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Vorwort

Das Tätigkeitsfeld des Fraunhofer-Instituts für Techno- und Wirtschaftsmathematik ITWM umfasst anwendungsnahe Grundlagenforschung, angewandte Forschung sowie Beratung und kundenspezifische Lösungen auf allen Gebieten, die für Techno- und Wirtschaftsmathematik bedeutsam sind.

In der Reihe »Berichte des Fraunhofer ITWM« soll die Arbeit des Instituts kontinuierlich einer interessierten Öffentlichkeit in Industrie, Wirtschaft und Wissenschaft vorgestellt werden. Durch die enge Verzahnung mit dem Fachbereich Mathematik der Universität Kaiserslautern sowie durch zahlreiche Kooperationen mit internationalen Institutionen und Hochschulen in den Bereichen Ausbildung und Forschung ist ein großes Potenzial für Forschungsberichte vorhanden. In die Berichtreihe sollen sowohl hervorragende Diplom- und Projektarbeiten und Dissertationen als auch Forschungsberichte der Institutsmitarbeiter und Institutsgäste zu aktuellen Fragen der Techno- und Wirtschaftsmathematik aufgenommen werden.

Darüber hinaus bietet die Reihe ein Forum für die Berichterstattung über die zahlreichen Kooperationsprojekte des Instituts mit Partnern aus Industrie und Wirtschaft.

Berichterstattung heißt hier Dokumentation des Transfers aktueller Ergebnisse aus mathematischer Forschungs- und Entwicklungsarbeit in industrielle Anwendungen und Softwareprodukte – und umgekehrt, denn Probleme der Praxis generieren neue interessante mathematische Fragestellungen.

Prof. Dr. Dieter Prätzel-Wolters
Institutsleiter

Kaiserslautern, im Juni 2001

Own-Company Stockholding and Work Effort Preferences of an Unconstrained Executive

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Abstract

We develop a framework for analyzing an executive's own-company stockholding and work effort preferences. The executive, characterized by risk aversion and work effectiveness parameters, invests his personal wealth without constraint in the financial market, including the stock of his own company whose value he can directly influence with work effort. The executive's utility-maximizing personal investment and work effort strategy is derived in closed-form, and an indifference utility rationale is demonstrated to determine his required compensation. Our results have implications for the practical and theoretical assessment of executive quality and the benefits of performance contracting. Assuming knowledge of the company's non-systematic risk, our executive's unconstrained own-company investment identifies his work effectiveness (i.e. quality), and also reflects work effort that establishes a base-level that performance contracting should seek to exceed.

JEL Classification: M52, G11

Key Words: optimal portfolio choice, executive compensation

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1 Introduction

Stemming from the agency theory fundamentals of Ross (1973), Jensen and Meckling (1976), Holmstrom (1979) and others, there has been much concern for the 'incentivization' link from equity-based executive compensation to corporate financial performance. The associated academic literature is extensive.[1] Counterpoint to past research, we consider the motivation for an executive with unconstrained (unincentivized) compensation to voluntarily performance-link his personal wealth. We develop a model framework that identifies the joint own-company stockholding and work effort strategy of a utility-maximizing executive. The executive's compensation is assumed to be incorporated into his up-front total personal wealth, which he invests variously in a risk-free money market account, a diversified market portfolio, or his own company's stock. The executive is able to beneficially influence the value of his company via work effort; he gains utility from the increased value of his direct stockholding (within his overall personal portfolio), but loses utility for his work effort. The executive is characterized by a risk aversion parameter (γ), and two work effectiveness parameters (κ, representing inverse work productivity, and α, representing disutility stress).

A feature of our framework is that the executive's work effort, specified in terms of two control variables, non-systematic expected return and volatility (μ and σ), can be restated in terms of a single control variable, the non-systematic Sharpe ratio ($\lambda = (\mu - r)/\sigma$, where r is the risk-free rate of return). This reduces the dimension of the problem and introduces a parameterization based on the well-known Sharpe ratio performance measure. The executive's optimal personal investment and work effort strategy is then derived in closed-form using stochastic control theory and the corresponding Hamilton-Jacobi-Bellman equations. Other technical papers similarly concerned with dynamic principal-agent models include Cadenillas, Cvitanic and Zapatero (2004), Korn and Kraft (2008) and Ou-Yang (2003), for example.

Our closed-form results demonstrate that an executive with superior work effectiveness (i.e. higher quality) will undertake more work effort for his company. Furthermore, depending on any change in the company's non-systematic volatility associated with the executive's work effort (i.e. control strategy), due to risk aversion a higher quality executive will not necessarily undertake a higher own-company stockholding. For application to empirical data, our framework allows an executive quality measure to be backed-out from the observed own-company stockholdings of unconstrained executives (assuming knowledge of non-systematic company volatility). Alternatively, with assumption of executive quality and risk aversion, our framework allows identification of the deviation in own-company stockholding that results from constraining an executive with performance contracting.

Freeing executives to self-incentivize may be a reasonable 'path of least resistance' in the light of some recent and not so recent research. For example, Dittmann and Maug

[1] The summaries of Murphy (1999) and Core, Guay and Larcker (2003) are useful references.

(2007) were unable to rationalize observed executive compensation. Using a 'standard' principal-agent efficient contracting model, their analysis indicated that executives should not, in general, be compensated with options, and that it would commonly be optimal for executives to use private savings to purchase additional stock in their own companies. Bettis, Bizjak and Lemmon (2001) found that high-ranking corporate insiders use collars and swaps to cover a significant proportion of their own-company stockholdings, allowing them to unwind the constraint of equity-based compensation. Ross (2004) repudiated the folklore that giving options to agents makes them more willing to take risks (also see Carpenter (2000)). Jensen and Murphy (1990) proposed that private political forces in the managerial labor market constrain pay-performance sensitivity, leading most CEOs to hold trivial fractions of their firms' stock. To the contrary, Hall and Liebman (1998) and Core and Larcker (2002), for example, found support for a link from equity-based executive compensation to corporate performance.

Whether subject to constrained or unconstrained compensation, an executive's performance incentive will reflect a total wealth perspective. Ofek and Yermack (2000) found that once managers reach a certain own-company ownership level, they actively rebalance their personal portfolios when awarded equity compensation. Garvey and Milbourn (2003) found that market risk has little effect on the use of stock-based pay for the average executive, suggesting that executives can undo any undesired market exposure from their incentive contracts by adjusting their personal portfolios. We thus maximize our risk averse executive's utility with respect to total wealth investable across his own company's stock, a diversified market portfolio and a risk-free money market account. Our approach has parallels with Jin (2002), but uses a continuous-time setting with arguably a more intuitively appealing specification of work effort and its disutility. See also Cvitanic (2008) for a more general continuous time framework emphasizing incentive effects when the executive can hedge equity-based compensation. A natural future extension for our framework is to specify a constrained executive subject to an imposed own-company stockholding representative of performance contracting, and to contrast his work effort strategy with that of our unconstrained executive.

