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Research Paper

Comparative Valuation of Employee Stock Options Using CRR and Enhanced American Models with Vesting and Exit Effects

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Abstract
Employee stock options (ESOs) are required to be measured at grant-date fair value under existing accounting standards, yet classical lattice models typically assume frictionless exercise behavior. In practice, ESO contracts incorporate vesting restrictions, employee exit risk, and behavioral exercise triggers that can materially affect valuation outcomes. This study provides a structural comparison between the Cox–Ross–Rubinstein (CRR) American model and the Enhanced American (EA) framework within a unified binomial setting in which the probabilistic return process constant to isolate employment-related frictions. An analytical dominance result is established, showing that EA valuations remain strictly below the CRR American benchmark under these frictions. Numerical experiments confirm the theoretical ordering and quantify its economic magnitude: under moderate frictions, valuation gaps remain limited to approximately 2–3%, whereas under high exit intensity and conservative trigger thresholds, the discount expands substantially to approximately 65–69%, particularly for long-dated and near-the-money contracts. Heatmap analysis across volatility and dividend regimes further demonstrates that this dominance ordering persists under economically relevant parameter variations. The findings indicate that employment-related frictions constitute a materially significant component of ESO valuation and that model choice within fair-value measurement frameworks can meaningfully influence reported compensation expenses.

Keywords
Employee Stock Options, Enhanced American Model, Cox–Ross–Rubinstein Model, Vesting Period, Exit Risk, Fair Value Measurement

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1. INTRODUCTION

Employee Stock Options (ESOs) are a widely used instrument in long-term corporate compensation schemes, granting employees the right, but not the obligation, to purchase company shares at a predetermined strike price upon satisfying specified contractual conditions (Lesmana et al., 2025; Secfi, 2023). Unlike standard traded options, ESOs are non-transferable and subject to employment-contingent restrictions that fundamentally alter their economic characteristics. Since their introduction in the United States during the 1950s, ESOs have been adopted across various industries and countries as a mechanism for aligning employee and shareholder interests, strengthening retention incentives, and supporting sustainable corporate growth (Adrianto et al., 2024; Alifianty and Susanty, 2016; Athar, 2020; Hull, 2022). Their use has expanded beyond developed markets to emerging economies, including Indonesia, where publicly listed firms have incorporated ESO programs into executive and employee compensation structures (Aran, 2018; Cable, 2025; Chendra et al., 2022). Despite their widespread adoption, however, accurately valuing ESOs remains technically challenging because these contracts contain institutional and behavioral features that distinguish them substantially from standard financial derivatives.

Accurate ESO valuation is essential for both financial reporting and managerial decision-making. Several accounting standards, including IFRS 2 (International Accounting Standards Board, 2016), FASB ASC Topic 718 (Financial Accounting Standards Board, 2021), and PSAK 53 (Ikatan Akuntan Indonesia, 2014), require firms to measure ESOs at grant-date fair value and recognize compensation expenses systematically over the vesting period. Although these standards emphasize reliability and consistency in share-based compensation reporting, none prescribes a specific valuation methodology. Consequently, the selection of an appropriate valuation model is left to the reporting firm, raising important questions about whether model choice materially affects reported compensation expenses. Such sensitivity becomes particularly consequential in environments characterized by high employee turnover and binding vesting restrictions, where alternative valuation frameworks may generate substantially different grant-date fair values.

Among the available valuation approaches, lattice-based models remain widely used in ESO valuation practice because of their computational tractability, intuitive structure, and flexibility in accommodating early exercise behavior. The Cox–Ross–Rubinstein (CRR) binomial model (Cox et al., 1979) continues to serve as the dominant benchmark framework, providing a discrete-time approximation to geometric Brownian motion. Various refinements and extensions of the lattice framework have also been proposed, including the trinomial model of Boyle (1986, 1988), the moment-matching approach of Tian (1998), and convergence-acceleration techniques developed by Abdurakhman et al. (2006) and Abdurakhman (2023). While these developments improve numerical accuracy and convergence properties, the classical CRR framework remains the standard reference point for comparative ESO valuation analysis.

A major limitation of the classical CRR American framework, however, is its assumption of frictionless exercise behavior. In practice, ESO contracts commonly incorporate employment-related restrictions that materially affect exercise decisions and continuation values. The first is the vesting restriction, which prohibits exercise before a specified date. The second is employee exit risk, which reflects the possibility that employees leave the firm prior to option maturity (Ammann and Seiz, 2004; Anggraeni, 2015). Employees who leave before vesting generally forfeit their options entirely, whereas those who depart after vesting may be required to exercise immediately or lose their entitlement. Ignoring these features may therefore lead to systematic overvaluation of ESO compensation expenses and distortions in reported fair values (Bahaji, 2018; Hull, 2022; Leung, 2022). In addition, empirical evidence suggests that employee exercise behavior often deviates from the fully rational optimal exercise policy implied by standard American option models. Employees frequently exercise options earlier than the theoretical American boundary due to factors such as risk aversion, liquidity needs, and subjective beliefs about future stock price performance (Arora and Kaur, 2024; Pendleton and Robinson, 2023). Capturing these behavioral effects requires extending the standard lattice framework to incorporate explicit exercise-trigger mechanisms.

To address these limitations, several ESO-specific valuation frameworks have been developed in the literature, including the Hull-White model (Hull and White, 1987), the Utility Maximization model Ammann and Seiz (2004), the FASB ASC Topic 718 framework (Financial Accounting Standards Board, 2021), and the Enhanced American (EA) model proposed by Ammann and Seiz (2004). The EA model is particularly relevant to the present study because it extends the CRR binomial framework by incorporating three important ESO-specific features within a unified lattice structure: a vesting period that restricts early exercise, a continuous exit rate governing employment termination risk, and a behavioral exercise trigger defined as a multiple of the strike price. This formulation allows the EA framework to capture the combined effects of contractual restrictions and non-standard exercise behavior while remaining computationally tractable and consistent with fair-value reporting requirements under IFRS 2, FASB ASC Topic 718, and PSAK 53.

From a mathematical perspective, the stock-price dynamics in both models are represented using the CRR binomial approximation to geometric Brownian motion. This assumption is adopted not as an empirical claim regarding the exact distribution of stock returns, but rather as a structural device that ensures identical return dynamics across both models, allowing employment-related frictions to be isolated as the sole source of valuation differences within the lattice structure. This approach differs from many previous studies that simultaneously modify stochastic assumptions and behavioral specifications, making it difficult to attribute observed valuation differences to specific model components (Devianto et al., 2018; Sayed and Muhammad, 2022; Yusof et al., 2021).

