

Appendix
A dynamic modeling approach for infrastructure project evaluation under evolving risks

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A. Pseudocode

Algorithm 1 Forward Monte Carlo evaluation of a specified policy π

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1: Input initial state  $S_0 = \{X_0, F_0, E_0\}$ 
2: Input policy  $\pi$ , horizon  $T$ , step  $\Delta t$ , discount factor  $\gamma$ 
3: Input number of replications  $N$ , parameter sets  $\Theta^X, \Theta^F, \Theta^E$ 
4: for  $n = 1$  to  $N$  do
5:   Set  $t \leftarrow 0$ 
6:   Set  $S(t) \leftarrow S_0$ 
7:   Initialise discounted outputs and trajectory indicators
8:   while  $t < T$  do
9:     Observe current state  $S(t)$ 
10:    Apply policy  $a_t \leftarrow \pi(S(t))$ 
11:    Realise stochastic drivers  $\xi_{t+\Delta t}$ 
12:     $S(t + \Delta t) \leftarrow \text{UPDATESTATE}(S(t), a_t, \xi_{t+\Delta t}, \Theta^X, \Theta^F, \Theta^E)$ 
13:    Record  $r(S(t), a_t)$ 
14:    Record selected indicators from  $S(t)$ ,  $a_t$ , and  $S(t + \Delta t)$ 
15:     $t \leftarrow t + \Delta t$ 
16:     $S(t) \leftarrow S(t + \Delta t)$ 
17:   end while
18:   Compute discounted trajectory outputs for replication  $n$ 
19:   Store replication results
20: end for
21: Aggregate replications to estimate  $\Psi(S_0, \pi)$ , distributions, shortfall probabilities, and summary statistics
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Algorithm 2 Coupled state update UPDATESTATE

- 1: **Input** current state $S(t) = \{X(t), F(t), E(t)\}$
 - 2: **Input** action $a_t = (a_t^P, a_t^F, a_t^E)$
 - 3: **Input** realised drivers $\xi_{t+\Delta t}$, parameter sets $\Theta^X, \Theta^F, \Theta^E$
 - 4: Decompose $S(t)$ into $X(t)$, $F(t)$, and $E(t)$
 - 5: $(X(t + \Delta t), \chi_{t+\Delta t}^X) \leftarrow \text{PHYSICALUPDATE}(X(t), a_t^P, \xi_{t+\Delta t}, \Theta^X)$
 - 6: $(E(t + \Delta t), \chi_{t+\Delta t}^E) \leftarrow \text{ENVIRONMENTALUPDATE}(E(t), X(t + \Delta t), a_t^E, \xi_{t+\Delta t}, \Theta^E)$
 - 7: $F(t + \Delta t) \leftarrow \text{FINANCIALUPDATE}(F(t), X(t + \Delta t), E(t + \Delta t), a_t^F, \chi_{t+\Delta t}^X, \chi_{t+\Delta t}^E, \xi_{t+\Delta t}, \Theta^F)$
 - 8: Assemble $S(t + \Delta t) \leftarrow \{X(t + \Delta t), F(t + \Delta t), E(t + \Delta t)\}$
 - 9: **Return** $S(t + \Delta t)$
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Algorithm 3 Physical update

- 1: **Input** physical state $X(t) = \{x_t, s_t\}$
 - 2: **Input** physical action a_t^P , realised drivers $\xi_{t+\Delta t}$
 - 3: **Input** physical parameters Θ^X
 - 4: Extract realised demand $D_{t+\Delta t}$ from $\xi_{t+\Delta t}$
 - 5: Compute time varying event intensity $\lambda(u; \Theta^X)$
 - 6: Compute event probability $p_{ev}^{[t, t+\Delta t]}$
 - 7: Draw event occurrence $I_{t+\Delta t}^{ev} \sim \text{Bernoulli}(p_{ev}^{[t, t+\Delta t]})$
 - 8: Compute deterioration increment $\delta_{t+\Delta t} \leftarrow \delta^X(X(t), D_{t+\Delta t}; \Theta^X)$
 - 9: Compute maintenance restoration $M_x(a_t^P)$ and maintenance cost $C_{t+\Delta t}^M$ from a_t^P and Θ^X
 - 10: **if** $I_{t+\Delta t}^{ev} = 1$ **then**
 - 11: Compute realised event loss $L_{t+\Delta t}^x$ from $X(t)$, a_t^P , and Θ^X
 - 12: Compute realised event repair cost $C_{t+\Delta t}^{ev}$ from $X(t)$, a_t^P , and Θ^X
 - 13: **else**
 - 14: Set $L_{t+\Delta t}^x \leftarrow 0$
 - 15: Set $C_{t+\Delta t}^{ev} \leftarrow 0$
 - 16: **end if**
 - 17: Update condition $x_{t+\Delta t} \leftarrow x_t - \delta_{t+\Delta t} + M_x(a_t^P) - L_{t+\Delta t}^x$
 - 18: Bound $x_{t+\Delta t}$ to the interval $[0, 1]$
 - 19: Update service $s_{t+\Delta t} \leftarrow s^X(x_{t+\Delta t}; \Theta^X)$
 - 20: Set $X(t + \Delta t) \leftarrow \{x_{t+\Delta t}, s_{t+\Delta t}\}$
 - 21: Set $\chi_{t+\Delta t}^X \leftarrow \{C_{t+\Delta t}^M, C_{t+\Delta t}^{ev}\}$
 - 22: **Return** $(X(t + \Delta t), \chi_{t+\Delta t}^X)$
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Algorithm 4 Environmental update

