two-berth container terminal is adopted as a base-case seaport facility in which the decision maker is the *port authority* operating in a *low interest-low growth economic environment*, typical of developed countries. Numerical values for all input parameters for this base case example are listed in Table 1. The assumed containerized cargo wharfage fee, f, is representative of the Port of Oakland (2015) tariff. A constant in time cumulative annual throughput growth (CAGR), g, is taken throughout the time horizon of the RO analysis H=30years regarded as a typical concession time-frame. The operational costs including maintenance costs are based on reported earnings before interest, taxes, depreciation, and amortization in terminals (see e.g., Port technology 2017), while repair and seismic upgrade costs are taken constant throughout the analysis, i.e. not indexed to inflation. The seaport (asset) value corresponds to the construction cost of a 2km long quay wall costed at $100.000/m, that a port authority would typically be responsible for construction and up-keeping. The base value for the discounting factor, reflects a relatively low WACC and is close to the long term average of 10-year US Treasury bond. A reference seismic event with MAF λ_{IM}= 0.2107% corresponding to seismic action having 10% probability to be exceeded in 50 years under the Poisson assumption for seismic occurrence is taken which is commonly set as the seismic intensity to verify life safety performance for ordinary structures by seismic codes of practice. The annual probability of occurrence P in Eq.(12) is 0.2105% and 6 months downtime (i.e., D=0.5 in Eq. (4)) is assumed.

Using the numerical values of the input parameters of Table 1, the RO analysis tree of Fig. 1 is obtained by means of straightforward spreadsheet-based calculations (see also Brandao *et al* 2005, De Neufville *et al* 2006). For illustration, numerical results for the first 5 years of the analysis are shown in the right panel of Fig. 1 and the NPV of the expected payoff for each year in Eq.(15) is plotted in Fig. 2 for the full 30 years of analysis. It is found that (i) a positive payoff is obtained for each year from the early stages of the RO analysis, confirming that seismic upgrading is a financially beneficial proposition, (ii) the NPV$\{EPO(t)\}$is increasing monotonically with time indicating that postponing the upgrade to take place later is potentially beneficial, and (iii) the NPV curve is convex (rate of increase saturates in time) and maximizes in year t=30 suggesting that postponing seismic upgrade at the end of the analysis horizon is most beneficial. Specifically, since the throughput is continuously increasing, the probability of more than one reference seismic event happens almost negligible, and the retrofit cost is constant from year to year, the payoff turns increase monotonically for this case.

Next, sensitivity analysis is undertaken by perturbing the values of CAGR, construction seaport value (and consequently cost of repair and seismic upgrade), downtime, and WACC used for the base case seaport as shown in Table 2. The aim is to validate the rationality of outcomes of the RO-based formulation and to investigate the influence of earthquake consequences vis-à-vis non-seismic-hazard related parameters to seismic upgrade timing. Each time only one of the considered parameters is varied while all others retain the base-case values.

Numerical results from the sensitivity analyses in terms of earthquake loss computed by Eq.(6) (i.e., assuming only one reference seismic event occurrence for each year) are plotted in Fig. 3, while Fig. 4 plots the NPV$\{EPO(t)\}$ in Eq.(15) obtained from solving the RO problem as illustrated in Fig. 1. Figures 3(a) and 3(c) demonstrate that the proposed RO analysis captures effectively the fact that seismic losses are significantly dependent on downtime but not so much on the asset value (and consequently on repair costs and upgrade costs) in alignment with seismic loss analysis of actual seaports [12]. It is further noted that the overall significance of asset value to earthquake loss reduces with time since the upgrade and repair costs are proportional to the initial value of the seaport, but not the generated revenue. On the antipode, an increase of downtime by 2 months compared to the base case may advance the decision to upgrade in time giving more than 20% earthquake losses compared to the base-case seaport. This conclusion is also confirmed by inspecting the NPV curves in Fig. 4(a): for any given year, the payoff of seismically upgrading is higher as downtime increases. Each curve corresponding to a fixed downtime is monotonic in time, but the rate of increase saturates faster for increasing downtime, suggesting that although postponing seismic upgrade in time increases the expected gains, the asymptotically highest NPV is achieved earlier if the anticipated downtime is longer. Still, it is seen that downtime does not significantly affect optimal timing t^* of seismic upgrade (i.e., the location of local maxima in Fig. 4(a) curves). Therefore, it can be argued that the herein proposed methodology yields a sufficiently accurate answer without requiring comprehensive loss analysis and only with limited resources and seismic risk analysis expertise within easy reach of the port management.