The paper is organized as follows. Section 2 introduces the notation and terminology, and as a first result the optimality problem is reformulated and simplified. In Section 3 the Hamilton-Jacobi-Bellman equation characterizing the utility maximization problem are derived, and a closed form solution is established. The results are illustrated in Section 4. Section 5 concludes.

2 Notation and Set-up

The financial market is defined on a filtered probability space $(\Omega, \mathcal{F}, P, (\mathcal{F}_t)_{t\geq 0})$ satisfying the usual hypothesis and large enough to support two independent standard Brownian motions, $W^P = (W_t^P)_{t\geq 0}$ and $W = (W_t)_{t\geq 0}$. The investment opportunities available to our executive are a risk-free money market account, a diversified market portfolio and his own company's stocks. The risk-free money market account has the price process $B = (B_t)_{t\geq 0}$, with dynamics

$$\mathrm{d}B_t = r\, B_t \,\mathrm{d}t\,, \quad B_0 = 1\,, \tag{2.1}$$

where r is the instantaneous risk-free rate of return, hence $B_t = e^{r\,t}$. The price process of the market portfolio, $P = (P_t)_{t\geq 0}$, follows the stochastic differential equation (SDE)

$$\mathrm{d}P_t = P_t\,(\mu^P\,\mathrm{d}t + \sigma^P\,\mathrm{d}W_t^P)\,, \quad P_0 \in \mathbb{R}^+\,, \tag{2.2}$$

where μ^P is the expected return rate of the market portfolio, σ^P is the market portfolio volatility and $W^P = (W_t^P)_{t\geq 0}$ denotes a standard Brownian motion. The company's non-systematic stock price process, $S^{\mu,\sigma} = (S_t^{\mu,\sigma})_{t\geq 0}$, is a controlled diffusion with SDE

$$\mathrm{d}S_t^{\mu,\sigma} = S_t^{\mu,\sigma}\,(\mu_t\,\mathrm{d}t + \sigma_t\,\mathrm{d}W_t)\,, \quad S_0 \in \mathbb{R}^+\,, \tag{2.3}$$

where μ is the company's expected return rate in excess of the beta-adjusted market portfolio's expected excess return rate (i.e. the expected return compensation for non-systematic risk), and σ is the company's non-systematic volatility, both controlled by the executive. The 'full' stock price process is simply a portfolio combination of P and S dependent on the company's beta.

The executive influences the company's stock price dynamics by choice of the control strategy (μ,σ), which is specified to be associated with work effort. Value is added if μ is greater than r, indicating excess return compensation for non-systematic risk.[2] The executive's instantaneous disutility of work effort is represented by $c_t(\mu_t,\sigma_t)$ for control strategy (μ_t,σ_t) at time t. We assume a Markovian disutility rate, i.e., $c_t(\mu_t,\sigma_t) = c(t,v,\mu_t,\sigma_t)$ where $c : [0,T]\times\mathbb{R}^+\times[r,\infty)\times\mathbb{R}^+ \to \mathbb{R}_0^+$ is a continuous and suitably differentiable function.

The executive's initial wealth, inclusive of his compensation, is invested in the financial market. Ongoing continuous time portfolio adjustment is assumed to be free of short-selling constraints, and self-financing (i.e. no funds are added to or withdrawn from the executive's portfolio). The portfolio is allocated with fraction $\pi^P = (\pi_t^P)_{t\geq 0}$ invested in the market portfolio, fraction $\pi^S = (\pi_t^S)_{t\geq 0}$ invested in the company's stocks, and the remainder in the risk-free account. For investment strategy $\pi = (\pi^P,\pi^S)$ and initial wealth $V_0 > 0$, the executive's wealth process, $V^\pi = (V_t^\pi)_{t\geq 0}$, is

$$\mathrm{d}V_t^\pi = V_t^\pi\left((1-\pi_t^P-\pi_t^S)\,\mathrm{d}B_t/B_t + \pi_t^P\mathrm{d}P_t/P_t + \pi_t^S\mathrm{d}S_t^{\mu,\sigma}/S_t^{\mu,\sigma}\right)\,, \quad V_0 > 0\,, \tag{2.4}$$

The executive is assumed to maximize his terminal utility for time horizon T, subject to some utility function U, which will be specified when deriving closed-from solutions.

Assuming the control of the company's stock price behavior (μ,σ) is determined exogenously, the executive's *optimal investment decision* is then described by

$$\widehat{\Phi}(t,v) = \sup_{\pi\in\Pi(t,v)} \mathbb{E}^{t,v}[U(V_T^\pi)]\,, \quad \text{for } (t,v)\in[0,T]\times\mathbb{R}^+, \tag{2.5}$$

[2]The control strategy (μ,σ) can be conceptualized as the executive's corporate investment or financing strategy. For example, identifying and initiating positive net present value projects and optimal debt versus equity financing entails work effort that adds value and affects volatility.

where $\Pi(t,v)$ denotes the set of all admissible portfolio strategies π at time t corresponding to the initial wealth v (see for example Korn and Korn (2001)), U is a utility function, and $\mathbb{E}^{t,v}$ denotes the conditional expectation with $V_t = v$; and the exogenously given control (μ,σ) affecting the dynamics of S in (2.3) is suppressed in our notation.

Definition 2.1. *Let $0 \le t \le T$, t fixed. Further let (μ,σ) take values in $(r,\infty)\times(0,\infty)\cup\{(r,0)\}$. By $A(t,v)$ we denote the set of admissible strategies $(\pi,\mu,\sigma) = \big((\pi^P,\pi^S),\mu,\sigma\big)$ corresponding to an initial capital of $v > 0$ at time t, i.e. $\{\mathcal{F}_u\,;\, t \le u \le T\}$-predictable processes such that,*

(i) the wealth equation

$$\mathrm{d}V_u^\pi = V_u^\pi\left((1-\pi_u^P-\pi_u^S)\,\mathrm{d}B_u/B_u + \pi_u^P\mathrm{d}P_u/P_u + \pi_u^S\mathrm{d}S_u^{\mu,\sigma}/S_u^{\mu,\sigma}\right), \quad V_t = v\,,$$

has a unique non-negative solution and satisfies

$$\int_t^T \left[(V_u^\pi)^2\left((\pi_u^P\sigma^P)^2 + (\pi_u^S\sigma_u)^2\right)\right] du \,<\, \infty \quad P-a.s.\,,$$

where (μ,σ) affects V^π via $S^{\mu,\sigma}$,

(ii) and

$$\mathbb{E}\left[U(V_T^\pi)^- + \int_t^T c_u(\mu_u,\sigma_u)du\right] \,<\, \infty\,.$$

The *optimal investment and control decision* is then the solution of

$$\Phi(t,v) = \sup_{(\pi,\mu,\sigma)\in A(t,v)} \mathbb{E}^{t,v}\left[U(V_T^\pi) - \int_t^T c_u(\mu_u,\sigma_u)\,\mathrm{d}u\right], \quad \text{for } (t,v)\in[0,T]\times\mathbb{R}^+, \quad (2.6)$$

where $\mathbb{E}^{t,v}$ denotes the conditional expectation at t with $V_t = v$, and the utility function U satisfies $U = U^\gamma$ for some $\gamma > 0$. To ensure sensible solutions we require $\mu \ge r$, which effectively bars the executive from destroying company value ($\mu < r$) and potentially profiting by shorting the company's stocks.

