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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 disproportionately 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

31 drivers of regional/National economies (e.g., Lam and Su 2015) while they constitute important lifelines supporting the  
32 resilience (i.e. ability to recover after a disaster) of local communities (e.g., Chang 2010, Stevenson *et al* 2011).

33 All the above aspects are particularly pertinent to seaports exposed to seismic hazard. Indeed, major seismic events  
34 can cause significant damage to seaport engineered structures such as cranes, wharves, and quay walls, which enable cargo  
35 handling and vessel docking (see e.g., Pachakis and Kiremidjian 2004, Na and Shinozuka 2009, Shafieezadeh and Burden  
36 2014). These structures have particularly high replacement costs and require considerable repair downtime in the aftermath  
37 of destructive earthquakes. For example, the Seventh Street Terminal in the Port of Oakland remained closed for 6 months  
38 following the Loma Prieta earthquake in North California (1989), while repairing the 922m-long damaged wharf costed  
39 \$14 million and took almost 23 months to complete as reported by Fotinos *et al* (1992). Importantly, such appreciable  
40 downtime entails significant revenue losses to the seaport and to the local economy, on top of the direct seismic repair  
41 costs, since they result to reduced, if not complete loss of, cargo throughput capacity. For instance, the estimated repair  
42 cost of the Port of Kobe in the aftermath of the Hyogoken Nanbu (Kobe) earthquake (1995) was amounted to about \$5.5  
43 billion while reported losses to the local port-related businesses due to loss/reduced operations were estimated to \$6 billion  
44 in the first 9 months after the earthquake as reported by Werner *et al* (1997). Moreover, in the case of large high-throughput  
45 seaports, several of which are located in medium-to-high seismicity regions along the West coast of US (Scharks *et al*  
46 2014) and in East Asia (Lam and Su 2015), throughput capacity reductions due to earthquakes can result to further financial  
47 losses due to disruption to various National and International/global MTNs and supply chains, while the unavoidable post-  
48 earthquake vessel re-routing can eventually have long-term/ permanent consequences to the seismically damaged seaport  
49 and to the local/National economy (Peng *et al* 2016). As an illustration, the Port of Kobe was ranked 6<sup>th</sup> in the World at  
50 the time of the Hyogoken Nanbu (1995) earthquake in terms of cargo throughput, and never recovered this position post-  
51 earthquake as discussed by Chang (2000). Lastly, even the relatively low throughput capacity seaports, whose loss of  
52 functionality may not be detrimental to global supply chains, are still critical for the resilience of the local communities in  
53 the aftermath of seismic events. Recent examples, are the Lyttelton, Port of Christchurch, which remained operational to a  
54 large extend following the Christchurch (2011) earthquake and significantly facilitated recovery efforts as reported by  
55 Stevenson *et al* (2011), whereas, on the antipode, both terminals of the Port-Au-Prince seaport suffered significant damaged  
56 during the Haiti (2010) earthquake rendering an important lifeline of the country non-functional at the time when it was  
57 mostly needed as discussed by Bono and Gutierrez (2011).

58 In this respect, undertaking local seismic upgrades of the most vulnerable and least resilient infrastructure  
59 identified in a seaport, that is quay walls and foundations of wharves and cranes, is a necessary step to increase the resilience  
60 of local communities to the earthquake hazard and to minimize earthquake-induced losses to seaport operations (see e.g.,

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

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

90 exclusively assumed in (real) options pricing (e.g., Cox *et al* 1979, Brandao *et al* 2005, De Neufville *et al* 2006) suffices  
91 to solve the RO problem at hand.

92

### 93 **Previous related studies and novel considerations**

94           Whilst various RO-based approaches have been proposed in the literature to facilitate decision-making for critical  
95 infrastructure investments under uncertainty in the energy sector (Thomas and Chrysanthou 2012), in road transportation  
96 networks (Power *et al* 2015), and in seaports (not in earthquake prone areas) (Taneja *et al* 2010), to the best of the authors'  
97 knowledge, it is the first time that RO analysis is considered to inform decisions on seismic upgrade of infrastructure  
98 exposed to the earthquake hazard. Indeed, standard cost-benefit analysis (CBA), sometimes supported by lifecycle cost  
99 considerations, is most often used financial analysis tool to address the questions of whether to undertake seismic retrofit,  
100 replace, or do nothing for a given structure (or a specific class of structures), and which type and/or target performance of  
101 retrofitting strategy should be adopted in doing so, out of a number of possible choices (e.g., Smyth *et al* 2004, Kappos  
102 and Dimitrakopoulos 2008, Chiu *et al* 2013, Liel and Deierlein 2013). This is typically achieved by first integrating local  
103 seismic hazard curves with pertinent fragility curves of the current/existing and of the seismically upgraded structure upon  
104 application of different retrofitting methods. Next, the most economically viable, if any, retrofitting strategy is chosen as  
105 the one that maximizes the net present value (NPV) of benefits over costs, as considered by Kappos and Dimitrakopoulos  
106 (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  
107 context, a recent application of CBA on seismic retrofit decisions for the Port of Portland is reported by McMahon *et al*  
108 (2016) and Graf *et al* (2016), which compares seaport reduction in annual losses (annual benefit) with and without seismic  
109 retrofit for various seismic intensity levels. The sum of the annualized benefits for all hazard levels is then discounted and  
110 divided by the retrofit or replacement cost for each option to form the benefit-cost ratio. Further, Taylor *et al* (2016) lists a  
111 number of actual seaport-related seismic risk evaluation and mitigation studies in which various mean-variance criterion  
112 based approaches have been considered in conjunction with CBA to account for the statistical variability of net costs and/or  
113 benefits in the decision-making process. Moreover, Caterino *et al* (2008) used multi-criteria decision making tools to  
114 appraise the optimal retrofitting strategy for a given structure in cases of conflicting cost-benefit criteria representing trade-  
115 offs.