Despite the growing literature on ESO valuation, a formal dominance relationship between the Enhanced American and CRR American frameworks within a unified binomial lattice has not been analytically established. More broadly, existing comparative studies generally emphasize differences in model specification or calibration rather than deriving rigorous valuation bounds between competing frameworks, and the magnitude and persistence of friction-induced valuation gaps across maturity and moneyness regimes remain insufficiently explored. Recent studies continue to advance behavioral exercise modeling and friction-adjusted pricing methodologies (Arora and Kaur, 2024; Pendleton and Robinson, 2023; Wang et al., 2025), yet a bound-based interpretation of ESO valuation distortions within a controlled probabilistic environment remains relatively absent from the literature.

This study addresses these issues through three main contributions. First, it establishes an analytical dominance result-Proposition 1, proving that the EA option value is bounded above by the CRR American value at every lattice node under any positive vesting period, exit rate, and trigger multiple. Second, by maintaining a common probabilistic return process across both frameworks, it isolates employment-related frictions as the sole source of structural valuation differences. Third, systematic numerical experiments quantify the magnitude and economic significance of friction-induced valuation distortions across maturity, strike price, volatility, and dividend yield regimes, providing explicit lower and upper valuation bounds that offer a structured interpretation of how vesting constraints, exit risk, and behavioral exercise rules alter continuation values and fair-value measurement within the lattice framework.

2. EXPERIMENTAL SECTION

This section presents the valuation frameworks, analytical properties, and numerical procedures used to compare the classical Cox–Ross–Rubinstein (CRR) American model with the Enhanced American (EA) model in valuing employee stock options (ESOs). The analysis is conducted within a discrete-time binomial lattice under identical contract assumptions to isolate the effects of vesting restrictions, employee exit risk, and behavioral exercise features. The section first outlines the underlying valuation models and their theoretical properties, followed by the simulation procedure, experimental design, and evaluation metrics employed in the numerical analysis.

2.1 Valuation Models (Methods–Model Framework)

This subsection describes the valuation models employed in the analysis. The classical CRR American binomial model is first introduced as a benchmark framework commonly used in applied option valuation. The Enhanced American (EA) model is then described as an extension that incorporates key employment-related features of ESOs, including vesting restrictions, employee exit risk, and behavioral exercise decisions. Both models are formulated within a unified binomial setting to ensure a consistent basis for comparison. Beyond their numerical implementation, several structural properties of the Enhanced American (EA) model can be established analytically under identical probabilistic assumptions.

2.1.1 Cox–Ross–Rubinstein (CRR) Binomial Model

The Cox–Ross–Rubinstein (CRR) model is one of the most widely used discrete-time frameworks for option valuation, representing the stochastic evolution of the underlying asset through a recombining binomial lattice (Cox et al., 1979). During each time step of length Δt, Equations (1) and (2) define the up and down movement factors in the recombining binomial lattice:

$$u = e^{\sigma\sqrt{\Delta t}}, \tag{1}$$

$$d = e^{-\sigma\sqrt{\Delta t}}. \tag{2}$$

Here, u and d denote the upward and downward movement factors in the recombining binomial lattice, and σ denotes the annualized volatility of the underlying asset. The corresponding risk-neutral probability of an upward move is given by Equation (3):

$$q = \frac{e^{(r-\delta)\Delta t} - d}{u - d}, \tag{3}$$

where r is the continuously compounded risk-free rate and δ is the continuous dividend yield (Hull, 2022). To ensure a valid risk-neutral probability and exclude arbitrage opportunities within the binomial lattice, Equation (4) specifies the no-arbitrage condition that must be satisfied by the binomial parameters:

$$0 < q < 1 \iff d < e^{(r-\delta)\Delta t} < u. \tag{4}$$

At maturity ($i = N$), Equation (5) gives the terminal option payoff:

$$V_{N,j} = \max(S_{N,j} - K, 0), \tag{5}$$

where $S_{N,j}$ is the stock price at node (N, j). Backward induction is then applied to compute $V_{i,j}$ for earlier nodes. Under the American specification, early exercise is permitted at any node prior to maturity. Accordingly, Equation (6) defines the option value as the maximum of the early exercise value and the discounted continuation value:

$$V_{i,j} = \max\left(S_{i,j} - K, e^{-r\Delta t}\left(qV_{i+1,j+1} + (1-q)V_{i+1,j}\right)\right), \tag{6}$$

where the first term represents the early exercise value and the second term the continuation value (Hull, 2022). The CRR American model provides a tractable and intuitive benchmark; however, it does not capture employment-related features of ESOs such as vesting restrictions, employee turnover, or behavioral exercise triggers (Ammann and Seiz, 2004). These frictions motivate the development of the Enhanced American (EA) model.

2.1.2 Enhanced American (EA) Model

The Enhanced American (EA) model, proposed by Ammann and Seiz (2004), extends the classical CRR framework by incorporating three essential ESO characteristics: the vesting period (v), the exit rate (w) representing employee exit risk, and a behavioral exercise trigger defined as a multiple of the strike price (M). Valuation is conducted through backward induction in two phases: the pre-vesting period, during which exercise is contractually prohibited, and the post-vesting period, during which rational early exercise may occur.

Let $V_{i,j}$ denote the option value at node (i, j), Equation (7) defines the one-step risk-neutral continuation value (prior to incorporating exit risk) as:

$$C_{i,j} = e^{-r\Delta t}\left(qV_{i+1,j+1} + (1-q)V_{i+1,j}\right), \tag{7}$$

where $C_{i,j}$ represents the discounted expected continuation value before accounting for employee exit risk.

During the vesting period ($i\Delta t < v$), exercise is disallowed. The employee faces a continuous exit rate w, with single-step survival probability $P_{stay} = e^{-w\Delta t}$. Because departure before vesting leads to forfeiture, Equation (8) gives the pre-vesting EA value:

$$V_{i,j} = e^{-w\Delta t}C_{i,j}. \tag{8}$$

After vesting ($i\Delta t \geq v$), employees may exercise their options if the stock price exceeds the behavioral trigger level MK, where M is the trigger multiple (Leung, 2022). The exercise decision compares the immediate payoff with the continuation value, subject to the feasibility condition that the option is in the money ($S_{i,j} > K$). Hence, early exercise occurs whenever both conditions are satisfied:

$$S_{i,j} > K, \text{ and } \max(S_{i,j} - MK, 0) \geq C_{i,j} \implies V_{i,j} = S_{i,j} - K. \quad (9)$$

The first condition ensures of Equation (9) that the option carries positive intrinsic value and is economically exercisable. The second condition compares the trigger-adjusted intrinsic value with the discounted continuation value, ensuring that exercise is optimal relative to holding the option. Both feasibility and optimality must hold simultaneously for early exercise to occur.