2.1 Restating the Set-up

First a decomposition result for the optimal investment and control problem in (2.6) is derived. The original four-dimensional maximization problem can be solved in two steps. The first step is minimizing the disutility rate for a target non-systematic Sharpe ratio $\lambda = (\mu - r)/\sigma$ obtaining $c^\star(t,v,\lambda)$. This will be done in Proposition 2.1. Then we will show in Theorem 2.2 that the optimal investment and control problem can then be restated as a maximization problem over the three controls π^P, π^S and λ, where c is replaced by $c^\star$ in (2.6).

The following conditions are required for existence and uniqueness of $c^\star$.

Assumption 2.1. *The function* $c : [0,T] \times \mathbb{R}^+ \times [r,\infty) \times \mathbb{R}^+ \to \mathbb{R}_0^+$, $(t,v,\mu,\sigma) \mapsto c(t,v,\mu,\sigma)$ *satisfies:*

(i) c *is continuous in* t *and* v*, and twice continuously differentiable in* μ *and* σ*;*

(ii) Fix $(t,v,\lambda) \in [0,T] \times \mathbb{R}^+ \times \mathbb{R}_0^+$*, then*

$$\limsup_{\sigma \searrow 0} \quad \lambda \frac{\partial c}{\partial \mu}(t,v,r+\lambda\,\sigma,\sigma) + \frac{\partial c}{\partial \sigma}(t,v,r+\lambda\,\sigma,\sigma) \quad \le \quad 0\,,$$

and

$$\sup_{\sigma>0} \quad \lambda \frac{\partial c}{\partial \mu}(t,v,r+\lambda\,\sigma,\sigma) + \frac{\partial c}{\partial \sigma}(t,v,r+\lambda\,\sigma,\sigma) \quad > \quad 0\,.$$

(iii) It holds

$$(\mu - r)^2 \frac{\partial^2 c}{\partial \mu^2} + 2\,\sigma\,(\mu - r)\frac{\partial^2 c}{\partial \mu\,\partial \sigma} + \sigma^2 \frac{\partial^2 c}{\partial \sigma^2} \quad > \quad 0\,.$$

(iv) For all (t,v)*:* $\inf_{\sigma>0} c(t,v,r,\sigma) = 0$.

In Assumption 2.1, (i) is a natural smoothness condition, (ii) and (iii) are ensuring uniqueness and existence, respectively, of the disutility $c^\star(t,v,\lambda)$ depending on the Sharpe ratio λ, and (iv) is a natural norming condition attributing no disutility when no excess return is generated ($\mu = r$) for a specific volatility choice.

A function c which fullfilles the conditions of Assumption 2.1 is for example

$$c(t,v,\mu,\sigma) = \kappa \left(\frac{\mu - r}{\sigma}\right)^\alpha + \nu\,(\sigma - \sigma_0)^2\,,$$

where $\mu \ge r$, $\sigma > 0$, $\kappa, \nu \ge 0$, $\alpha > 0$ and $\sigma_0 > 0$ is the base-level own-company risk.

Lemma 2.1. *Suppose Assumption 2.1 holds, then the minimization problem*

$$\min_{\{\sigma>0:\mu=r+\lambda\,\sigma\}} c(t,v,\mu,\sigma)\,, \quad \textit{for } (t,v,\lambda) \in [0,T] \times \mathbb{R}^+ \times \mathbb{R}_0^+\,, \tag{2.7}$$

admits a unique solution $\sigma^\star(t,v,\lambda)$.

Proof. Fix $(t,v,\lambda) \in [0,T] \times \mathbb{R}^+ \times \mathbb{R}_0^+$ and define the function f by $f(\sigma) = c(t,v,r+\lambda\,\sigma,\sigma)$, for $\lambda \ge 0$. We need to show that for f a minimizing $\sigma^\star = \sigma^\star(t,v,\lambda)$ exists and is unique. Computing the first and second derivatives and Assumption 2.1 gives

$$f'(\sigma) = \lambda \frac{\partial c}{\partial \mu}(t,v,r+\lambda\,\sigma,\sigma) + \frac{\partial c}{\partial \sigma}(t,v,r+\lambda\,\sigma,\sigma)\,,$$

and

$$f''(\sigma) = \lambda^2 \frac{\partial^2 c}{\partial \mu^2}(t,v,r+\lambda\,\sigma,\sigma) + 2\,\lambda \frac{\partial^2 c}{\partial \sigma \partial \mu}(t,v,r+\lambda\,\sigma,\sigma) + \frac{\partial^2 c}{\partial \sigma^2}(t,v,r+\lambda\,\sigma,\sigma)\,,$$

Now f' is continuous differentiable and f'' is continuous by the differentiability assumptions on c. Using elementary calculus rationale, the minimization problem $\min_{\sigma>0} f(\sigma)$ admits a solution if $f'(\sigma^\star) = 0$ has a solution and $f''(\sigma^\star) > 0$, moreover, the stronger condition f is strictly convex, i.e. $f'' > 0$, implies the solution is a minimizer and unique. Part (iii) of Assumption 2.1 gives the strict convexity of f.

Finally, for $f'(\sigma^\star) = 0$ to admit a solution it is sufficient that f' starts below zero, $f'(0+) < 0$, and then the strict convexity implies that f' is strictly increasing. Thus requiring that f' takes on a positive value for some σ ensures the existence of σ with $f'(\sigma^\star) = 0$. Assumption 2.1 (ii) implies these conditions. □

Changing the parameters as described above from π^P, π^S, and (μ, σ) to π^P, π^S, and λ, and replacing c by $c^\star$ requires adapting Definition 2.1 to the new setting. Before we present the new framework, observe that the company's non-systematic stock dynamics w.r.t. to λ (and $\sigma^\star(\lambda)$) now read:

$$\mathrm{d}S_t^\lambda = S_t^\lambda \left[r\,\mathrm{d}t + \lambda\sigma^\star(t,v,\lambda)\,\mathrm{d}t + \sigma^\star(t,v,\lambda)\,\mathrm{d}W_t \right] , \quad S_0 \in \mathbb{R}^+ . \tag{2.8}$$

Definition 2.2. *Let $0 \le t \le T$, t fixed, and let λ take values in $[0, \infty)$. Define $c^\star$ by*

$$c^\star(t,v,\lambda) := c(t,v,r+\lambda\,\sigma^\star(t,v,\lambda),\sigma^\star(t,v,\lambda)) = \min_{\{\sigma>0:\mu=r+\lambda\,\sigma\}} c(t,v,\mu,\sigma) . \tag{2.9}$$

Then by $A'(t,v)$ we denote the set of admissible strategies $(\pi,\lambda) = \big((\pi^P,\pi^S),\lambda\big)$ corresponding to an initial capital of $v > 0$ at time t, i.e. $\{\mathcal{F}_u\,;\, t \le u \le T\}$-predictable processes such that,