Table 1. Assumed parameter values for the base-case seaport

Parameter	Value
Wharfage fee	f=\$83 / TEU
Wharfage of total revenue	q= 0.85
Initial throughput	1M TEU/year
Annual throughput growth rate (CAGR)	g=2%
Asset (terminal) value	\$200M
Operational and maintenance cost	60% of yearly revenue
Repair cost (percentage of asset value)	\$10M (5%)
Seismic retrofit/upgrade cost (percentage of asset value)	\$20M (10%)
Downtime	6 months
Annual probability of reference seismic event occurrence	0.2105%
Discounting factor (WACC)	2%

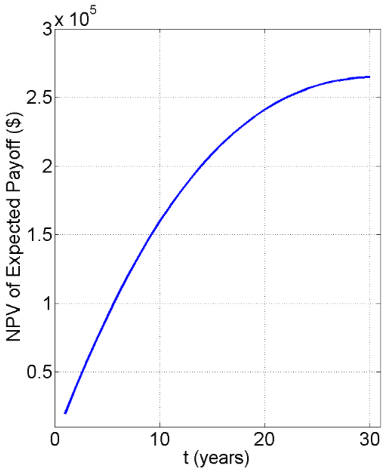

Fig. 2. Net present value of expected payoff for the base case seaport

Table 2. Parameter values for the sensitivity analysis

Parameter	Values
Annual throughput growth rate (CAGR)	g=*0.5*, 2, 4, 6%
Asset value	\$150, 200, 250M
Downtime	4, 6, 8 months
Discounting factor (WACC)	4, 6, 8%

Figure 3(b) quantifies the effect of different projected average throughput growth rates, CAGRs, to the aggregate earthquake loss, through the increase of the income. It is seen that for high CAGRs, the analysis yields significantly higher monetary losses as the seismic upgrading is postponed in time. For a risk-averse decision maker this would translate into a decision of an early seismic upgrade as the seaport will also incur reduced downtime revenue loss. At the same time, the effect of CAGR in revenues (and hence in expected losses) is compounded in later years. For a risk prone decision maker Fig. 4(b) suggests inversely that for higher CAGR, the NPV of the benefit increases as the decision to retrofit is postponed.