If either condition is not satisfied, the option is held for one additional step. With probability $1 - P_{stay}$, an exit occurs after vesting, resulting in forced exercise if the option is in the money and forfeiture otherwise. With probability P_{stay}, employment continues, and Equation (10) defines the node value as the weighted combination of the forced-exit payoff and the discounted continuation:

$$V_{i,j} = (1 - e^{-w\Delta t}) \max(S_{i,j} - K, 0) + e^{-w\Delta t} C_{i,j}. \quad (10)$$

This formulation captures both the possibility of forced exercise upon exit and the continuation value under employment survival.

The behavioral parameter M governs the exercise threshold relative to the standard American boundary. When $M < 1$, employees exercise prematurely; when $M > 1$, they delay exercise, reflecting optimism or retention incentives. Setting $M = 1$ reduces the EA model to the standard American model adjusted for vesting and exit. Through these recursive relations, the EA framework jointly accounts for vesting restrictions, exit probabilities, and behavioral triggers within a parsimonious binomial structure. This formulation is consistent with IFRS 2, FASB ASC TOPIC 718, and PSAK 53 (International Accounting Standards Board, 2016; Financial Accounting Standards Board, 2021; Ikatan Akuntan Indonesia, 2014), and provides a realistic yet tractable model for ESO valuation. The complete backward-induction procedure implementing the EA recursion is summarized in Table 1. The range of trigger multiples considered in this study is calibrated to reflect empirically plausible exercise behavior documented in the ESO literature. Values of M slightly above unity represent delayed exercise attributable to optimism, risk aversion, or retention incentives, while larger values correspond to more conservative exercise thresholds. This specification is consistent with the behavioral interpretation of exercise policies discussed in Ammann and Seiz (2004) and Leung (2022), and allows the EA model to capture heterogeneous employee behavior without introducing additional structural complexity.

2.1.3 Theoretical Properties of the EA Model

Before presenting the numerical analysis, several structural properties of the EA model are established under identical probabilistic assumptions. These properties clarify the valuation relationships between the EA model and the classical CRR American model and characterize the sensitivity of the ESO value with respect to key parameters.

Proposition 1 (Dominance of the CRR American Model). Under identical binomial parameters $(S_0, K, r, \delta, \sigma, T, N)$ and for any $v \geq 0$, $w \geq 0$, and $M > 0$, the EA option value is bounded above by the CRR American option value:

$$V_{i,j}^{EA}(v, w, M) \leq V_{i,j}^{CRR,Am}, \text{ for all nodes } (i, j). \quad (11)$$

Consequently,

$$V_0^{EA}(v, w, M) \leq V_0^{CRR,Am}. \quad (12)$$

Proof. At maturity $i = N$, both models yield the same terminal payoff

$$V_{N,j}^{EA} = V_N^{CRR,Am} = X_{i,j},$$

where $X_{i,j} = \max(S_{i,j} - K, 0)$.

Assume the inequality holds at time $i + 1$. Because the continuation operator

$$C_{i,j}(V) = e^{-r\Delta t}(qV_{i+1,j+1} + (1 - q)V_{i+1,j}),$$

is monotone in V, the inductive hypothesis gives

$$C_{i,j}(V^{EA}) \leq C_{i,j}(V^{CRR,Am}).$$

During the vesting period,

$$V_{i,j}^{EA} = e^{-w\Delta t} C_{i,j}(V^{EA}) \leq C_{i,j}(V^{CRR,Am}) \leq V_{i,j}^{CRR,Am}.$$

After vesting, if the EA rule prescribes exercise, $V_{i,j}^{EA} = X_{i,j} \leq V_{i,j}^{CRR,Am}$. Otherwise,

$$V_{i,j}^{EA} = (1 - \alpha)X_{i,j} + \alpha C_{i,j}(V^{EA}), \quad \alpha = e^{-w\Delta t} \in (0, 1],$$

which is a convex combination of $X_{i,j}$ and $C_{i,j}(V^{EA})$. Hence

$$V_{i,j}^{EA} \leq \max\{X_{i,j}, C_{i,j}(V^{CRR,Am})\} \leq V_{i,j}^{CRR,Am}.$$

By backward induction the inequality holds for all nodes.

Proposition 2 (Monotonicity in the Exit Rate). For fixed vesting period v and trigger multiple M, the EA value is non-increasing in the exit rate w:

$$w_1 < w_2 \Rightarrow V_0(v, w_1, M) \geq V_0(v, w_2, M). \quad (13)$$

Let $\alpha(w) = e^{-w\Delta t}$ denote the single step employment survival probability. Since $\alpha(w)$ is strictly decreasing in w, an increase in w reduces α.

During the vesting period,

$$V_{i,j}^{EA} = \alpha(w)C_{i,j},$$

so a reduction in α directly reduces the continuation value.

After vesting, in the continuation region,

$$V_{i,j}^{EA} = (1 - \alpha(w))X_{i,j} + \alpha(w)C_{i,j}.$$

Differentiating with respect to α gives

$$\frac{\partial V}{\partial \alpha} = C_{i,j} - X_{i,j}.$$

Since continuation occurs only when $C_{i,j} \geq X_{i,j}$, it follows that

$$\frac{\partial V}{\partial \alpha} \geq 0.$$

Because

$$\frac{d\alpha}{dw} = -\Delta t e^{-w\Delta t} < 0,$$

the chain rule yields we obtain

$$\frac{\partial V}{\partial w} \leq 0.$$

Thus the EA value is non-increasing in w, and backward induction preserves this ordering for all nodes.

Proposition 3 (Monotonicity in the Trigger Multiple). For fixed v and w, the EA value is non-increasing in the trigger multiple M:

$$M_1 < M_2 \Rightarrow V_0(v, w, M_1) \geq V_0(v, w, M_2). \tag{14}$$

Proof. The behavioral exercise rule uses the threshold MK. Increasing M raises this threshold and thereby reduces the set of nodes at which early exercise occurs.

Let $\mathcal{T}(M)$ denote the set of admissible stopping times under trigger multiple M. If $M_1 < M_2$, then

$$\mathcal{T}(M_2) \subseteq \mathcal{T}(M_1).$$

Since the ESO value equals the supremum of expected discounted payoffs over admissible stopping times,

$$V(M) = \sup_{\tau \in \mathcal{T}} E[e^{-r\tau} X_\tau],$$

restricting the stopping set cannot increase the value. Hence the EA value is non-increasing in M.