(i) the wealth equation

$$\mathrm{d}V_u^\pi = V_u^\pi \left((1-\pi_u^P - \pi_u^S)\,\mathrm{d}B_u/B_u + \pi_u^P \mathrm{d}P_u/P_u + \pi_u^S \mathrm{d}S_u^\lambda/S_u^\lambda \right) , \quad V_t = v ,$$

has a unique non-negative solution and satisfies

$$\int_t^T \left[(V_u^\pi)^2 \left((\pi_u^P\sigma^P)^2 + (\pi_u^S\sigma_u^\star)^2 \right) \right] \mathrm{d}u < \infty \quad P-a.s. ,$$

where λ affects V^π via S^λ ,

(ii) and

$$\mathbb{E}\left[U(V_T^\pi)^- + \int_t^T c_u^*(\lambda_u)\,\mathrm{d}u \right] < \infty .$$

Theorem 2.2. *Suppose* (2.6) *admits a solution Φ, then it coincides with the value function of the optimal control problem*

$$\Phi(t,v) = \sup_{(\pi,\lambda)\in A'(t,v)} \mathbb{E}^{t,v}\left[U(V_T^\pi) - \int_t^T c^\star(u,V_u^\pi,\lambda_u)\,\mathrm{d}u \right] , \quad \textit{for } (t,v) \in [0,T]\times\mathbb{R}^+ , \tag{2.10}$$

where $A'(t,v)$ and $c^\star$ are given in Definition 2.2.

Proof. Let

$$J(t,v;\pi,\mu,\sigma) := \mathbb{E}^{t,v}\left[U(V_T^\pi) - \int_t^T c(u,V_u^\pi,\mu(u,V_u^\pi),\sigma(u,V_u^\pi))\,\mathrm{d}u\right]$$

and

$$J'(t,v;\pi,\lambda) := \mathbb{E}^{t,v}\left[U(V_T^\pi) - \int_t^T c^\star(u,V_u^\pi,\lambda(u,V_u^\pi))\,\mathrm{d}u\right] .$$

The assertion is proven if we show that

$$\sup_{(\pi,\mu,\sigma)\in A(t,v)} J(t,v;\pi,\mu,\sigma) = \sup_{(\pi,\lambda)\in A'(t,v)} J'(t,v;\pi,\lambda) \ ,$$

i.e. the performance functionals J and J' admit the same value function $\Phi(t,v)$.
By $c^\star(t,v,\lambda) := c(t,v,r+\lambda\sigma^\star,\sigma^\star) = \min_{\{\sigma>0:\mu=r+\lambda\sigma\}} c(t,v,\mu,\sigma)$ we have:

$$\begin{aligned} J(t,v;\pi,\mu,\sigma) &= \mathbb{E}^{t,v}\left[U(V_T^\pi) - \int_t^T c(u,V_u^\pi,\mu(u,V_u^\pi),\sigma(u,V_u^\pi))\,\mathrm{d}u\right] \\ &\le \mathbb{E}^{t,v}\left[U(V_T^\pi) - \int_t^T c^\star\left(u,V_u^\pi,\frac{\mu(u,V_u^\pi)-r}{\sigma(u,V_u^\pi)}\right)\,\mathrm{d}u\right] = J'\left(t,v;\pi,\frac{\mu-r}{\sigma}\right) \ , \end{aligned}$$

implying

$$\sup_{(\pi,\mu,\sigma)\in A(t,v)} J(t,v;\pi,\mu,\sigma) \le \sup_{(\pi,\mu,\sigma)\in A(t,v)} J'(t,v;\pi,\frac{\mu-r}{\sigma}) = \sup_{(\pi,\lambda)\in A'(t,v)} J'(t,v;\pi,\lambda)\,. \quad (*)$$

Now $c^\star(t,v,\lambda) := c(t,v,r+\lambda\sigma^\star,\sigma^\star)$ gives:

$$\begin{aligned} J'(t,v;\pi,\lambda) &= \mathbb{E}^{t,v}\left[U(V_T^\pi) - \int_t^T c^\star(u,V_u^\pi,\lambda(u,V_u^\pi))\,\mathrm{d}u\right] \\ &= \mathbb{E}^{t,v}\left[U(V_T^\pi) - \int_t^T c(u,V_u^\pi,r+\lambda\sigma^\star,\sigma^\star)\,\mathrm{d}u\right] = J(t,v;\pi,r+\lambda\sigma^\star,\sigma^\star)\,, \end{aligned}$$

and then

$$\sup_{(\pi,\lambda)\in A'(t,v)} J'(t,v;\pi,\lambda) = \sup_{(\pi,\lambda)\in A'(t,v)} J(t,v;\pi,r+\lambda\sigma^\star,\sigma^\star) \le \sup_{(\pi,\mu,\sigma)\in A(t,v)} J(t,v;\pi,\mu,\sigma)\,. \quad (**)$$

Combining $(*)$ and $(**)$ finishes the proof. □

3 Optimal Strategies

In this section we will use stochastic control techniques to derive closed-form solutions to our investment and control decision problem in Equation (2.10) for special choices of the utility and disutility function, in particular we derive closed-form solutions for utility functions with constant relative risk aversion. For the relative risk aversion parameter $\gamma > 0$ the utility function U is:

$$U(v) = \begin{cases} \dfrac{v^{1-\gamma}}{1-\gamma}\,, & \text{for } \gamma > 0 \text{ and } \gamma \neq 1 \\ \log(v)\,, & \text{for } \gamma = 1\,, \end{cases} \tag{3.1}$$

and the cost of effort (or disutility) $c^\star$ is assumed to satisfy:

$$c^\star(t, v, \lambda) = \kappa\, v^{1-\gamma}\, \frac{\lambda^\alpha}{\alpha}\,, \quad \gamma > 0\,, \tag{3.2}$$

where $\kappa > 0$ is the inverse work productivity, $\alpha > 2$ the disutility stress, and the scaling factor $v^{1-\gamma}$ is based on a similar formulation for the intertemporal utility from consumption in a constant relative risk aversion setting.

For the remainder of the paper we assume that the control problem (2.10) admits a value function $\Phi \in C^{1,2}$.