116           Despite their appropriateness to inform decisions on economically viable seismic upgrade solutions and  
117 prioritization of funding allocation to undertake seismic upgrading, none of the above financial tools and approaches aimed  
118 to provide for the optimal timing of undertaking a pre-specified seismic upgrading to bring an existing (seaport) structured  
119 facility to a particular/target level of seismic performance. The latter aim has been addressed by Nuti and Vanzi (2003)

120 based on an analytical expression derived for the equivalent annual cost (EAC) of seismic upgrading as a function of the  
121 future time that retrofit takes place. In theory, a local minimum of the EAC in time provides an optimal timing for seismic  
122 upgrading under the various assumptions made in deriving the EAC including memoryless (Poisson) process to model the  
123 temporal distribution of exceedances of a given limit state of the structure. However, it is found that the EAC is either  
124 monotonically increasing or decreasing, which leads to the trivial timing solutions of either retrofit at present time or never  
125 (Nutti and Vanzi 2003). More recently, Bradley et al. (2009) defined analytically the point (year) in time that a particular  
126 seismic upgrade solution becomes economically neutral and proposed this timing to be a criterion to decide on competitive  
127 retrofitting solutions to be undertaken at present time. This critical time is defined as the year when the NPVs of the  
128 expected annual loss, computed through probabilistic seismic loss analyses (see e.g., Porter *et al* 2004), of the upgraded  
129 structure and the existing structure become equal. Clearly, this critical time is not the optimal (future) time for a given  
130 seismic upgrade to be undertaken such that potential benefits are maximized.

131 Collectively, all the above reviewed non-RO studies treat the case of structures and infrastructure that do not  
132 accrue time-dependent revenues which, in practice, means that loss of revenue due to business interruption are stationary  
133 (time-invariant). In this regard, the problem of finding an optimal seismic upgrade time/year, if there is one, in a regime of  
134 increasing operational revenues for a certain *a priori* decided (e.g., based on CBA) retrofit strategy has not been addressed.  
135 As previously discussed, determining such a point in time in a rational and systematic manner for any (given) seismic  
136 retrofitting strategy is of significant practical importance for seaport authorities as well as for terminal operators. To this  
137 end, the herein proposed RO formulation contributes a novel tool filling a niche gap in the overall decision-making process  
138 for seaport seismic risk mitigation. Notably, this tool facilitates decoupling the type/level of seismic retrofit from the  
139 problem of the timing that this retrofit should take place. In this manner, it allows for studying the influence of economic  
140 factors which are uncorrelated to seismicity and structural vulnerability, such as throughput traffic growth in cargo seaport  
141 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  
142 factors influence most the optimal timing of seismic upgrading which, contrary to the case of EAC considered by Nutti and  
143 Vanzi (2003), turns out to have a non-trivial solution for certain economic environments and/or decision-makers.

## 144 **Definitions and assumptions**

### 145 *Seaport revenue and earnings model*

146 Container seaports can be seen as complex engineered systems comprising several different types of infrastructure  
147 such as quay walls, wharves, cranes, warehouses, and gates. These components enable various inter-related operations  
148 associated with container loading and unloading to and from vessels, storage, and movement within the seaport premises  
149 (see e.g. Na and Shinozuka 2009, Burden *et al* 2016 and references therein). Such seaports benefit from numerous types

150 of revenues collected in the form of port dues (e.g., Pachakis and Kiremidjian 2004). For the purposes of this work, the  
 151 total cargo-related revenues are assumed to be proportional to the wharfage fee collected for every twenty-foot equivalent  
 152 container unit (TEU) loaded and discharged to and from a vessel. In this manner, throughput capacity in terms of TEUs  
 153 can be related to seaport revenues in a straightforward manner. It is further assumed that there is an increase in the annual  
 154 seaport throughput volume  $T$  (i.e., in the number of TEUs handled per year) by a throughput growth rate,  $g$ , in alignment  
 155 with the increase to global seaborne trade demands (UN 2015). Therefore, the throughput at a given year  $t$  is written as

$$156 \quad T(t) = T(t-1)(1 + g(t)) \quad (1)$$

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

$$159 \quad I(t) = \frac{T(t)f}{q} \quad (2)$$

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

$$162 \quad E(t) = I(t) - CO(t) - CM(t) \quad (3)$$

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

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

$$168 \quad ER(t) = (1 - D)E(t) \quad (4)$$

169 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  
 170 case of 6 months of equivalent downtime). On the year of earthquake damage, a reduced throughput volume  $TR$  is observed  
 171 equal to

$$172 \quad TR(t) = (1 - D)T(t) = (1 - D)T(t-1)(1 + g). \quad (5)$$

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

$$175 \quad L(t) = E(t)D + CR. \quad (6)$$

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

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

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

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

$$188 \quad \lambda_{CR}(cr) = \int_{rr} \int_{dm} \int_{edp} \int_{im} G(cr|rr) \left| dG(rr|dm) \right| \left| dG(dm|edp) \right| \left| dG(edp|im) \right| d\lambda_{IM}(im) \quad (7)$$

189 and

$$190 \quad \lambda_D(d) = \int_{rr} \int_{dm} \int_{edp} \int_{im} G(d|rr) \left| dG(rr|dm) \right| \left| dG(dm|edp) \right| \left| dG(edp|im) \right| d\lambda_{IM}(im) \quad (8)$$

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

206 which cost of repair,  $CR$ , and downtime,  $D$ , of the seaport system in Eqs. (6) and (4), respectively, can be estimated  
207 individually.

208 Given loss curves in Eqs. (7) and (8) for an existing seaport, a decision-maker can select the *reference seismic*  
209 *event* that they want to retrofit/upgrade for defined through a pair of minimum unacceptable repair cost and downtime  
210 threshold values ( $cr^*$ ,  $d^*$ ) having a particular MAF  $\lambda_{CRD}$  to be exceeded. It is acknowledged that this selection depends on  
211 the decision maker risk tolerance profile against repair cost and downtime separately, though decision will be mostly  
212 dominated by downtime since this is by far most significant contributor to total seismic loss. It is further acknowledged  
213 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  
214 address the above issues in a practical manner, it is herein suggested that a single MAF corresponding to the reference  
215 seismic event is conservatively defined as

$$216 \quad \lambda_{CRD} = \max \{ \lambda_{CR}(cr^*), \lambda_D(d^*) \} . \quad (9)$$

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

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

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

$$231 \quad CR = E \{ cr | IM \geq im^* \} = \int_{cr} \int_{rr} \int_{dm} \int_{edp} \int_{im} cr dF(cr|rr) dF(rr|dm) dF(dm|edp) dF(edp|im) dG(im) \quad (10)$$

232 and

$$233 \quad D = E \{ d | IM \geq im^* \} = \int_d \int_{rr} \int_{dm} \int_{edp} \int_{im} d dF(d|rr) dF(rr|dm) dF(dm|edp) dF(edp|im) dG(im) . \quad (11)$$

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

#### 240 *Temporal occurrence of reference seismic event*

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

$$248 \quad P = 1 - \exp(-\lambda), \quad (12)$$

249 where  $\lambda = \lambda_{CRD}$  in Eq.(9) if reference seismic event is defined using seismic loss curves (top-down approach) or  $\lambda = \lambda_{IM}(im^*)$   
250 if reference seismic event is defined by means of a nominal earthquake shaking level having a specific probability to be  
251 exceeded in a given time-span (bottom-up approach). The use of  $\lambda_{CRD}$  value in Eq.(12) is justified by the fact that any  
252 arrival process of a consequence-indicator random variable  $X$  (such as repair cost, downtime etc.) with MAF  $\lambda_x$  derived  
253 from a seismic hazard curve  $\lambda_{IM}$  via a cascade of relationships of the type  $\lambda_x = \Pr(x|im) \lambda_{IM}$ , are Poisson. This property  
254 follows from combining and splitting Poisson processes as discussed in the standard texts of Parzen (1999) and Ross  
255 (2014).