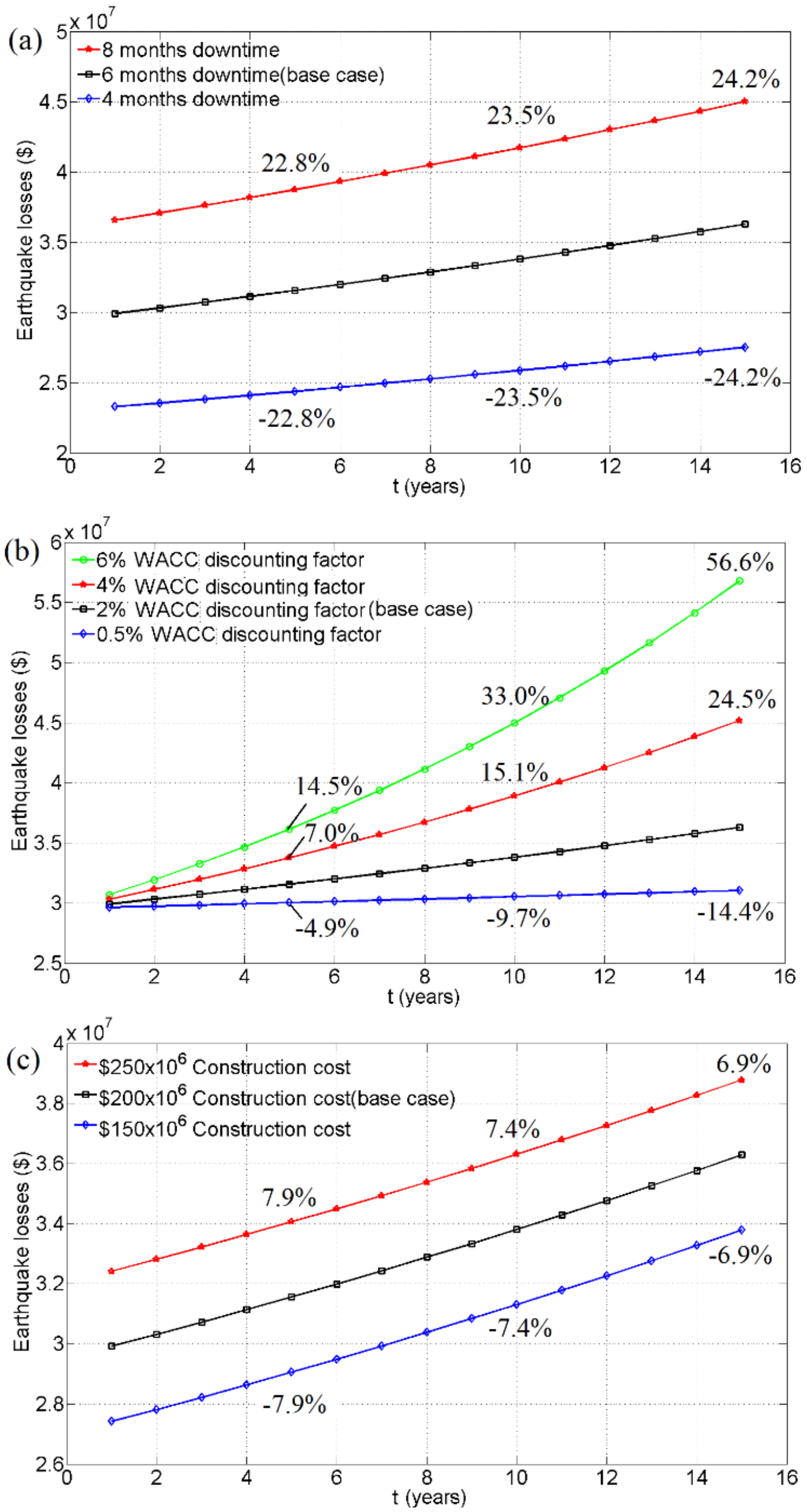

Fig. 3. Sensitivity of monetary losses due to a single reference seismic event occurring at year *t* for (a) different downtime, (b) different throughout growth rate, (c) different asset value.

Lastly, discounting factor WACC, *r*, influences significantly the NPV of the annual expected payoff from the early years of the analysis and this influence becomes more evident at later years, because of the compounding effect on NPV. It is concluded that a high interest rate may differentiate the expected payoff and therefore the investment decision by dampening the long term benefit. In low interest rate regimes, such as at the time this article is written, the NPV of the expected payoff increases significantly in later years, providing a stronger incentive to postpone the retrofit decision. Interestingly, this example suggests that in low interest rate environments, the "kick the can down the road" strategy of risk mitigation is more appealing.