Proposition 4 (Monotonicity in the Vesting Period). For fixed w and M, the EA value is non-increasing in the vesting period v:

$$v_1 < v_2 \Rightarrow V_0(v_1, w, M) \geq V_0(v_2, w, M). \tag{15}$$

Proof.

The vesting constraint prevents exercise before time v. Extending v enlarges the interval during which exercise is prohibited thereby reducing the feasible stopping set.

Let $\mathcal{T}(v)$ denote the admissible stopping times under vesting period v. If $v_1 < v_2$, then

$$\mathcal{T}(v_2) \subseteq \mathcal{T}(v_1).$$

Since the ESO value equals the supremum of expected discounted payoffs over feasible stopping times, restricting the stopping region cannot increase the value. Hence the EA value is weakly decreasing in v.

Taken together, Equations (11)–(12) establish the structural dominance of the CRR American framework, while Equations (13), (14), and (15) characterize the monotonic sensitivity of the EA value with respect to the exit rate, trigger multiple, and vesting period, respectively.

Remark 1 (Although $V_0(v, w, M)$ is non–increasing in v, it need not be strictly decreasing. If the optimal stopping boundary lies strictly beyond the vesting date, the vesting constraint is non–binding and the option value remains unchanged for a range of v.).

2.2 Methods

This subsection describes the numerical procedure and experimental framework used to compare the classical CRR American model with the EA model (Ammann and Seiz, 2004; Cox et al., 1979). Both models are implemented within a discrete-time binomial framework over a finite horizon T, divided into N equal intervals of length $\Delta t = T/N$. The study adopts a simulation-based design using synthetic parameter configurations rather than empirical calibration to enable a controlled structural comparison between the two models under identical ESO contract assumptions.

2.2.1 Input Parameters

Table 2 summarizes the input parameters used across both models. Unless explicitly varied, all parameters are held constant throughout the valuation horizon. The baseline strike price is set below the initial stock price to reflect common ESO grant practices. For instance, under Telkom Indonesia's ESO scheme, the strike price is set at 90% of the average closing price over the 25 trading days preceding the grant date (PT Telkom Indonesia (Persero) Tbk., 2022) , introducing an in-the-money feature at grant while remaining consistent with prevailing market conditions.

2.2.2 Simulation Procedure

Each model valuation is implemented by constructing a recombining binomial lattice under the risk-neutral measure, following the standard option pricing framework (Hull, 2022). The procedure begins by generating the underlying stock price tree using the movement factors and risk-neutral probability given in Equations (1)–(3), subject to the no-arbitrage condition in Equation (4). At maturity, terminal option payoffs are

Table 1. Backward-Induction Procedure for the Enhanced American ESO Model

Require: $S_0, K, r, \delta, T, N, v, w, M$
Ensure: ESO Value V_0

```
dt ← T/N; u ← e^{σ√dt}; d ← e^{−σ√dt}
a ← e^{(r−δ)dt}; q = (a−d)/(u−d); disc = e^{−rdt}
surv ← e^{−wdt}; exit p ← 1 − surv
If q ∉ (0, 1) then
   return NAN
end if
vIdx ← min{max(⌈v/dt⌉, 0), N}
Initialize terminal payoff: V^(N)[j] ← max(S0 u^j d^(N−j) − K, 0) for j = 0, . . . , N
for i = N − 1 downto 0 do
   for j = 0 to i do
      C ← disc[qV^(i+1)[j + 1] + (1 − q)V^(i+1)[j]]
      S ← S0 u^j d^(i−j)
      if i < vIdx then
         V^(i)[j] ← surv · C
      else
         X ← max(S − K, 0)
         Trig ← [max(S − MK, 0) ≥ C]
         Wait ← exit p · X + surv · C
         V^(i)[j] ← 1_Trig(S − K) + (1 − 1_Trig)Wait
      end if
   end for
end for
return V^(0)[0]
```

initialized as specified in Equation (5). Option values at earlier nodes are then computed through backward induction: under the CRR American model, the recursion in Equation (6) is applied at each node. Under the EA model, backward induction proceeds in two phases. In the pre-vesting phase ($t < v$), the node value follows the survival-adjusted continuation in Equation (8), with the one-step continuation value computed as in Equation (7). In the post-vesting phase ($t \geq v$), the behavioral exercise rule in Equation (9) is evaluated; if the trigger condition is satisfied, the option is exercised immediately, otherwise the node value follows the weighted combination in Equation (10).

2.2.3 Experimental Design

Three simulation experiments are conducted to quantify the valuation gaps between the EA model and the CRR American benchmark. The first experiment examines parameter sensitivity within the EA model by varying the vesting period v, exit rate w, and trigger multiple M across the discrete grids $v \in \{2, 3, 4, 5\}$ years, $w \in \{0.01, 0.05, 0.10, 0.15, 0.20\}$ per year, and $M \in \{1, 1.25, 1.5, 1.75, 2\}$. The minimum and maximum ESO values obtained from this parameter sweep, denoted EA_{min} and EA_{max}, are used to represent lower- and upper-bound valuation scenarios, respectively.

The second experiment benchmarks EA_{min} and EA_{max} against the CRR American model across maturities T {8, 9, 10} years, using $N = 1000$ time steps. This maturity range is consistent with common ESO practice, in which contracts typically extend up to 10 years with vesting periods of two to five years (Hull, 2022; Leung, 2022).

The third experiment investigates the joint effects of maturity and strike by comparing EA_{max} with the CRR American benchmark over a two-dimensional grid of maturities $T \in \{8, 9, 10\}$ and strike prices $K \in \{50, 55, \ldots, 90\}$. The resulting valuation gaps are illustrated using heatmaps showing both absolute and percentage deviations across the (K, T) domain. Additional robustness experiments vary volatility $\sigma \in [0.15, 0.40]$ and dividend yield $\delta \in [0.00, 0.05]$ to verify that the dominance ordering established analytically in Proposition 1 remains stable under market-relevant parameter shifts.