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

## 261 **Methodology of the real options (RO) approach**

### 262 *Stock options and real options*

263 In the field of financial investment valuation, an option is the right, but not the obligation, to buy (call option) or to  
264 sell (put option) an asset (e.g., a number of stocks or commodities) at a certain price (strike price) either only on a pre-  
265 specified expiration date (European option), or anytime in between the commencement and the expiration date (American  
266 option) of the contract (Luenberger 1998). On the expiration date, or on any other previous date in case of the American  
267 option, the profit (payoff) of exercising (i.e., buying or selling) the option is calculated by subtracting the strike price from  
268 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  
269 particular date before or on the expiration date, and that the value of the underlying stock is  $S$ . If  $S > K$  the option holder  
270 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  
271 should be postponed at a later date unless the considered date is the expiration date. In the latter case, the option does not  
272 have to be exercised as the stocks can be purchased from the market for the lower price of  $S$ ; clearly, the investor suffers a  
273 loss equal to the acquisition price of the option.

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

285 Following the above developments in stock options analysis, the concept of the financial option migrated to decision-  
286 making under uncertainty in engineering problems where an option involves taking (or postponing) a decision on a “real”  
287 action which yields a certain profit/payoff (e.g., Trigeorgis 1996, Trigeorgis and Reuer 2017). Hence, in cases where a  
288 manager/decision-maker has a set of operational options on which to decide upon under uncertainty, the financial options  
289 mathematical framework can be readily deployed to obtain the value of these real (as opposed to financial) options.  
290 Specifically, the pay-off of the real decision is modelled as a derivative on an underlying uncertain asset or parameter. The

291 uncertainty of the asset or parameter is then quantified commonly through a binomial lattice and the decision pay-off is  
292 calculated and discounted backwards to find the value of the real option (Luenberger 1998). Since the mathematical  
293 framework of option theory can become quite complex, it is often common to adapt the formulation of the RO problem to  
294 a financial option pricing problem (e.g. call option pricing via Black-Scholes solution) with known solution (Canada *et al.*  
295 2004). Nevertheless, even in cases that financial option assumptions may not readily fit a particular RO problem, a solution  
296 process involving the representation of all possible futures into a lattice/tree and then valuing the decision going backwards  
297 from the final outcomes may still be applicable.

298 Examples of real actions (or options) are the adoption of an alternative engineering design or expansion in a given  
299 structured facility (De Neufville *et al* 2006), the retrofit of a critical component within a complex engineering network  
300 (Taneja *et al* 2010), the investment on alternative types of energy sources (Thomas and Chrysanthou 2012), and the  
301 adoption of different risk mitigation measures to address security risks in transportation systems networks (Power *et al*  
302 2015). The next section casts the problem of seismic upgrading of an existing seaport under the assumptions set in previous  
303 sections within a RO framework and solves it in discrete-time such that it accounts for the “flexibility” to postpone the  
304 upgrading and its potential benefits. These benefits need to be further weighted by an increasing probability in time of the  
305 reference seismic event having a yearly probability  $P$  in Eq.(12) to occur.

306

### 307 *Proposed RO formulation and solution in discrete-time*

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

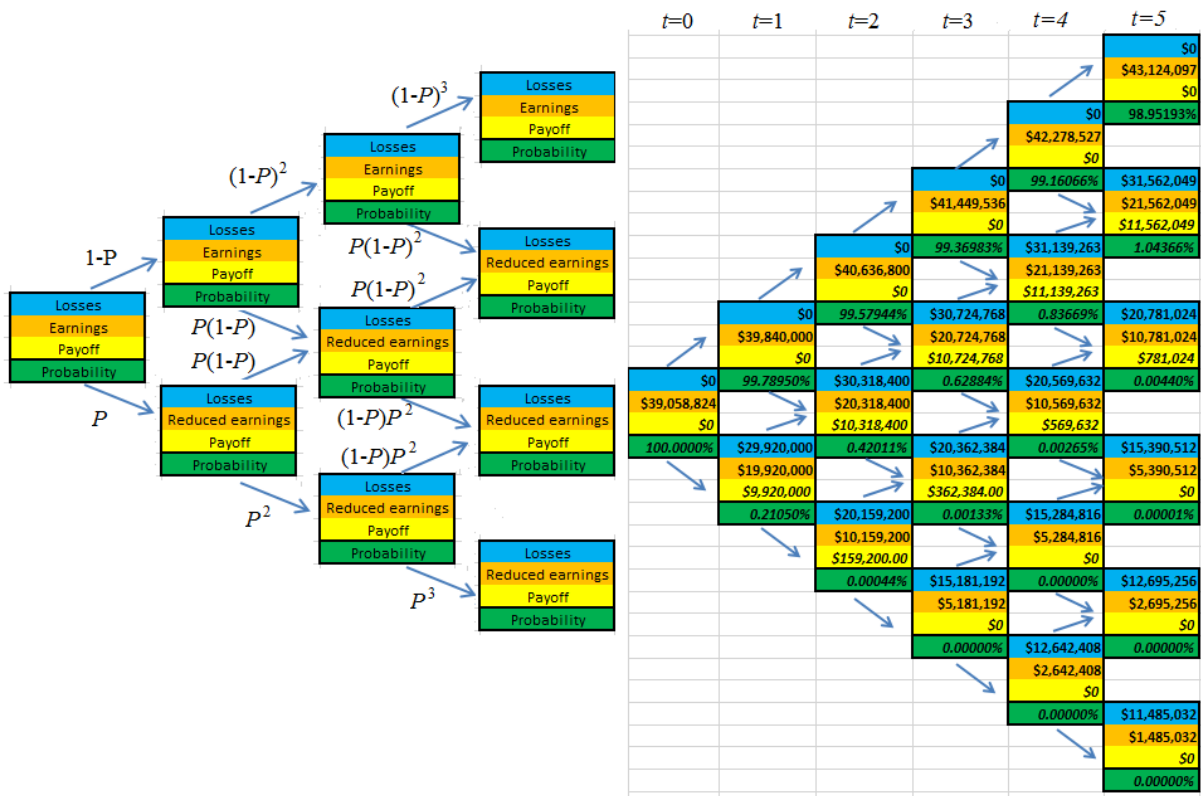
320 benefit from exercising the option, that is the *payoff*, will be the difference between seismic losses (caused by repair costs  
321 and downtime revenue losses) and upgrade cost.