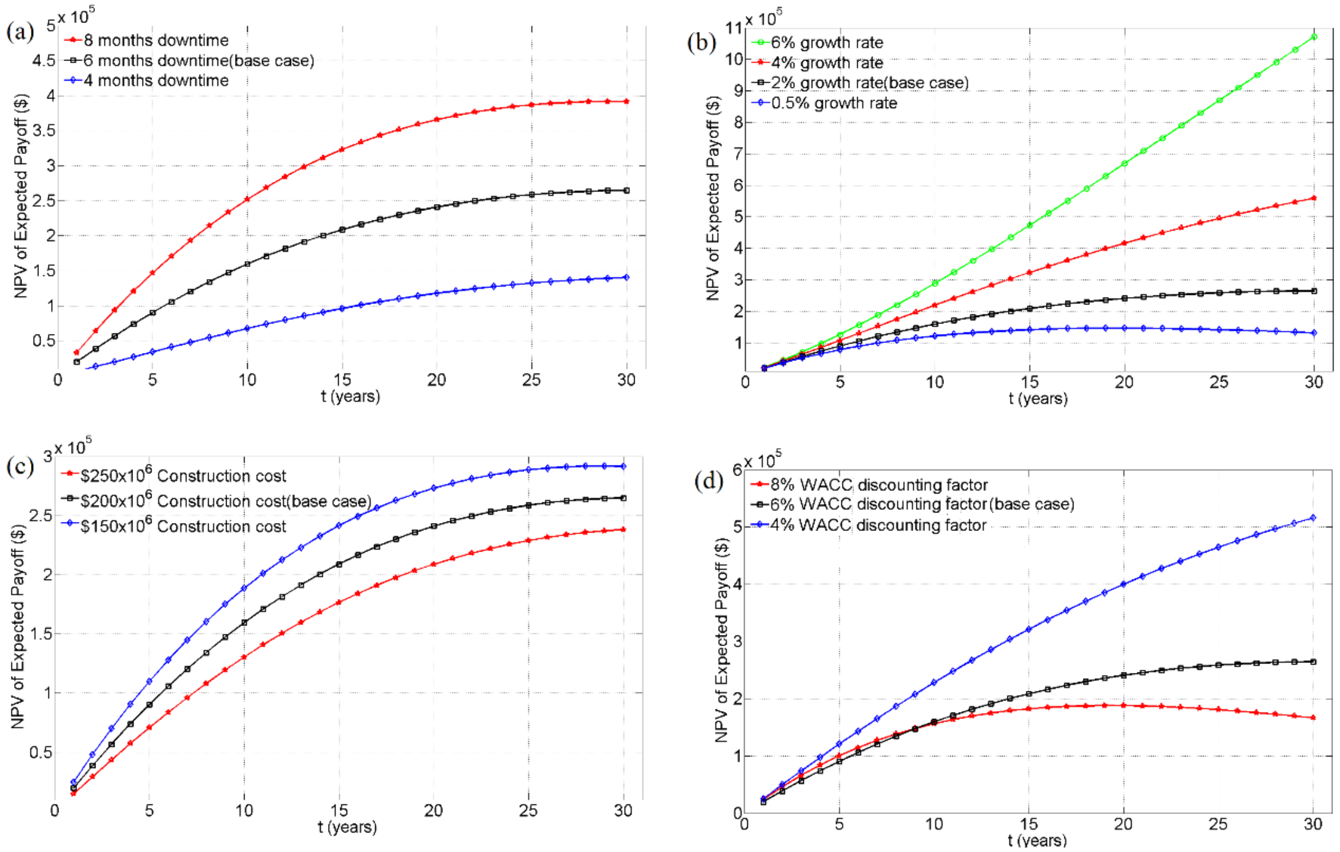

Fig. 4. Sensitivity of expected payoff in year *t* to (a) different downtime, (b) different throughout growth rate, (c) different asset value, and (d) for different discount factor

Terminal operator

In this example, the proposed RO-based approach is applied to a notional terminal operator to support a decision on optimal time for seismic retrofit/upgrade of the quay cranes, critical mobile equipment for the operations of the terminal. Typically, terminal operators are responsible for installing and maintaining these cranes and other lifting equipment as well as the buildings, pavement and utilities, whereas the port authority would be responsible for the fixed infrastructure (e.g. quay walls), coastal protection and reclamation. A two berth terminal would typically have 8 quay cranes. The values of the parameters for this example are shown in Table 3. Three cases of increasing downtime, retrofit, and repair costs are considered, in order to assess the sensitivity of the optimal retrofit time to these parameters, obtained from probabilistic seismic loss analyses for seaports as in Burden *et al* (2016). In cases 1 and 2, the repair cost is equal with the retrofit cost. In case 3 the repair cost is double that of the retrofit cost. What should also be observed here is the relatively high discounting factor, WACC in Eq. (17), which reflects the financing cost for a private terminal operator and includes debt-to-equity ratio, market risk as well as country risk. Indeed, cost of capital between 8-16% is not uncommon for this type of investment. For example, assuming a single debt source, k=1, no tax rebate, ETR=0, DR_1=60% debt ratio of total capital, target return on equity e= 16%, and interest on debt financing i_1=10% gives WACC= 12.4% in Eq.(17).