To guarantee that the candidates which we will derive for the optimal Sharpe ratio, stockholding strategy and value function are indeed the optimal ones, we have to consider a more restrictive class of admissible strategies:

Definition 3.1. *Let $0 \le t \le T$, t fixed, and let λ take values in $[0, \infty)$. Then by $A'_\gamma(t, v)$ we denote the set of admissible strategies $(\pi, \lambda) \in A'(t, v)$, such that*

(i) for $0 < \gamma < 1$:

$$\int_t^T \lambda_u^2\, du \le C < \infty\ ,\ \textit{for some } C \in \mathbb{R}_0^+\,, \tag{3.3}$$

(ii) for $\gamma = 1$:

$$\mathbb{E}\left[\int_t^T (\pi_u^P \sigma^P)^2 + (\pi_u^S \sigma_u^\star)^2\, du\right] < \infty\,, \tag{3.4}$$

(iii) for $\gamma > 1$:

$$\int_t^T \left(\pi_u^P \sigma^P\right)^4 + \left(\pi_u^S \sigma_u^\star\right)^4\, du \le C_1 < \infty \quad ,\ \textit{for some } C_1 \in \mathbb{R}_0^+\,, \tag{3.5}$$

$$\int_t^T \pi_u^S \sigma_u^\star \lambda_u\, du \ge C_2 > -\infty \quad ,\ \textit{for some } C_2 \in \mathbb{R}_0^+\,. \tag{3.6}$$

The optimal investment and control decision then reads:

$$\Phi(t, v) = \sup_{(\pi,\lambda) \in A'_\gamma(t,v)} \mathbb{E}^{t,v}\left[U(V_T^\pi) - \int_t^T c^\star(u, V_u^\pi, \lambda_u)\, \mathrm{d}u\right]\,, \quad \text{for } (t, v) \in [0, T] \times \mathbb{R}^+\,, \tag{3.7}$$

Remark 3.1. *One directly sees that $A'_\gamma(t, v)$ is a subset of $A'(t, v)$. Therefore the results derived in the previous sections remain valid for $A'_\gamma(t, v)$, too.*

3.1 Hamilton-Jacobi-Bellman Equation

Having formulated the optimal investment and control decision problem with respect to the parameter set (π, λ) as in equation (3.7), we can write down the corresponding Hamilton-Jacobi-Bellman equation; thereby note that we formulate this equation w.r.t. general utility functions U and disutility functions $c^\star$:

$$\begin{aligned} 0 &= \sup_{(\pi,\lambda)\in\mathbb{R}\times[0,\infty)} \left[(L^{(\pi,\lambda)}\,\Phi)(t,v) - c^\star(t,v,\lambda)\right], \quad \text{for } (t,v)\in[0,T)\times\mathbb{R}^+, \\ U(v) &= \Phi(T,v), \quad \text{for } v\in\mathbb{R}^+, \end{aligned} \tag{3.8}$$

where the differential operator $L^{(\pi,\lambda)}$ is given by

$$\begin{aligned} (L^{\pi,\lambda}g)(t,v) = {} & \frac{\partial g}{\partial t}(t,v) + \frac{\partial g}{\partial v}(t,v)\,v\,(r + \pi^S\,\lambda\,\sigma^\star(t,v,\lambda) + \pi^P\,(\mu^P - r)) \\ & + \frac{1}{2}\,\frac{\partial^2 g}{\partial v^2}(t,v)\,v^2\,((\pi^S\,\sigma^\star(t,v,\lambda))^2 + (\pi^P\,\sigma^P)^2)\,. \end{aligned} \tag{3.9}$$

Potential maximizers $\pi^{P^\star}$, $\pi^{S^\star}$ and $\lambda^\star$ of the HJB (3.8) can be calculated by establishing the first order conditions:

$$\begin{aligned} \pi^{P^\star}(t,v) &= -\frac{(\mu^P - r)}{v(\sigma^P)^2}\,\frac{\Phi_v(t,v)}{\Phi_{vv}(t,v)}\,, \\ \pi^{S^\star}(t,v) &= -\frac{\lambda^\star(t,v)}{v\sigma^\star(t,v,\lambda^\star(t,v))}\,\frac{\Phi_v(t,v)}{\Phi_{vv}(t,v)}\,, \end{aligned} \tag{3.10}$$

where $\lambda^\star$ is the solution of the implicit equation

$$\lambda\,\frac{\Phi_v^2(t,v)}{\Phi_{vv}(t,v)} + c^\star_\lambda(t,v,\lambda) = 0 \quad \text{for all } (t,v)\in[0,T]\times\mathbb{R}^+\,, \tag{3.11}$$

where we have already used representation (3.10) to simplify the equation.

The executive's optimal wealth allocation to his own company depends on his stock price dynamics control decision, $\lambda = \lambda^\star$, whereas allocation to the market portfolio does not. However, recalling that the own-company allocation is with respect to the company's non-systematic stock price process, implicit to this result is that the executive's actual market portfolio allocation is the net of his 'full' market portfolio allocation (π^P) and the systematic exposure of his own-company stockholding dependent on the company's beta.

Substituting the maximizers (3.10) in the HJB (3.8) then yields:

$$\Phi_t(t,v) + \Phi_v(t,v)\,v\,r - \frac{1}{2}(\lambda^\star(t,v))^2\,\frac{\Phi_v^2(t,v)}{\Phi_{vv}(t,v)} - \frac{1}{2}(\lambda_P)^2\,\frac{\Phi_v^2(t,v)}{\Phi_{vv}(t,v)} - c^\star(t,v,\lambda^\star(t,v)) = 0\,, \tag{3.12}$$

where $\lambda_P := \dfrac{\mu^P - r}{\sigma^P}$.

In the following we aim at solving Equation (3.12) for the choices (3.1) and (3.2) of the utility and disutility functions.

3.2 Closed-Form Solutions

In this section we present the closed-form solutions to our control problem (3.7) for the utility and disutility functions specified in (3.1) and (3.2).

Theorem 3.1 (The power utility case: $\gamma > 0$ and $\gamma \neq 1$)**.** *The full solution of the maximization problem (3.7) can then be summarized by the strategy*

$$\lambda^\star(t,v) = \left(\frac{1}{\kappa\,\gamma}\,f(t)\right)^{\frac{1}{\alpha-2}}\,, \quad \pi^{P\star}(t,v) = \frac{\mu^P - r}{\gamma\,(\sigma^P)^2}\,, \quad \pi^{S\star}(t,v) = \frac{\lambda^\star(t,v)}{\gamma\,\sigma^\star(t,v,\lambda^\star(t,v))}\,, \tag{3.13}$$

and value function

$$\Phi(t,v) = \frac{v^{1-\gamma}}{1-\gamma}\,f(t)\,, \tag{3.14}$$

where

$$f(t) = e^{(1-\gamma)\left(r+\frac{1}{2}\frac{\lambda_P^2}{\gamma}\right)(T-t)}\left(1 - \frac{(\alpha-2)\left(\frac{1}{\kappa\,\gamma}\right)^{\frac{2}{\alpha-2}}}{\alpha\,(2\,\gamma\,r + \lambda_P^2)}\left(e^{\frac{1-\gamma}{\alpha-2}\left(2\,r+\frac{\lambda_P^2}{\gamma}\right)(T-t)} - 1\right)\right)^{-\frac{\alpha-2}{2}}\,. \tag{3.15}$$

Proof. First observe that a function F of the form $F(\lambda) = a\,\lambda^2 - b\,\lambda^\alpha$, $\lambda \geq 0$, for given constant $a, b > 0$ and $\alpha > 2$, has a unique maximizer $\lambda^\star$ and maximized value $F(\lambda^\star)$ given by

$$\lambda^\star = \left(\frac{2\,a}{\alpha\,b}\right)^{\frac{1}{\alpha-2}}\,, \quad \text{and} \quad F(\lambda^\star) = (\alpha-2)\,\alpha^{-\frac{\alpha}{\alpha-2}}\,2^{\frac{2}{\alpha-2}}\,a^{\frac{\alpha}{\alpha-2}}\,b^{-\frac{2}{\alpha-2}}\,. \tag{3.16}$$