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

330 For each scenario (node of the tree), four different quantities (cells) are computed and reported. The upper cell of  
331 each node displays the calculated earthquake loss for the corresponding scenario. This value is trivially null for scenarios  
332 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  
333 the end of the decision horizon  $H$  (which could be the end of a concession or the time of pre-determined port expansion),  
334 the earthquake loss  $L(t)$  is computed using Eq. (6), if only one reference seismic event occurred (regardless of when). For  
335 scenarios corresponding to a number of  $n \geq 2$  reference seismic events occurred up to and including year  $t$ , earthquake loss  
336 is determined by using reduced earnings  $ER(t)$  corresponding to  $n-1$  number of reference seismic events in Eq.(7) in place  
337 of earnings  $E(t)$ . The second cell of each node reports seaport earnings. These are computed by Eq. (3) if no reference  
338 seismic event has occurred, or by Eq.(4) (reduced earnings) corresponding to the reduced throughput volume in Eq.(5).  
339 The third cell of each node displays the non-negative payoff (profit) if a seismic upgrade is decided computed as

$$340 \quad PO(t) = \max \{0; L(t) - Cu\} \quad (13)$$

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



348

349 **Fig. 1.** Construction of real options binomial lattice (left panel) and numerical application (right panel)  
 350

351 It is important to note that the above RO modelling and analysis take into account that in all years following a  
 352 reference earthquake, the seaport throughput is affected (reduced) and so are the net earnings. These effects stem from the  
 353 assumptions made in setting up the problem at hand, and are in alignment with reported data in the literature demonstrating  
 354 that in the aftermath of major seismic events, seaports continue to suffer reduced throughput and revenue for several years.  
 355 In fact, the Port of Kobe never recovered throughput rates and revenues after the Hyogoken Nanbu (Kobe) earthquake in  
 356 1995 since cargo traffic was rerouted within regional MTNs in a permanent manner (Change 2000). Furthermore, it is  
 357 noted that reduced throughput and earnings accrue as more and more reference seismic events occur, however, in a given  
 358 year  $t$  their values depend only on the total number of events occurred in all years up to and including year  $t$ : no  
 359 discrimination on the times/years that the earthquakes occur is made. For instance, for the scenario that one reference  
 360 earthquake occurs up to  $t=2$ , the reduced throughput and earnings at  $t=2$  are the same no matter if the earthquake occurred  
 361 at the first or at the second year from the origin. This attribute stems from the assumption that the maintenance and  
 362 operational costs in Eq.(2) are proportional to the income which, in turn, is proportional to the throughput through the  
 363 wharfage fee in Eq.(1). Conveniently, it allows for coupling in pairs the inner nodes of the full binomial lattice, which  
 364 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  
 365 Neufville *et al* 2006). Nevertheless, this simplification does not harm the generality of the herein considered RO-based

366 interpretation and formulation of the problem at hand since it would still be valid and applicable in case net earnings and/or  
 367 revenues were not defined to be throughput-proportional. In such cases, the full binomial tree would be required to solve  
 368 the RO formulation in discrete-time.

369

### 370 *Probabilistic determination of annual payoff and optimal seismic upgrade time*

371 The solution of the previously described RO formulation supports the definition of an *annual expected payoff* which  
 372 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  
 373 year  $t$  from the present time. Specifically, at each year  $t$ , the annual expected payoff,  $EPO$ , is defined as the sum of the  
 374 payoffs  $PO_k(t)$  of all possible scenarios  $k=1,2,\dots,t+1$  weighted by the probability,  $P_k$ , corresponding to each scenario. That  
 375 is,

$$376 \quad EPO(t) = \sum_{k=1}^{t+1} PO_k(t) P_k(t) \quad (14)$$

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

$$380 \quad NPV\{EPO(t)\} = \frac{EPO(t)}{(1+r)^t} \quad (15)$$

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

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

$$392 \quad t^* \triangleq t \in (0, H] : NPV\{EPO(t^*)\} = \max_t \{NPV\{EPO(t)\}\} \quad (16)$$

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

## 400 **Practical considerations**

### 401 *Reference Seismic Event*

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

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

423 compared to the throughput growth,  $g$ , and to the discount factor  $r$ . This finding (further discussed in the following  
424 section) suggests that *decision-making on the timing of the upgrade based on a single level of ground shaking may suffice*  
425 *in many practical cases.*

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

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

#### 443 *Options valuation methodology and discounting factor*

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

452 discussion: (I) the estimation of the probability distribution (measure) of the future cash flows involved in the option  
453 pricing and (II) the choice of discounting factor  $r$ .

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

$$471 \quad WACC = (1 - ETR) \sum_k (DR_k \times i_k) + \left( 1 - \sum_k DR_k \right) e \quad (17)$$

472 where  $\sum_k DR_k$  is the debt ratio (sum of the fractions of total capital  $DR$  obtained by each debt source  $k$ ),  $ETR$  the effective  
473 income tax percentage rate,  $i_k$  is the interest on debt financing for source  $k$ ,  $(1 - \sum_k DR_k)$  is the proportion of equity finance,  
474 and  $e$  is the target return on equity. The target return on equity ranges depending on its source, own cost of capital, risk  
475 appetite and mandate. In absence of any available information, an indicative return on equity  $e$  (equity risk premium) can  
476 be estimated by the capital asset pricing model (Canada *et al* 2004). For more guidance on selecting  $e$ , one is referred to  
477 [53]. In general, the debt ratio  $\sum_k DR_k$ , effective tax rate  $ETR$  and return on equity depend on the different industry sectors.  
478 If port industry-specific measures are not available, one can consider the transport, energy, marine and shipbuilding, and  
479 marine cargo handling industrial sectors or labor classifications as substitutes. The interest on debt,  $i_k$ , depends on the

480 borrower credit worthiness, type of debt issued and debt ratio. For an overview of sources of port infrastructure  
481 financing, the interested reader is directed to Byrne *et al* (1996).