Numerical values obtained from Eqs.(15) and (16) are provided in Fig. 5 and Table 4, respectively. Although the NPV of the expected payoff increases as the repair/ retrofit cost (cases 1, 2, 3) increase, the optimal times to retrofit remain the same for case 1 and 2 (repair cost equal to retrofit cost), but are slightly earlier when the repair cost is much larger than the retrofit cost (case 3) unless WACC becomes excessive (WACC>14%). Hence, *it is seen that there are minor differences in optimal times when differentiating upgrade from retrofit cost and that, in general, the influence of earthquake consequences to t* is insignificant.*

Table 3. Terminal Operator example parameters

Parameter	**Value**		
	Case 1	**Case 2**	**Case 3**
Wharfage fee	f=\$150 / TEU		
Wharfage of total revenue	q= 0.85		
Initial throughput	1.5M TEU/year		
Annual throughput growth rate (CAGR)	g=1%-6% (variable)	g=4%	g=4%
Asset value (includes equipment and topside infrastructure)	\$250M		
No. quay cranes	8		
Operational and maintenance cost	60% of yearly revenue		
Repair cost	\$4M (\$0.5M per crane for the reference earthquake)	\$8M (\$1M per crane for the reference earthquake)	\$16M (\$2M per crane for the reference earthquake)
Seismic retrofit/upgrade cost (see table 2 in [12])	\$4M (\$0.5M per crane)	\$8M (\$1M per crane)	\$8M (\$1M per crane)
Downtime (see table 2 in [12])	2 months	3 months	4 months
Annual probability of reference seismic event occurrence	0.2105%		
Discounting factor (WACC)	8%-16% (variable)		

To examine further the combined effect of WACC and CAGR to the optimal seismic upgrade time, case 1 is run under throughput growth rates ranging from 1-6% and time t^* values are plotted in Fig. 6. As CAGR increases, the optimal time is pushed back in time. In the case of high WACC the change is almost linear but as the WACC reduces, the optimal time increases non-linearly towards the end of the analysis horizon (30 years). These results demonstrate significant non-linear sensitivity of the optimal retrofit time to the discounting factor and the throughput growth rate. High growth rates and low cost of capital again push the optimal seismic upgrade timing for later. In other words, *in high growth, low capital cost environments it is more beneficial to postpone the retrofit because the expected payoff increases and the dampening effect of discounting is small.* On the contrary, *in low growth, high capital cost environments a point appears within the 30* *year horizon where the NPV of the expected payoff is maximized, providing thus an optimal non-trivial time for seismic upgrading*. This is a novel finding/outcome that no previous work or established approach has reached before.