- 1: **Input** environmental state $E(t) = \{e_t, \bar{e}_t, p_t^C\}$
 - 2: **Input** updated physical state $X(t + \Delta t) = \{x_{t+\Delta t}, s_{t+\Delta t}\}$
 - 3: **Input** environmental action a_t^E , realised drivers $\xi_{t+\Delta t}$
 - 4: **Input** environmental parameters Θ^E
 - 5: Update carbon price $p_{t+\Delta t}^C \leftarrow p^E(p_t^C, \xi_{t+\Delta t}; \Theta^E)$
 - 6: Compute action adjusted emissions factor $\eta_{t+\Delta t}^E \leftarrow \eta_E(a_t^E; \Theta^E)$
 - 7: Compute period emissions $e_{t+\Delta t} \leftarrow e^E(X(t + \Delta t), \eta_{t+\Delta t}^E, \xi_{t+\Delta t}; \Theta^E)$
 - 8: Update cumulative emissions $\bar{e}_{t+\Delta t} \leftarrow \bar{e}_t + e_{t+\Delta t}$
 - 9: Compute environmental cash charge $C_{t+\Delta t}^E \leftarrow C^E(e_{t+\Delta t}, p_{t+\Delta t}^C, a_t^E, \xi_{t+\Delta t}; \Theta^E)$
 - 10: Set $E(t + \Delta t) \leftarrow \{e_{t+\Delta t}, \bar{e}_{t+\Delta t}, p_{t+\Delta t}^C\}$
 - 11: Set $\chi_{t+\Delta t}^E \leftarrow \{C_{t+\Delta t}^E\}$
 - 12: **Return** $(E(t + \Delta t), \chi_{t+\Delta t}^E)$
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Algorithm 5 Financial update

- 1: **Input** financial state $F(t) = \{c_t, DS_t, DSCR_t\}$
 - 2: **Input** updated physical state $X(t + \Delta t) = \{x_{t+\Delta t}, s_{t+\Delta t}\}$
 - 3: **Input** updated environmental state $E(t + \Delta t) = \{e_{t+\Delta t}, \bar{e}_{t+\Delta t}, p_{t+\Delta t}^C\}$
 - 4: **Input** financial action a_t^F , realised drivers $\xi_{t+\Delta t}$
 - 5: **Input** auxiliary outputs $\chi_{t+\Delta t}^X = \{C_{t+\Delta t}^M, C_{t+\Delta t}^{ev}\}$, $\chi_{t+\Delta t}^E = \{C_{t+\Delta t}^E\}$
 - 6: **Input** financial parameters Θ^F
 - 7: Compute operating revenue $R_{t+\Delta t} \leftarrow R^F(X(t + \Delta t), E(t + \Delta t), a_t^F, \xi_{t+\Delta t}; \Theta^F)$
 - 8: Compute scheduled debt service $DS_{t+\Delta t} \leftarrow DS^F(t + \Delta t, F(t), a_t^F, \xi_{t+\Delta t}; \Theta^F)$
 - 9: Compute operating and recovery outflow $C_{t+\Delta t}^{O\&M} \leftarrow C_{t+\Delta t}^M + C_{t+\Delta t}^{ev}$
 - 10: Compute $CFADS_{t+\Delta t} \leftarrow R_{t+\Delta t} - C_{t+\Delta t}^{O\&M} - C_{t+\Delta t}^E$
 - 11: **if** $DS_{t+\Delta t} > 0$ **then**
 - 12: Compute $DSCR_{t+\Delta t} \leftarrow CFADS_{t+\Delta t} / DS_{t+\Delta t}$
 - 13: **else**
 - 14: Set $DSCR_{t+\Delta t} \leftarrow +\infty$
 - 15: **end if**
 - 16: Compute policy induced financial adjustment $B_{t+\Delta t}(a_t^F, \xi_{t+\Delta t})$
 - 17: Update available cash $c_{t+\Delta t} \leftarrow c_t + CFADS_{t+\Delta t} - DS_{t+\Delta t} + B_{t+\Delta t}(a_t^F, \xi_{t+\Delta t})$
 - 18: Set $F(t + \Delta t) \leftarrow \{c_{t+\Delta t}, DS_{t+\Delta t}, DSCR_{t+\Delta t}\}$
 - 19: **Return** $F(t + \Delta t)$
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