Using this insight the first order condition for $\lambda^\star$ in Equation (3.11) is now solved. Set

$$a = \frac{1}{2}\,\frac{\Phi_v^2}{-\Phi_{vv}}\,, \quad \text{and} \quad b = \frac{\kappa}{\alpha}\,v^{1-\gamma}\,,$$

then Equation (3.16) gives

$$\lambda^\star = \left(\frac{1}{\kappa\,v^{1-\gamma}}\,\frac{\Phi_v^2}{-\Phi_{vv}}\right)^{\frac{1}{\alpha-2}}\,, \quad \text{and} \quad F(\lambda^\star) = \frac{\alpha-2}{2\,\alpha}\,\left(\kappa\,v^{1-\gamma}\right)^{-\frac{2}{\alpha-2}}\left(\frac{\Phi_v^2}{-\Phi_{vv}}\right)^{\frac{\alpha}{\alpha-2}}\,.$$

Now Equation (3.12) reads

$$0 = \Phi_t + \Phi_v\,v\,r + \frac{1}{2}\,\frac{\Phi_v^2}{-\Phi_{vv}}\left(\frac{\mu^P - r}{\sigma^P}\right)^2 + \frac{\alpha-2}{2\,\alpha}\,\left(\kappa\,v^{1-\gamma}\right)^{-\frac{2}{\alpha-2}}\left(\frac{\Phi_v^2}{-\Phi_{vv}}\right)^{\frac{\alpha}{\alpha-2}}\,. \tag{3.17}$$

Using the separation ansatz $\Phi(t,v) = f(t)\,\frac{v^{1-\gamma}}{1-\gamma}$ results in

$$\Phi_t = \dot{f}\,\frac{v^{1-\gamma}}{1-\gamma}\,, \quad \Phi_v = f\,v^{-\gamma}\,, \quad \Phi_{vv} = -\gamma\,f\,v^{-\gamma-1}\,, \quad \text{and} \quad f(T) = 1\,. \tag{3.18}$$

Equation (3.17) then becomes

$$0 = \dot{f}\,\frac{v^{1-\gamma}}{1-\gamma} + f\,v^{1-\gamma}\,r + \frac{1}{2}\,\frac{f\,v^{1-\gamma}}{\gamma}\,\left(\frac{\mu^P - r}{\sigma^P}\right)^2 + \frac{\alpha-2}{2\,\alpha}\,\left(\kappa\,v^{1-\gamma}\right)^{-\frac{2}{\alpha-2}}\,\left(\frac{f\,v^{1-\gamma}}{\gamma}\right)^{\frac{\alpha}{\alpha-2}}.$$

Dividing by $\frac{v^{1-\gamma}}{1-\gamma}$ and recalling $\lambda_P = (\mu^P - r)/\sigma^P$ gives

$$\dot{f} = f\,\left[-(1-\gamma)\,\left(r + \frac{1}{2}\,\frac{\lambda_P^2}{\gamma}\right)\right] + f^{\frac{\alpha}{\alpha-2}}\,\left[-(1-\gamma)\,\frac{\kappa}{2}\,\frac{\alpha-2}{\alpha}\,\left(\frac{1}{\kappa\,\gamma}\right)^{\frac{\alpha}{\alpha-2}}\right]. \tag{3.19}$$

This is a Bernoulli ODE of the form $\dot{f} = a_1\,f + a_n\,f^n$, with solution

$$f(t)^{1-n} = C\,e^{G(t)} + (1-n)\,e^{G(t)}\,\int_0^t e^{-G(s)}\,a_n\,\mathrm{d}s\,,$$

where $G(t) = (1-n)\,\int_0^t a_1(s)\,\mathrm{d}s$ and C an arbitrary constant. In our setting we have $n = \frac{\alpha}{\alpha-2}$ and

$$(1-n) = \frac{-2}{\alpha-2}\,,\ a_1 = -(1-\gamma)\,\left(r + \frac{1}{2}\,\frac{\lambda_P^2}{\gamma}\right)\,,\ \text{and } a_n = -(1-\gamma)\,\frac{\kappa}{2}\,\frac{\alpha-2}{\alpha}\,\left(\frac{1}{\kappa\,\gamma}\right)^{\frac{\alpha}{\alpha-2}}.$$

The formal solution $f(t)^{1-n}$ is explicitly calculated in three steps. First, compute

$$G(t) = -\frac{2\,a_1\,t}{\alpha-2}\,,\quad \text{and} \quad \int_0^t e^{-G(s)}\,a_n(s)\,\mathrm{d}s = \frac{\alpha-2}{2}\,\frac{a_n}{a_1}\,\left(e^{\frac{2\,a_1\,t}{\alpha-2}} - 1\right)\,,$$

then

$$f(t) = e^{a_1\,t}\,\left(C - \frac{a_n}{a_1}\,\left(e^{\frac{2\,a_1\,t}{\alpha-2}} - 1\right)\right)^{-\frac{\alpha-2}{2}}.$$

Finally, solve for C by using $f(T) = 1$ and

$$C = e^{\frac{2\,a_1\,T}{\alpha-2}} + \frac{a_n}{a_1}\,\left(e^{\frac{2\,a_1\,T}{\alpha-2}} - 1\right).$$

Note also that $f(0) = C^{-\frac{\alpha-2}{2}}$. Now

$$f(t) = e^{-a_1\,(T-t)}\,\left(1 - \frac{a_n}{a_1}\,\left(e^{-\frac{2\,a_1}{\alpha-2}\,(T-t)} - 1\right)\right)^{-\frac{\alpha-2}{2}}.$$

Plugging in a_1 and a_n then yields the result for $f(t)$. Using $\frac{\Phi_v}{\Phi_{vv}} = -\frac{v}{\gamma}$ and the first order condition in Equation (3.10) we obtain the claimed optimal strategies $\lambda^\star$, $\pi^{P\star}$ and $\pi^{S\star}$. Note that our claimed optimal controls are deterministic and continuous on a compact support, so there are uniformly bounded, which shows that $(\pi^{S\star}, \pi^{P\star}, \lambda^\star) \in A'_\gamma(t,v)$. □

The following theorem gives the results for the log-utitility case.