482

### 483 **Illustrative numerical applications and parametric investigations**

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

490

#### 491 *Port authority in a developed country*

492 For a first numerical example of the proposed RO-based approach, a typical two-berth container terminal is  
493 adopted as a base-case seaport facility in which the decision maker is the *port authority* operating in a *low interest-low*  
494 *growth economic environment*, typical of developed countries. Numerical values for all input parameters for this base case  
495 example are listed in Table 1. The assumed containerized cargo wharfage fee,  $f$ , is representative of the Port of Oakland  
496 (2015) tariff. A constant in time cumulative annual throughput growth (CAGR),  $g$ , is taken throughout the time horizon of  
497 the RO analysis  $H=30$  years regarded as a typical concession time-frame. The operational costs including maintenance costs  
498 are based on reported earnings before interest, taxes, depreciation, and amortization in terminals (see e.g., Port technology  
499 2017), while repair and seismic upgrade costs are taken constant throughout the analysis, i.e. not indexed to inflation. The  
500 seaport (asset) value corresponds to the construction cost of a 2km long quay wall costed at \$100.000/m, that a port  
501 authority would typically be responsible for construction and up-keeping. The base value for the discounting factor, reflects  
502 a relatively low WACC and is close to the long term average of 10-year US Treasury bond. A reference seismic event with  
503 MAF  $\lambda_{IM}= 0.2107\%$  corresponding to seismic action having 10% probability to be exceeded in 50 years under the Poisson  
504 assumption for seismic occurrence is taken which is commonly set as the seismic intensity to verify life safety performance  
505 for ordinary structures by seismic codes of practice. The annual probability of occurrence  $P$  in Eq.(12) is 0.2105% and 6  
506 months downtime (i.e.,  $D=0.5$  in Eq. (4)) is assumed.

507 Using the numerical values of the input parameters of Table 1, the RO analysis tree of Fig. 1 is obtained by means  
508 of straightforward spreadsheet-based calculations (see also Brandao *et al* 2005, De Neufville *et al* 2006). For illustration,

509 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  
510 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  
511 obtained for each year from the early stages of the RO analysis, confirming that seismic upgrading is a financially beneficial  
512 proposition, (ii) the  $NPV\{EPO(t)\}$  is increasing monotonically with time indicating that postponing the upgrade to take  
513 place later is potentially beneficial, and (iii) the NPV curve is convex (rate of increase saturates in time) and maximizes in  
514 year  $t=30$  suggesting that postponing seismic upgrade at the end of the analysis horizon is most beneficial. Specifically,  
515 since the throughput is continuously increasing, the probability of more than one reference seismic event happens almost  
516 negligible, and the retrofit cost is constant from year to year, the payoff turns increase monotonically for this case.

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

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

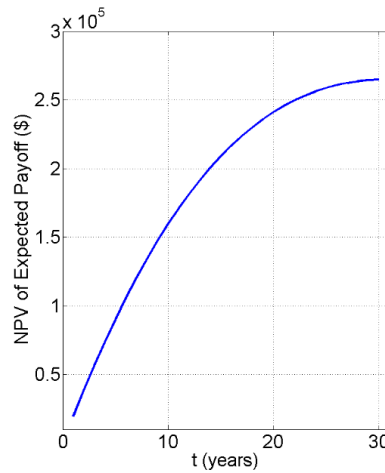
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**Table 1.** Assumed parameter values for the base-case seaport

Parameter	Value
Wharfage fee	$f = \$83 / \text{TEU}$
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%