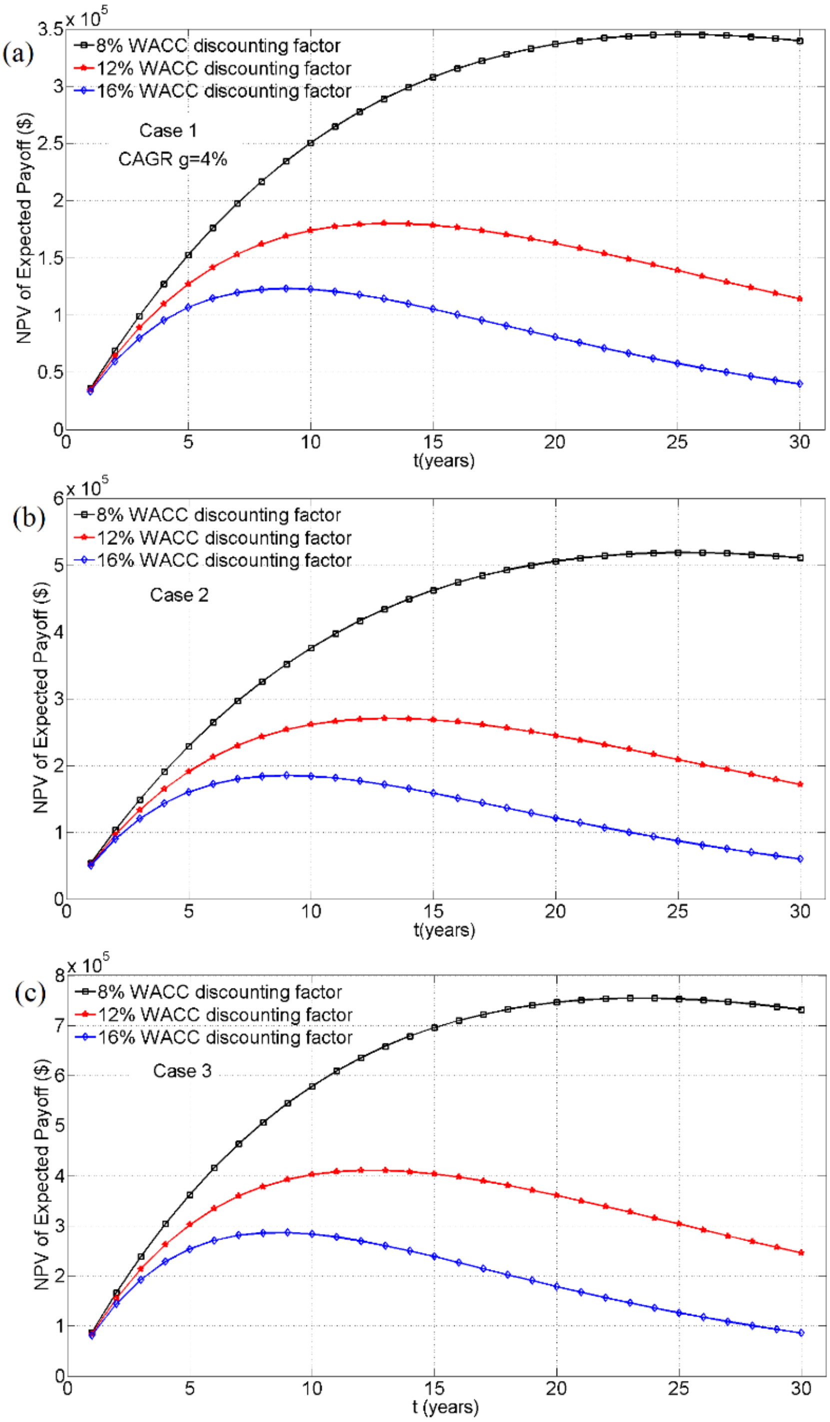

Fig. 5. NPV of expected payoff in year *t* for container terminal operator example (a) Case 1, (b) Case 2, (c) Case 3 in Table 3.

Table 4. Terminal Operator example - optimal times for retrofit

WACC	**Optimal time (years)**		
	Case 1	*Case 2*	*Case 3*
8%	25	25	23
10%	17	17	16
12%	13	13	12
14%	11	11	10
16%	9	9	9