Theorem 3.2 (The log-utility case, $\gamma = 1$)**.** *The full solution of the maximization problem (3.7) can then be summarized by the strategy*

$$\lambda^\star(t,v) = \kappa^{-\frac{1}{\alpha-2}}\,, \quad \pi^{P\star}(t,v) = \frac{\mu^P - r}{(\sigma^P)^2}\,, \quad \textit{and} \quad \pi^{S\star}(t,v) = \frac{\lambda^\star(t,v)}{\sigma^\star(t,v,\lambda^\star(t,v))}\,, \tag{3.20}$$

and value function

$$\Phi(t,v) = \log(v) + \left[r + \frac{1}{2}\left(\frac{\mu^P - r}{\sigma^P}\right)^2 + \frac{\alpha-2}{2\,\alpha}\,\kappa^{-\frac{2}{\alpha-2}} \right] (T-t)\,. \tag{3.21}$$

Proof. As in the power-utility case, first the implicit first order condition for $\lambda^\star$ in Equation 3.11 is made explicit. This time set

$$a = \frac{1}{2}\,\frac{\Phi_v^2}{-\Phi_{vv}}\,, \quad \text{and} \quad b = \frac{\kappa}{\alpha}\,,$$

then Equation 3.16 gives

$$\lambda^\star = \left(\frac{1}{\kappa}\,\frac{\Phi_v^2}{-\Phi_{vv}}\right)^{\frac{1}{\alpha-2}}\,, \quad \text{and} \quad F(\lambda^\star) = \frac{\alpha-2}{2\,\alpha}\,\kappa^{-\frac{2}{\alpha-2}}\left(\frac{\Phi_v^2}{-\Phi_{vv}}\right)^{\frac{\alpha}{\alpha-2}}\,.$$

The PDE for log-utility reads now

$$0 = \Phi_t + \Phi_v\,v\,r + \frac{1}{2}\,\frac{\Phi_v^2}{-\Phi_{vv}}\left(\frac{\mu^P - r}{\sigma^P}\right)^2 + \frac{\alpha-2}{2\,\alpha}\,\kappa^{-\frac{2}{\alpha-2}}\left(\frac{\Phi_v^2}{-\Phi_{vv}}\right)^{\frac{\alpha}{\alpha-2}}\,. \tag{3.22}$$

Using the ansatz $\Phi(t,v) = \log(v) + \varphi(T-t)$ results in

$$\Phi_t = -\varphi\,, \quad \Phi_v = \frac{1}{v}\,, \quad \Phi_{vv} = -\frac{1}{v^2}\,, \quad \text{and} \quad \Phi(T,v) = \log(v) = U(v)\,.$$

Then Equation (3.22) reduces to

$$\varphi = r + \frac{1}{2}\left(\frac{\mu^P - r}{\sigma^P}\right)^2 + \frac{\alpha-2}{2\,\alpha}\,\kappa^{-\frac{2}{\alpha-2}}\,.$$

Finally noting $\Phi_v^2/\Phi_{vv} = -1$ and recalling the first order condition for the portfolio strategy in Equation (3.10) establish the claimed optimal controls. Again, our claimed controls are deterministic and continuous on a compact support, so there are uniformly bounded, which then proves that $(\pi^{S\star}, \pi^{P\star}, \lambda^\star) \in A'_\gamma(t,v)$. Note that we also obtain the form of the optimal strategies by formally setting $\gamma = 1$ in Theorem 3.1. □

3.3 Verification Theorem

The solutions of the maximization problems given in Theorem 3.1 and Theorem 3.2 are candidates for the optimal work effort and own-company stockholding of the control problem in (3.7). In this section we will verify that under sufficient assumptions these are indeed optimal.

Theorem 3.3 (Verification Result)**.** *Let $\kappa > 0$ and $\alpha > 2$. Assume that the investor has a utility and disutility function of the form given in (3.1) and (3.2). Then the candidates given in (3.13) - (3.15) are the optimal Sharpe ratio and stockholding strategy and value function of the optimal control problem (3.7) for the case $\gamma > 0$ and $\gamma \neq 1$ and the candidates given in (3.20) and (3.21) are the optimal Sharpe ratio and stockholding strategy and value function of the optimal control problem (3.7) for the case $\gamma = 1$.*

Proof. Define the performance functional of our optimal investment and control decision by

$$J'(t, v; \pi, \lambda) := \mathbb{E}^{t,v}\left[U\left(V_T^\pi\right) - \int_t^T c_u^\star(\lambda_u)\,\mathrm{d}u\right].$$

Our candidates are optimal if we have

$$J'(t, v; \pi^\star, \lambda^\star) = \Phi(t, v) \text{ and } J'(t, v; \pi, \lambda) \leq \Phi(t, v)\,, \text{ for all } (\pi, \lambda) \in A'_\gamma(t, v)\,.$$

Part 1: $\gamma > 0$ and $\gamma \neq 1$.
Let $(\pi, \lambda) \in A'_\gamma(t, v)$. Since $\Phi \in C^{1,2}$, we obtain by Ito's formula:

$$\begin{aligned}
\Phi(T, V_T^\pi) - \int_t^T \kappa\,(V_u^\pi)^{1-\gamma}\,\frac{\lambda_u^\alpha}{\alpha}\,\mathrm{d}u \quad &= \quad \Phi(t, v) + \int_t^T \Phi_t(u, V_u^\pi)\,\mathrm{d}u \\
&+ \int_t^T \Phi_v(u, V_u^\pi)V_u^\pi\left[(1 - \pi_u^P - \pi_u^S)\,r + \pi_u^P\,\mu^P + \pi_u^S\,(r + \lambda\,\sigma_u^\star)\right]\mathrm{d}u \\
&+ \int_t^T \Phi_v(u, V_u^\pi)V_u^\pi\pi_u^P\sigma^P\,\mathrm{d}W_u^P + \int_t^T \Phi_v(u, V_u^\pi)V_u^\pi\pi_u^S\,\sigma_u^\star\,\mathrm{d}W_u \\
&+ 1/2\int_t^T \Phi_{vv}(u, V_u^\pi)\,(V_u^\pi)^2\left[(\pi_u^P\sigma^P)^2 + (\pi_u^S\sigma_u^\star)^2\right]\mathrm{d}u - \int_t^T \kappa\,(V_u^\pi)^{1-\gamma}\,\frac{\lambda_u^\alpha}{\alpha}\,\mathrm{d}u \\
= \Phi(t, v) + \int_t^T &\Big\{\Phi_t(u, V_u^\pi) + \Phi_v(u, V_u^\pi)V_u^\pi\left[r + \pi_u^S\,\lambda\,\sigma_u^\star + \pi_u^P(\mu^P - r)\right] \\
&+ 1/2\,\Phi_{vv}(u, V_u^\pi)\,(V_u^\pi)^2\left[(\pi^P\sigma^P)^2 + (\pi_u^S\sigma_u^\star)^2\right] - \kappa\,(V_u^\pi)^{1-\gamma}\,\frac{\lambda_u^\alpha}{\alpha}\Big\}\,\mathrm{d}u \\
&+ \int_t^T \Phi_v(u, V_u^\pi)V_u^\pi\pi_u^P\sigma^P\,dW_u^P + \int_t^T \Phi_v(u, V_u^\pi)V_u^\pi\pi_u^S\sigma_u^\star\,\mathrm{d}W_u\,. \qquad (3.23)
\end{aligned}$$

For the optimality candidates given in (3.13 - 3.15) we have

$$\mathbb{E}^{t,v}\left[\int_t^T \Phi_v(u, V_u^{\pi^\star})V_u^{\pi^\star}\pi_u^{P^\star}\sigma^P\,\mathrm{d}W_u^P + \int_t^T \Phi_v(u, V_u^{\pi^\star})V_u^{\pi^\star}\,\pi_u^{S^\star}\,\sigma_u^\star\,\mathrm{d}W_u\right] = 0\,. \qquad (3.24)$$