540



541

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

542

543

544

**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%

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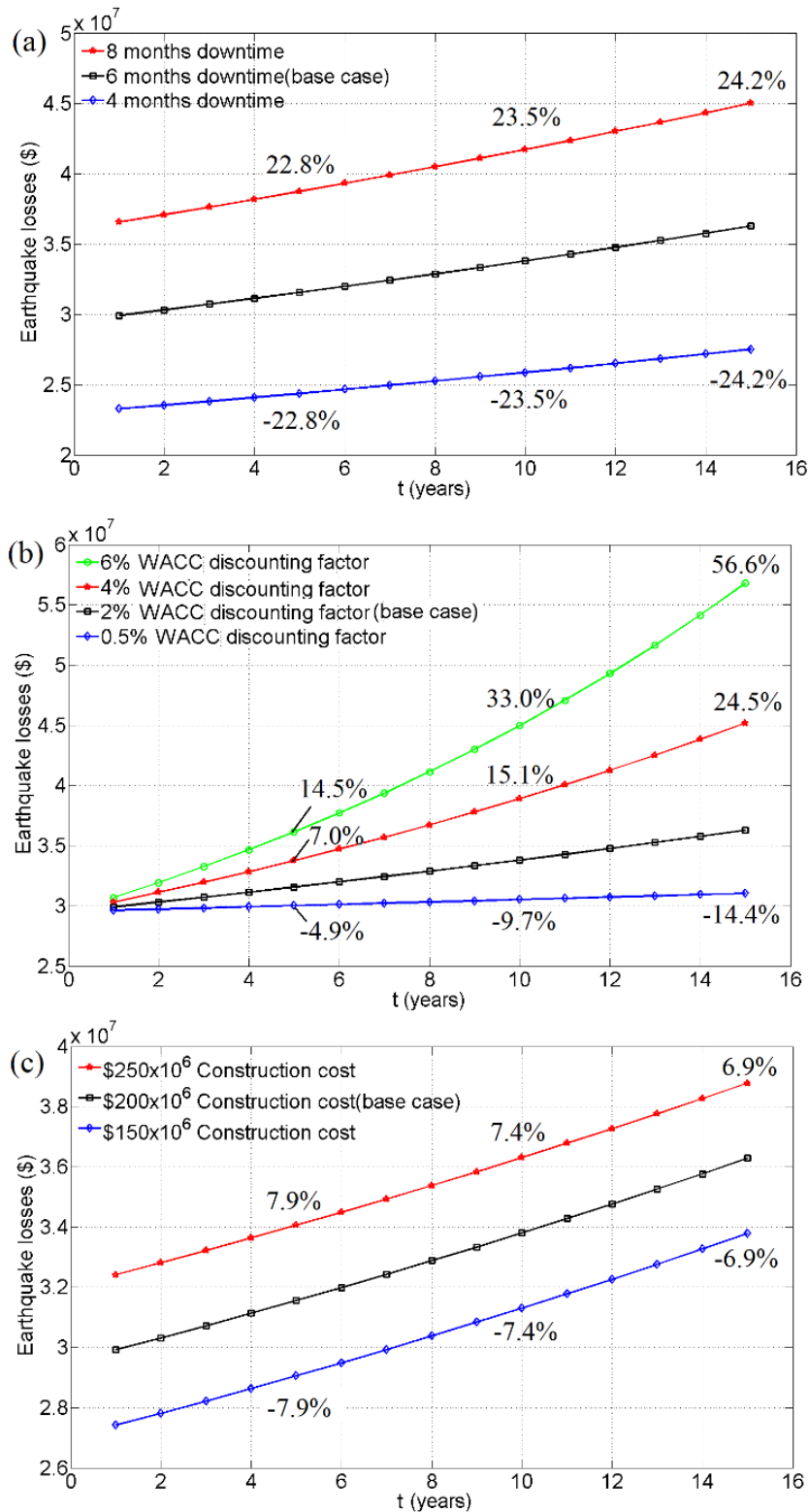
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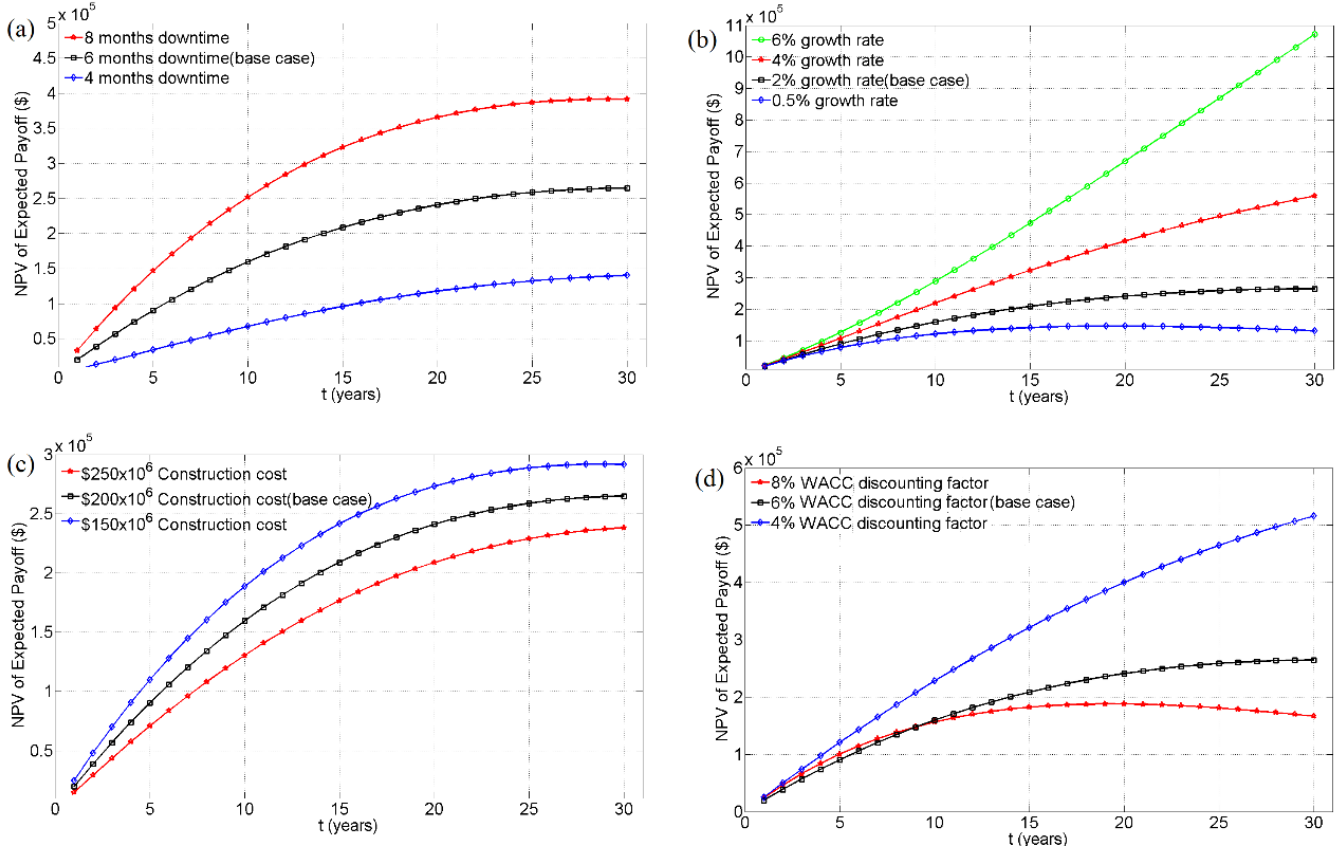
Figure 3(b) quantifies the effect of different projected average throughput growth rates, CAGRs, to the aggregate earthquake loss, through the increase of the income. It is seen that for high CAGRs, the analysis yields significantly higher monetary losses as the seismic upgrading is postponed in time. 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 throughput 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

559 expected payoff increases significantly in later years, providing a stronger incentive to postpone the retrofit decision.  
 560 Interestingly, this example suggests that in low interest rate environments, the “kick the can down the road” strategy of  
 561 risk mitigation is more appealing.



562 **Fig. 4.** Sensitivity of expected payoff in year  $t$  to (a) different downtime, (b) different throughput growth rate, (c)  
 563 different asset value, and (d) for different discount factor  
 564  
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### 566 *Terminal operator*

567 In this example, the proposed RO-based approach is applied to a notional terminal operator to support a decision  
 568 on optimal time for seismic retrofit/upgrade of the quay cranes, critical mobile equipment for the operations of the terminal.  
 569 Typically, terminal operators are responsible for installing and maintaining these cranes and other lifting equipment as well  
 570 as the buildings, pavement and utilities, whereas the port authority would be responsible for the fixed infrastructure (e.g.  
 571 quay walls), coastal protection and reclamation. A two berth terminal would typically have 8 quay cranes. The values of  
 572 the parameters for this example are shown in Table 3. Three cases of increasing downtime, retrofit, and repair costs are  
 573 considered, in order to assess the sensitivity of the optimal retrofit time to these parameters, obtained from probabilistic  
 574 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.  
 575 In case 3 the repair cost is double that of the retrofit cost. What should also be observed here is the relatively high  
 576 discounting factor, WACC in Eq. (17), which reflects the financing cost for a private terminal operator and includes debt-

577 to-equity ratio, market risk as well as country risk. Indeed, cost of capital between 8-16% is not uncommon for this type of  
 578 investment. For example, assuming a single debt source,  $k=1$ , no tax rebate,  $ETR=0$ ,  $DR_T=60\%$  debt ratio of total capital,  
 579 target return on equity  $e=16\%$ , and interest on debt financing  $i_1=10\%$  gives  $WACC=12.4\%$  in Eq.(17).