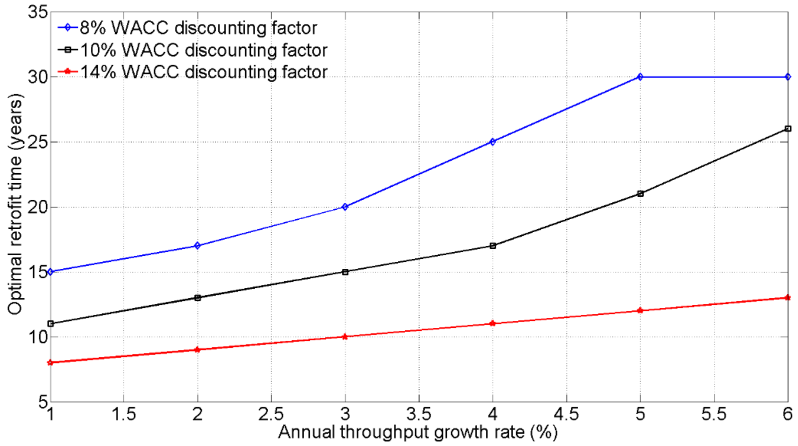

Fig. 6. Optimal seismic upgrade time t^* for *t*erminal operator case 1 as a function of CAGR and for various WACC values

Port authority in a developing country

In this example, the growth rate and capital cost parameters reflect a high growth-high capital cost environment of a port in an emerging market country. Such developments are usually Public-Private-Partnerships, based on a Build-Operate-Transfer model (Carmichael 2014). The financing is a combination of low interest International Financial Institutions loan or load guarantee, private equity, and syndicated international bank loan (Byrne *et al* 1996). The high country and market risks result usually in high cost of capital, but the additional high growth potential make the investment attractive. In this particular hypothetical scenario, the port authority is responsible for a 3km quay wall that risks having 60% of its length rendered inoperable under the reference seismic event. All adopted parameter values for this example are provided in Table 5. Results in terms of NPV{EPO(t)} and t^* in Eqs. (15) and (16) respectively are plotted in Fig. 7. As in the previous example (terminal operator) it is confirmed that as throughput growth rate increases and/or as WACC decreases, optimal retrofit time becomes longer. In this case, for all the parameter combinations there is an optimal retrofit time, which is less than 30 years and for 6% CAGR the retrofit time is well within the first 15 years for all WACC values examined indicating that seismic seaport upgrade should happen earlier in developing vis-à-vis developed countries from a financial viewpoint.

Table 5. Assumed parameters for port in an emerging market country

Parameter	**Value**
Wharfage fee	*f*=\$120 / TEU
Wharfage of total revenue	*q*= 0.85
Initial throughput	3.5M TEU/year
Annual throughput growth rate (CAGR)	*g*=6,8,10%
Asset (terminal) value	\$150M
Operational and maintenance cost	60% of yearly revenue
Repair cost	\$10.8M
Seismic retrofit/upgrade cost	\$18M
Downtime	6 months
Annual probability of reference seismic event occurrence	0.2105%
Discounting factor (WACC)	14,16,18%