2.2.4 EA_{min}, EA_{max} Relative to the CRR American Benchmark

From the first experiment, the minimum and maximum ESO values EA_{min} and EA_{max} define the range of structurally plausible outcomes under varying (v, w, M) configurations. These extremal values are subsequently used in the second experiment as fixed lower- and upper-bound reference scenarios. It is important to note that while the parameter configurations

Table 2. Input Parameters Used in CRR and EA Models for ESO Valuation

Parameter	Description	Model(s)
S_0	Initial stock price	All
K	Strike price of the option	All
T	Time to maturity (in years)	All
r	Continuously compounded risk-free rate	All
δ	Continuous dividend yield	All
σ	Annualized volatility of the underlying asset	All
w	Employee exit rate	EA only
v	Vesting period length	EA only
M	Exercise trigger multiple	EA only

Table 3. Parameter-Sweep Procedure for Identifying EA_{min} and EA_{max}

```
Require: S_0, K, r, δ, σ, T, N; lists v_list, w_list, M_list
Ensure: Grid 𝒢 of (v, w, M, EA_price) and extrema EA_min, EA_max
𝒢 ← ∅
for each v ∈ v_list do
    for each w ∈ w_list do
        for each M ∈ M_list do
            p ← EA_CORE(S_0, K, r, δ, σ, T, N, v, w, M)
            𝒢 ← 𝒢 ∪ {(v, w, M, p)}
        end for
    end for
end for
EA_min ← arg min_{(v,w,M)∈𝒢} EA_price
EA_max ← arg max_{(v,w,M)∈𝒢} EA_price
return (𝒢, EA_min, EA_max)
```

(v, w, M) corresponding to EA_{min} and EA_{max} are fixed across experiments, the resulting option values vary with maturity T, since the binomial lattice spans a longer horizon as T increases. Both EA_{min} and EA_{max} are compared directly with the CRR American benchmark to quantify the lower- and upper-bound valuation gaps, and the third experiment further examines how these gaps evolve across the (K, T) domain.

Given the analytical dominance result established in Proposition 1, the CRR American model serves as the unique benchmark throughout the numerical analysis. Accordingly, all valuation gaps are computed relative to this benchmark.

2.2.5 Comparison Metrics

Two quantitative metrics are used to evaluate valuation gaps between the EA model and the CRR American benchmark. Let $V^A(K,T)$ and $V^B(K,T)$ denote the option values under models A and B, respectively, where A refers to the EA model and B to the CRR American benchmark. The absolute difference and relative deviation are defined as:

$$\Delta^{A-B}(K,T) = V^A(K,T) - V^B(K,T), \quad \rho^{A-B}(K,T) = \frac{V^A(K,T) - V^B(K,T)}{V^B(K,T)}. \tag{16}$$

Equation (16) allows the structural valuation gap between the EA framework and the CRR American benchmark to be assessed in both nominal and percentage terms across different (K, T) regions. Results are visualized through line plots and two-dimensional heatmaps.

Table 4. EA Sweep: Extrema within the (v, w, M) Grid at $T = 8$ Years and $N = 1000$ Steps

Label	v(years)[a]	w(per year)[b]	M^c	EA Price
EA_{min}	5	0.20	2.00	15.23
EA_{max}	2	0.01	1.00	42.04

2.2.6 Simulation Setup and Baseline Parameters

All simulations are implemented in Python using Google Colab. Synthetic ESO parameter settings approximate typical corporate settings. Unless stated otherwise, the baseline parameters are:

$$S_0 = 100, \quad K = 90, \quad T = 5 \text{ years}, \quad r = 7\%, \quad \delta = 2\%, \quad N = 1000$$

The vesting period (v), exit rate (w), and trigger multiple (M) are varied during the parameter sweep in the first experiment to identify $EA_{\min}$ and $EA_{\max}$ configurations, which are then held fixed in the subsequent cross-maturity and heatmap comparisons. All other baseline values remain constant unless otherwise stated.

2.2.7 Scope and Evaluation Approach

This study does not aim to replicate market prices or perform statistical calibration against observed ESO transactions; accordingly, error metrics such as RMSE or MAPE are not applied. The objective is to examine structural valuation gaps between the EA model and the CRR American benchmark under identical assumptions, and to quantify the influence of vesting restriction, employee exit risk, and behavioral exercise features on ESO pricing. The results are therefore interpreted as model-based valuation gaps rather than measures of empirical pricing accuracy. The use of synthetic parameter settings enables a controlled structural comparison free from confounding effects arising from market calibration noise. Empirical calibration of turnover intensity and exercise behavior using firm-level ESO data is left for future research.

3. RESULTS AND DISCUSSIONS

This section reports and interprets the numerical results obtained from the three simulation experiments. The analysis proceeds in four stages: parameter sensitivity of the EA model, comparison of EA valuation bounds with the CRR American benchmark across maturities, heatmap visualization of valuation gaps across the maturity–strike domain, and robustness analysis with respect to volatility and dividend yield. Together, these experiments confirm the analytical dominance result established in Proposition 1 and quantify the economic magnitude of friction induced valuation distortions under a range of contractually and empirically relevant parameter configurations.

3.1 Parameter Sensitivity of EA Model

The first experiment examines how the three employment-related parameters of the EA model the vesting period (v), exit rate (w), and the trigger multiple (M) jointly affect ESO valuation. The experiment is conducted with $T = 8$ years, $N = 1000$ time steps, and baseline parameters $S_0 = 100$, $K = 90$, $r = 0.07$, $\delta = 0.02$, and $\sigma = 0.30$. The parameter grids are $v \in \{2, 3, 4, 5\}$, $w \in \{0.01, 0.05, 0.10, 0.15, 0.20\}$, and $M \in \{1.00, 1.25, 1.50, 1.75, 2.00\}$. The parameter-sweep procedure is summarized in Table 3.

The resulting extremal configurations are reported in Table 4, $EA_{\min} = 15.23$ at $(v, w, M) = (5, 0.20, 2.00)$ and $EA_{\max} = 42.04$ at $(v, w, M) = (2, 0.01, 1.00)$. These configurations define the lower and upper structural bounds of the EA model under the given parameter grid and serve as fixed reference scenarios in the subsequent experiments.

The results are consistent with the analytical monotonicity properties established in Propositions 2, 3, and 4. A higher exit rate (w) reduces the single-step survival probability and compounds survival discounting across the lattice, thereby lowering the EA value. A longer vesting period (v) restricts early exercise during the pre-vesting phase and reduces the feasible stopping set. A higher trigger multiple (M) raises the effective exercise threshold and delays exercise, which further suppresses the option value. Thus, the pair (EA_{min} and EA_{max}) represents two economically distinct valuation scenarios: EA_{min} corresponds to severe employment-related frictions, while EA_{max} corresponds to relatively mild frictions. These bounds provide the basis for comparison with the CRR American benchmark in the next experiment.