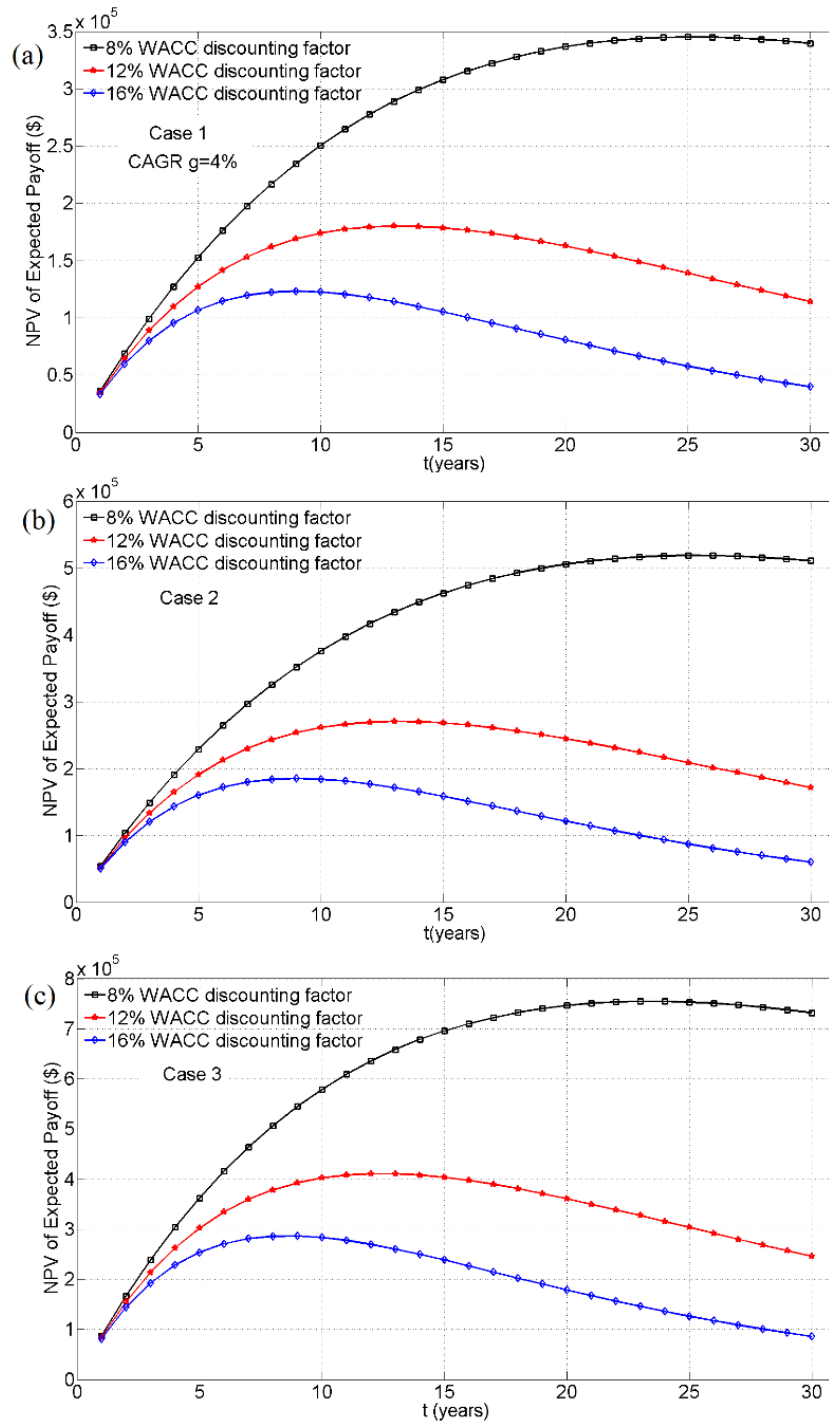
580 Numerical values obtained from Eqs.(15) and (16) are provided in Fig. 5 and Table 4, respectively. Although the  
 581 NPV of the expected payoff increases as the repair/ retrofit cost (cases 1, 2, 3) increase, the optimal times to retrofit remain  
 582 the same for case 1 and 2 (repair cost equal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

586 **Table 3.** Terminal Operator example parameters

Parameter	Value		
	Case 1	Case 2	Case 3
Wharfage fee	$f=\$150 / \text{TEU}$		
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)		

587  
 588 To examine further the combined effect of WACC and CAGR to the optimal seismic upgrade time, case 1 is run  
 589 under throughput growth rates ranging from 1-6% and time  $t^*$  values are plotted in Fig. 6. As CAGR increases, the optimal  
 590 time is pushed back in time. In the case of high WACC the change is almost linear but as the WACC reduces, the optimal  
 591 time increases non-linearly towards the end of the analysis horizon (30 years). These results demonstrate significant non-  
 592 linear sensitivity of the optimal retrofit time to the discounting factor and the throughput growth rate. High growth rates  
 593 and low cost of capital again push the optimal seismic upgrade timing for later. In other words, *in high growth, low capital*  
 594 *cost environments it is more beneficial to postpone the retrofit because the expected payoff increases and the dampening*  
 595 *effect of discounting is small. On the contrary, in low growth, high capital cost environments a point appears within the 30*

596 year horizon where the NPV of the expected payoff is maximized, providing thus an optimal non-trivial time for seismic  
 597 upgrading. This is a novel finding/outcome that no previous work or established approach has reached before.



598  
 599 **Fig. 5.** NPV of expected payoff in year  $t$  for container terminal operator example (a) Case 1, (b) Case 2, (c) Case 3 in  
 600 Table 3.  
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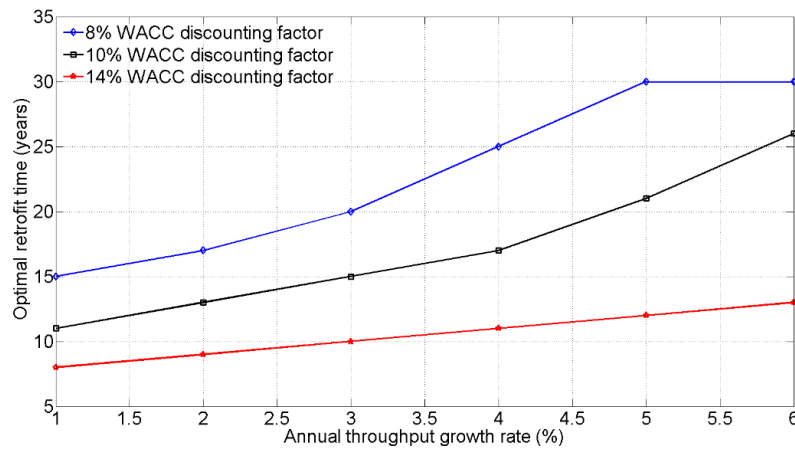
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**Table 4.** Terminal Operator example - optimal times for retrofit