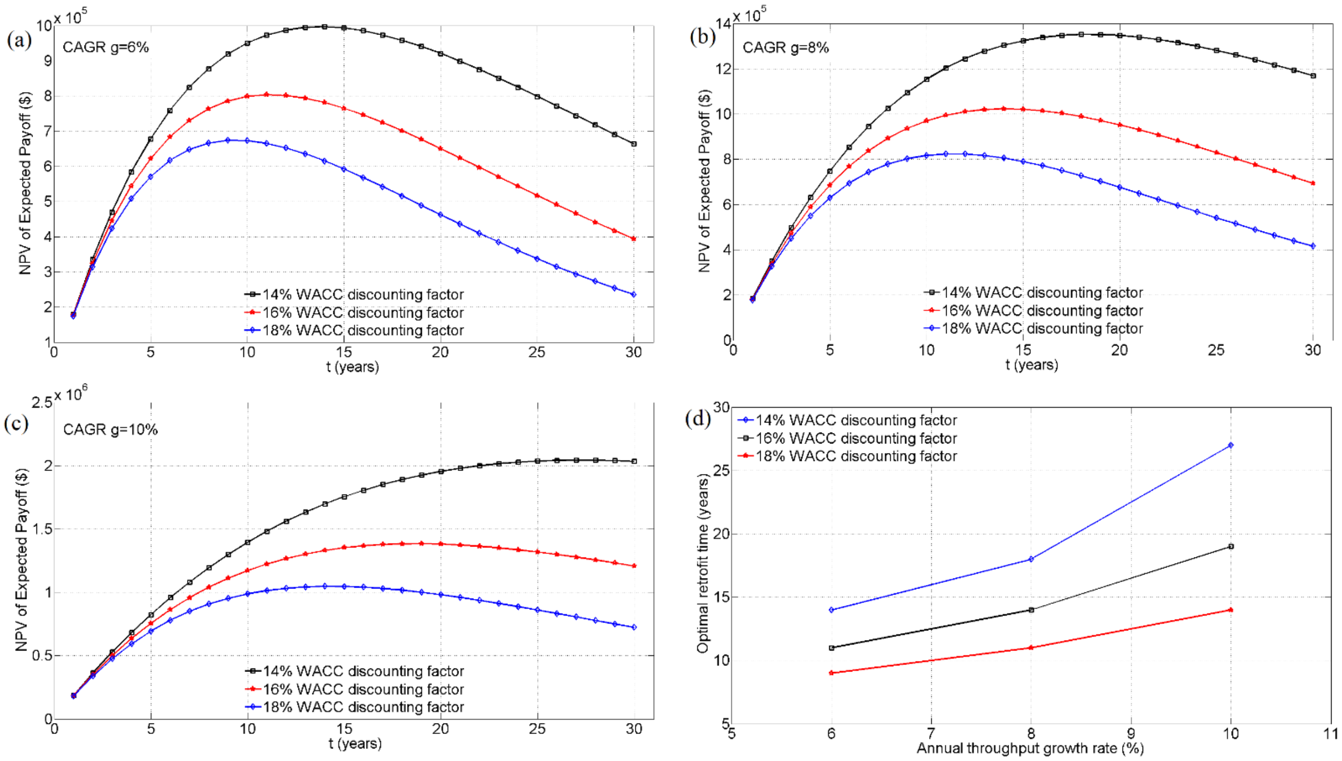

Fig. 7. NPV of expected payoff in year *t* for port authority in developing country and for throughput growth rate (a) 6%, (b) 8%, (c) 10%. (d): Sensitivity of optimal time of seismic upgrade versus throughput growth rate

Concluding remarks

A real options (RO) approach has been proposed for decision-making on the appropriate time to seismically upgrade a given seaport (e.g. within a practical time-frame of a typical concession period), such that negligible damage occurs for a reference seismic event. The problem has been formulated in discrete-time by considering a RO binomial lattice (tree). In the proposed RO formulation, earthquake consequences having an annual probability of occurrence *P* have been associated with the reference seismic event with small MAF of occurrence following a Poisson temporal distribution. The proposed formulation fits well within the existing and recently developed frameworks for seaport risk analysis, and can be adapted to sit either on top of probabilistic seismic loss analysis (i.e., loss curves) or a site-specific seismic hazard curve. By considering a series of simplified yet realistic assumptions the NPV of the expected payoff of the option to seismically upgrade a seaport has been estimated using straightforward spreadsheet-based calculations that can automate the analysis and visualize pertinent results. A sensitivity analysis with respect to the assumed downtime, growth throughput rate, initial seaport asset value and weighted average cost of capital demonstrates that the economic factors (growth rate and cost of capital), 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 has been 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. Qualitatively reasonable and quantitatively valuable and consistent conclusions have been drawn in view of the presented numerical data. In particular, it was shown that in the high growth-low interest environment of a booming developed economy, although there are positive benefits in retrofitting, early retrofit is not optimal, whereas 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. Consistently, the optimal time to retrofit increases as the throughput growth rate increases and the cost of capital decreases.

Despite its simplicity, which is an inherent advantage of any discrete-time RO approach, the herein conceived RO formulation may be extended to accommodate more refined models for the earthquake occurrence informed by regional seismicity as well as valuation methodologies to estimate seaport revenue and seismic losses. Such extensions are left for future work. It is envisioned that the herein developed approach and numerical data provided will further familiarize the engineering community with RO approaches and their potential to inform decisions not only on wise resource allocation at the local/national levels, but also on ensuring supply chain resiliency to natural hazards, given that seaports are the critical nodes in seaborne transportation networks.

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