Table 5. Maturity Sweep: Comparison of EA_{min} and EA_{max} Prices Against the CRR American Benchmark

T (years)	CRR-American	EA_{min}	EA_{max}
8	43.34	15.23	42.04
9	45.08	15.50	43.64
10	46.62	15.71	45.04

3.2 Comparison of EA Bounds with the CRR American Benchmark

This second experiment compares EA_{min} and EA_{max} with the CRR American benchmark across maturities $T \in \{8, 9, 10\}$, using $N = 1000$ time steps and the previously defined baseline parameters. The parameter configurations identified in the first experiment are held fixed; only T is varied. The results are summarized in Table 5.

As reported in Table 5, both $EA_{\min}$ and $EA_{\max}$ remain strictly below the CRR American benchmark across all maturities, confirming the dominance result of Proposition 1. At $T = 10$, the CRR American value equals 46.62, while $EA_{\max} = 45.04$ and $EA_{\min} = 15.71$, indicating that employment-related frictions systematically reduce ESO valuations relative to the frictionless benchmark.

Figure 1 illustrates how this gap evolves with maturity. From $T = 8$ to $T = 10$, the CRR American value rises from 43.34 to 46.62, while $EA_{\max}$ increases from 42.04 to 45.04 and $EA_{\min}$ rises only slightly from 15.23 to 15.71. The asymmetric growth rates reflect the differential impact of maturity under the two configurations. Under $EA_{\max}$, the low exit rate implies modest survival discounting at each step, so the cumulative impact of extending maturity remains small. Under $EA_{\min}$, the high exit rate causes survival discounting to compound aggressively across the lattice; while absolute values increase slightly with T, the gain is largely offset by the heightened survival penalty, leaving $EA_{\min}$ nearly flat relative to the benchmark.

This pattern has a clear economic interpretation. In the standard CRR American model, continuation values are discounted solely by the risk-free rate $e^{-r\Delta t}$ at each step. In the EA model, continuation values are additionally multiplied by the survival factor $e^{-w\Delta t}$, effectively applying a higher discount

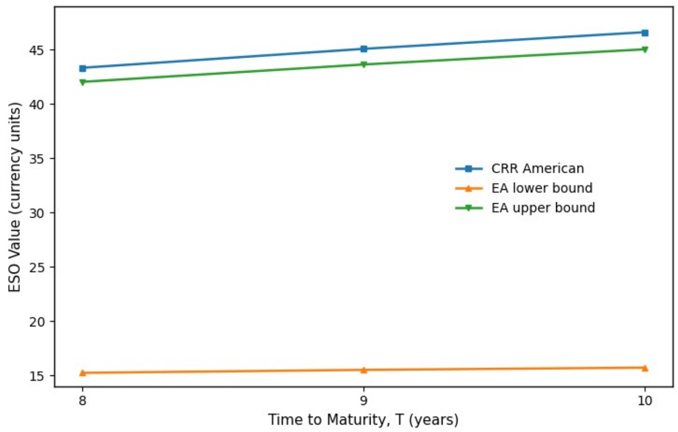

Figure 1. Comparison of CRR American and EA Bounds Across Maturities

rate to every node. As T increases, this additional discounting compounds across more time steps, generating progressively larger valuation distortions relative to the frictionless CRR benchmark. The result is that the CRR American model lies uniformly above both EA bounds for all tested maturities, indicating that ignoring employment-related frictions leads to systematic overvaluation of ESOs, an effect that intensifies with contract length.

3.3 Heatmap Analysis Across the Maturity–Strike Domain

The third experiment extends the comparison to a two-dimensional grid of maturities $T \in \{8, 9, 10\}$ years and strike prices $K \in \{50, 55, \dots, 90\}$, with all other parameters fixed at baseline values. The computational procedure is summarized in Table 6.

Figures 2(a)–2(b) and 3(a)–3(b) present heatmaps of the absolute and percentage valuation gaps between EA_{max} and the CRR American benchmark, and between EA_{min} and the CRR American benchmark, respectively. Valuation gaps are quantified using the absolute and percentage metrics defined in Equation (16). Both configurations remain strictly below the benchmark across the entire (K, T) domain, consistent with Proposition 1, with distortions increasing with maturity and most pronounced near at-the-money regions where continuation value dominates intrinsic value.

For the upper-bound configuration EA_{max} (Figure 2), absolute differences range from approximately -1.30 to -1.58, and percentage deviations lie between -2.3% and -3.4%. The discount is systematic but moderate, increasing gradually with maturity and becoming slightly more pronounced as the strike price approaches the initial stock price. At $T = 10$ and $K = 90$, the percentage deviation reaches approximately -3.39%, while at $T = 8$ and $K = 50$ it is approximately -2.30%. The limited magnitude of the discount reflects the mild frictions in this configuration: with a low exit rate and a trigger multiple close to unity, survival discounting reduces continuation value only marginally at each step, and the cumulative effect over the lattice horizon remains small. Even under these favorable conditions, however, the discount is strictly positive and uniform across the entire grid, confirming that the inclusion of even minimal vesting and survival adjustments consistently reduces ESO valuations relative to the frictionless benchmark.

For the lower-bound configuration EA_{min} (Figure 3), the valuation distortions are substantially larger. Absolute differences range from approximately -31 to -39, and percentage deviations lie between -64% and -66%. The gap intensifies with maturity and is most pronounced at higher strike prices, reaching its largest magnitude at $T = 10$ and $K = 90$, where the percentage deviation approaches -66.31%. These results indicate that under conditions of high exit intensity and a conservative exercise trigger, employment-related frictions severely compress ESO value, particularly for long-dated contracts near the money.

Under EA_{max}, the low exit rate and near-unity trigger multiple keep exercise behavior close to the classical American policy, with weak survival discounting generating discounts of only 2–3%. Under EA_{min}, two reinforcing mechanisms operate simultaneously: the high exit rate compounds the survival penalty across lattice steps, raising the effective discount rate well above the risk–free rate, while the large trigger multiple shrinks the admissible stopping region and delays realized intrinsic value. Their interaction produces valuation gaps of approximately 65%, structural in origin rather than numerical. Across both configurations, distortions increase with maturity and are most pronounced near at-the-money regions, where continuation value dominates intrinsic value and employment–related frictions therefore exert the greatest economic impact.

3.4 Robustness Analysis: Volatility and Dividend Yield

To assess the structural robustness of the dominance ordering and valuation gaps beyond the baseline parameters, additional experiments vary volatility $\sigma \in [0.15, 0.40]$ and dividend yield $\delta \in [0.00, 0.05]$ across maturities $T \in \{8, 9, 10\}$, with $K = 90$ and all other parameters held at baseline values. The results are presented as heatmaps.