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

606



607

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

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611 *Port authority in a developing country*

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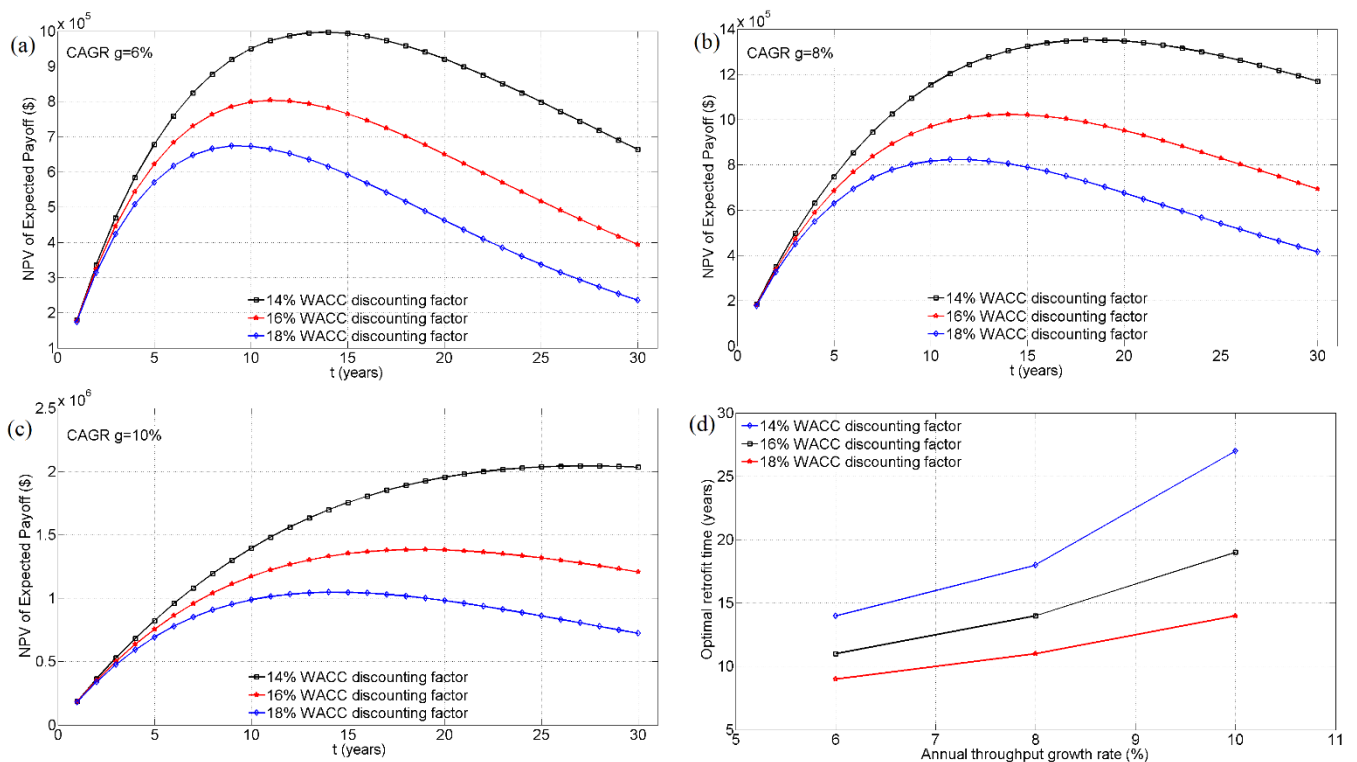
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In this example, the growth rate and capital cost parameters reflect a high growth-high capital cost environment of a port in an emerging market country. Such developments are usually Public-Private-Partnerships, based on a Build-Operate-Transfer model (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.

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

Parameter	Value
Wharfage fee	$f = \$120 / \text{TEU}$
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%

626  
627



628 **Fig. 7.** NPV of expected payoff in year  $t$  for port authority in developing country and for throughput growth rate (a) 6%,  
629 (b) 8%, (c) 10%. (d): Sensitivity of optimal time of seismic upgrade versus throughput growth rate  
630  
631

632 **Concluding remarks**

633 A real options (RO) approach has been proposed for decision-making on the appropriate time to seismically  
634 upgrade a given seaport (e.g. within a practical time-frame of a typical concession period), such that negligible damage  
635 occurs for a reference seismic event. The problem has been formulated in discrete-time by considering a RO binomial  
636 lattice (tree). In the proposed RO formulation, earthquake consequences having an annual probability of occurrence  $P$  have  
637 been associated with the reference seismic event with small MAF of occurrence following a Poisson temporal distribution.  
638 The proposed formulation fits well within the existing and recently developed frameworks for seaport risk analysis, and

639 can be adapted to sit either on top of probabilistic seismic loss analysis (i.e., loss curves) or a site-specific seismic hazard  
640 curve. By considering a series of simplified yet realistic assumptions the NPV of the expected payoff of the option to  
641 seismically upgrade a seaport has been estimated using straightforward spreadsheet-based calculations that can automate  
642 the analysis and visualize pertinent results. A sensitivity analysis with respect to the assumed downtime, growth throughput  
643 rate, initial seaport asset value and weighted average cost of capital demonstrates that the economic factors (growth rate  
644 and cost of capital), overshadow the engineering-related factors (total asset value, downtime, retrofit and repair costs), in  
645 the determination of the optimal seismic upgrade time. The usefulness and applicability of the developed approach has  
646 been illustrated by application to typical scenario cases of ports and terminals in economic environments ranging from low  
647 growth-low cost of capital to high growth, high cost of capital. Qualitatively reasonable and quantitatively valuable and  
648 consistent conclusions have been drawn in view of the presented numerical data. In particular, it was shown that in the  
649 high growth-low interest environment of a booming developed economy, although there are positive benefits in retrofitting,  
650 early retrofit is not optimal, whereas in a high growth, high cost of capital economy (reflecting an emerging market  
651 economy in a developing country) the optimal time to retrofit appears early on. Consistently, the optimal time to retrofit  
652 increases as the throughput growth rate increases and the cost of capital decreases.

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

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