3.4.1 Volatility–Maturity Analysis

Figure 4 presents the relative percentage deviations between the EA bounds and the CRR American benchmark across the volatility–maturity grid. For both EA configurations, the dominance ordering established in Proposition 1 is strictly preserved across the entire (σ, T) domain: neither $EA_{\max}$ nor $EA_{\min}$ exceeds the CRR American benchmark at any parameter combination.

For the upper-bound configuration $EA_{\max}$ (Figure 4(a)), the percentage deviations remain moderate and stable, ranging from approximately -2.95% to -3.57%. At $T = 8$, the deviation narrows slightly as volatility increases, moving from -3.12% at $\sigma = 0.15$ to -2.95% at $\sigma = 0.40$. A similar pattern holds at longer maturities. This behavior is consistent with standard option convexity: higher volatility raises the absolute value of

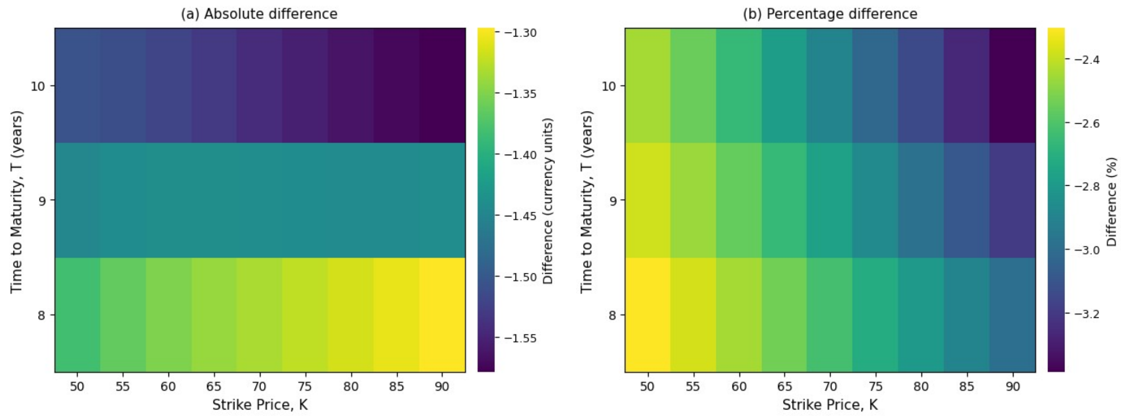

Figure 2. Comparison of EA_{max} and CRR American Across Maturities and Strikes: (a) Absolute Difference, and (b) Percentage Difference

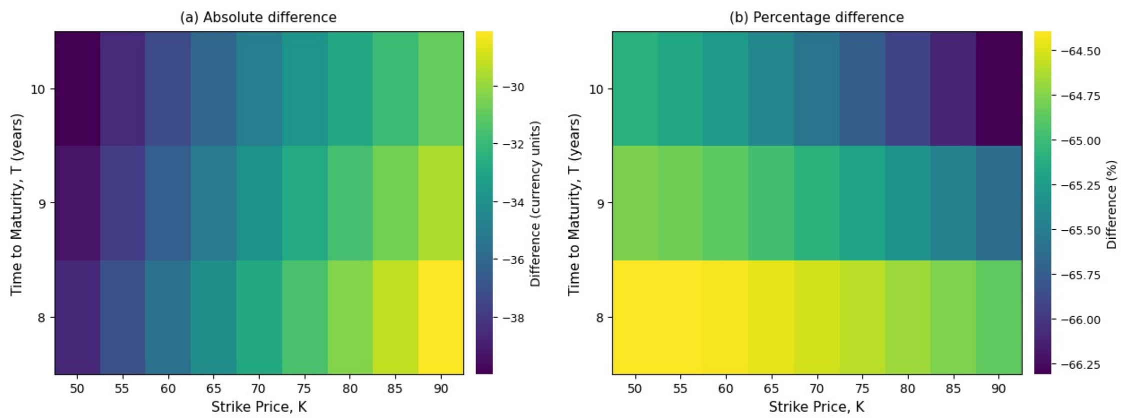

Figure 3. Comparison of EA_{min} and CRR American Across Maturities and Strikes: (a) Absolute Difference, and (b) Percentage Difference

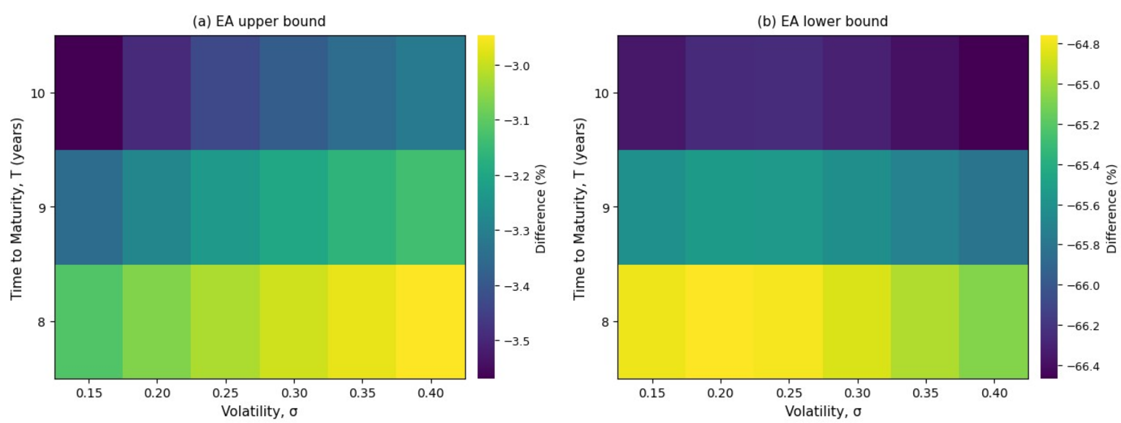

Figure 4. Relative Percentage Differences Between EA Bounds and the CRR American Benchmark Across the Volatility–Maturity ($\sigma - T$) Grid ($K = 90$)

both the CRR American and EA models, but since survival discounting in the $EA_{\max}$ configuration is weak, the proportional gap changes only slightly. The discount therefore remains confined to a narrow band of approximately 3% across the entire volatility range.

For the lower-bound configuration $EA_{\min}$ (Figure 4(b)),

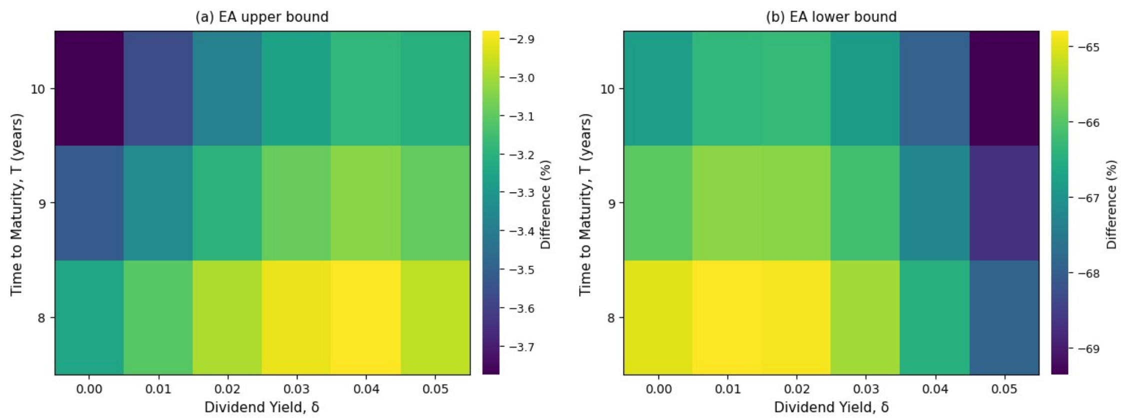

Figure 5. Relative Percentage Differences between EA Bounds and the CRR American Benchmark Across the Dividend Yield–Maturity ($\delta - T$) Grid ($K = 90$)

Table 6. Computational Procedure for Heatmap Analysis Across the Maturity-Strike Domain

Require: $S_0, K, r, \delta, \sigma, N$; maturities $\{T_1, \ldots, T_m\}$; fixed EA bound parameter configurations defined in Table 3
Ensure: Summary table and comparison plots

for each T in $\{T_1, \ldots, T_m\}$ do
  Compute CRR American call at T
  Compute EA_min and EA_max prices at maturity T using the fixed parameter defined in Table 3
end for
Collect results into a table: $\{T$, CRR-American, EA_min, EA_max$\}$
Plot four curves across maturities for visual comparison
return summary table and figure

the percentage deviations range from approximately -64.76% and -66.46%. The magnitude of the discount increases with maturity: for example, the deviation moves from -64.86% at $T = 8$ to -66.31% at $T = 10$, but depends only weakly on volatility, with deviations clustered around 65% regardless of σ. This pattern reflects the dominance of exit intensity and delayed exercise in suppressing continuation value; once survival discounting is sufficiently severe, additional volatility does not materially alter the structural gap relative to the CRR American benchmark, because the survival penalty overwhelms the incremental gains in continuation value from higher uncertainty.

Taken together, the volatility-maturity heatmap confirms that the dominance ordering is structurally robust across the full range of empirically plausible volatility levels. While higher volatility raises absolute ESO values under both frameworks, it does not overturn the ordering or materially alter the relative discount patterns induced by employment-related frictions.

3.4.2 Dividend Yield–Maturity Analysis

Figure 5 presents the relative percentage deviations across the dividend yield-maturity grid. As in the volatility analysis, the dominance ordering of Proposition 1 is strictly preserved: both $EA_{\min}$ and $EA_{\max}$ remain below the CRR American benchmark across the entire parameter domain.

For the upper-bound configuration $EA_{\max}$ (Figure 5(a)), the percentage deviations range from approximately -2.88% to -3.77%, remaining confined to a narrow band of roughly 3%. The deviations vary slightly across maturities and dividend levels without exhibiting a strictly monotonic pattern, suggesting that the valuation response reflects non-linear interactions between dividend-induced early exercise incentives and the survival discounting embedded in the EA framework, rather than a mechanically linear relationship. For the lower-bound configuration $EA_{\min}$ (Figure 5(b)), the percentage deviations range from approximately -64.80% to -69.35%. The discount generally deepens with both maturity and dividend yield: at $T = 10$, for instance, the deviation moves from -66.82% at $\delta = 0.00$ to -69.35% at $\delta = 0.05$. This amplification arises from an interaction effect: higher dividends reduce the continuation value of holding the option under both the CRR and EA frameworks by lowering the expected stock price, but the employment-constrained EA structure further suppresses continuation value through the survival factor and trigger restriction. As a result, the ESO holder under the EA model faces compounding downward pressure on continuation value from both dividend leakage and employment frictions, generating a larger structural gap relative to the frictionless CRR American benchmark. The dividend yield-maturity heatmap thus confirms that the valuation discount is structurally robust across economically relevant dividend regimes. Variations in dividend yield affect absolute ESO values but do not reverse the dominance ordering or eliminate the persistent valuation gap attributable to vesting restrictions, exit risk, and behavioral exercise rules.

3.4.3 Structural Interpretation

Across both robustness dimensions, the relative deviation between the EA bounds and the CRR American benchmark remains strictly negative at every parameter combination in the (σ, T) and (δ, T) domains. No configuration reverses the ordering established in Proposition 1. This invariance confirms that the observed valuation gap is not a numerical artifact tied to specific baseline parameter choices, but rather a structurally persistent consequence of the employment-related frictions embedded in the EA recursion—namely, the survival discounting applied at each lattice step during the vesting period, the forced-exit mechanism operative after vesting, and the behavioral trigger restriction on the stopping set. The robustness experiments also reveal an important asymmetry between the two EA configurations. The upper-bound discount is relatively stable across both σ and δ, confined to approximately 3% regardless of market parameter shifts. The lower-bound discount, by contrast, is sensitive to maturity and dividend yield, deepening as either increases, because these factors interact with the high exit intensity and conservative trigger to amplify the suppression of continuation value. This asymmetry implies that the practical consequences of ignoring employment frictions are most severe for long-dated, near-the-money ESOs in high-dividend, high-turnover environments—precisely the settings in which fair-value measurement is most consequential for financial reporting.

4. CONCLUSIONS

The EA model yields ESO valuations strictly below the CRR American benchmark under any positive vesting period, exit rate, and trigger multiple a dominance result established analytically via backward induction and confirmed numerically across maturity, strike, volatility, and dividend yield regimes. Valuation discounts range from approximately 2-3% under mild frictions to 65-69% under high exit intensity and conservative exercise triggers, with the largest gaps occurring in long-dated near-the-money contracts. Consequently, applying the frictionless CRR American model systematically overstates ESO compensation expenses under IFRS 2, FASB ASC Topic 718, and PSAK 53, with distortions most consequential in high-turnover, long-horizon settings. Empirical calibration using firm-level ESO data represents a natural direction for future research.

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