To verify Equation (3.24) it is sufficient to prove the square-integrability condition

$$\mathbb{E}\left[\int_t^T \left(\Phi_v(u, V_u^{\pi^\star})V_u^{\pi^\star}\left[\pi_u^{P^\star}\sigma^P + \pi_u^{S^\star}\sigma_u^\star\right]\right)^2\mathrm{d}u\right] \;<\; \infty\,. \qquad (*)$$

Now plugging in the candidates from (3.13 - 3.15) yields

$$\Phi_v(u, V_u^{\pi^\star}) V_u^{\pi^\star} \left[\pi_u^{P\star} \sigma^P + \pi_u^{S\star} \sigma_u^\star\right] = \frac{\left(V_u^{\pi^\star}\right)^{1-\gamma}}{\gamma} \left[\frac{\mu^P - r}{\sigma^P} + \left(\frac{1}{\kappa\gamma} f(u)\right)^{\frac{1}{\alpha-2}}\right]. \qquad (**)$$

The RHS of $(**)$ is $\left(V_u^{\pi^\star}\right)^{1-\gamma}$ times a deterministic and continuous function on the compact set $[0, T]$. The deterministic part is therefore uniformly bounded and additionally, $V_u^{\pi^\star}$ satisfies the wealth equation

$$\mathrm{d}V_t^{\pi^\star} = V_t^{\pi^\star} \left[r \,\mathrm{d}t + \lambda_P^2/\gamma \,\mathrm{d}t + (\lambda^\star(t, V_t^{\pi^\star}))^2/\gamma \,\mathrm{d}t \; + \lambda_P/\gamma \,\mathrm{d}W_t^P + \lambda^\star(t, V_t^{\pi^\star})/\gamma \,\mathrm{d}W_t\right].$$

Recalling that $\lambda^\star(t, v)$ is a deterministic function in t and does further not depend on v, we see that $V_t^{\pi^\star}$ follows a log-normal distribution for all $t \geq 0$ with parameters being uniformly bounded for all $t \in [0, T]$. Since all moments of a log-normally distributed random variable exist, $(*)$ holds proving (3.24).

Additionally, Φ satisfies the HJB equation (3.8), i.e. for $(\pi, \lambda) = (\pi^\star, \lambda^\star)$ and the choice (3.2) of the disutility function we have:

$$\begin{aligned}\Phi_t(u, V_u^{\pi^\star}) \; + \; &\Phi_v(u, V_u^{\pi^\star}) V_u^{\pi^\star} \left[r + \pi_u^{S\star} \,\lambda^\star \,\sigma_u^\star + \pi_u^{P\star} (\mu^P - r)\right] \\ &+ 1/2\, \Phi_{vv}(u, V_u^{\pi^\star}) \left[(V_u^{\pi^\star} \pi^{P\star} \sigma^P)^2 + (V_u^{\pi^\star} \pi_u^{S\star} \sigma_u^\star)^2\right] - \kappa \left(V_u^{\pi^\star}\right)^{1-\gamma} \frac{(\lambda_u^\star)^\alpha}{\alpha} = 0\,.\end{aligned}$$

For $(\pi, \lambda) = (\pi^\star, \lambda^\star)$, the expectation of equation (3.23) using that $\Phi(T, v) = v^{1-\gamma}/(1-\gamma)$ is:

$$\mathbb{E}^{t,v}\left[\frac{\left(V_T^{\pi^\star}\right)^{1-\gamma}}{1-\gamma}\right] - \mathbb{E}^{t,v}\left[\int_t^T \kappa \left(V_u^{\pi^\star}\right)^{1-\gamma} \frac{(\lambda_u^\star)^\alpha}{\alpha} \,\mathrm{d}u\right] = J'(t, v; \pi^\star, \lambda^\star) = \Phi(t, v)\,.$$

The optimality of our candidates is finally shown if we have for all $(\pi, \lambda) \in A'_\gamma(t, v)$:

$$\mathbb{E}^{t,v}\left[\frac{(V_T^{\pi})^{1-\gamma}}{1-\gamma}\right] - \mathbb{E}^{t,v}\left[\int_t^T \kappa \,(V_u^{\pi})^{1-\gamma} \frac{(\lambda_u)^\alpha}{\alpha} \,\mathrm{d}u\right] = J'(t, v; \pi, \lambda) \leq \Phi(t, v)\,. \qquad (3.25)$$

Also, since Φ satisfies the HJB equation (3.8), we get for all $(\pi, \lambda) \in A'_\gamma(t, v)$:

$$\begin{aligned}\Phi_t(u, V_u^{\pi}) \; + \; &\Phi_v(u, V_u^{\pi}) V_u^{\pi} \left[r + \pi_u^{S} \,\lambda \,\sigma_u^\star + \pi_u^{P} (\mu^P - r)\right] \\ &+ 1/2\, \Phi_{vv}(u, V_u^{\pi}) \left[(V_u^{\pi} \pi^{P} \sigma^P)^2 + (V_u^{\pi} \pi_u^{S} \sigma_u^\star)^2\right] - \kappa \,(V_u^{\pi})^{1-\gamma} \frac{(\lambda_u)^\alpha}{\alpha} \leq 0\,.\end{aligned}$$

Substituting this in Equation (3.23) and recalling that

$$\Phi_t(t, v) = \dot{f}(t) \,\frac{v^{1-\gamma}}{1-\gamma}\,, \quad \Phi_v(t, v) = f(t)\, v^{-\gamma}\,, \quad \Phi_{vv}(t, v) = -\gamma\, f(t)\, v^{-\gamma-1} \qquad (3.26)$$

we get:

$$\begin{aligned}\Phi(T, V_T^{\pi}) - &\int_t^T \kappa \,(V_u^{\pi})^{1-\gamma} \frac{\lambda_u^\alpha}{\alpha} \,\mathrm{d}u \\ &\leq \Phi(t, v) + \underbrace{\int_t^T (V_u^{\pi})^{1-\gamma} f(u) \pi_u^P \sigma^P \, dW_u^P + \int_t^T (V_u^{\pi})^{1-\gamma} f(u) \pi_u^S \sigma_u^\star \,\mathrm{d}W_u}_{=: M_T^t}\,.\end{aligned} \qquad (3.27)$$

Part 1.1: $0 < \gamma < 1$.

To verify equation (3.25) for the case $0 < \gamma < 1$ we will show that the local martingale M_T^t is a supermartingale. Applying again Ito's formula and using (3.26) yields:

$$\begin{aligned}\Phi(T, V_T^\pi) = \Phi(t,v) &+ \int_t^T \dot f(u)\frac{(V_u^\pi)^{1-\gamma}}{1-\gamma}\,du + \int_t^T f(u)(V_u^\pi)^{1-\gamma}\big[r + \pi_u^P(\mu^P - r)\\ &+ \pi_u^S\lambda\sigma_u^\star\big]\,du + \int_t^T (V_u^\pi)^{1-\gamma}\pi_u^P\sigma^P\,dW_u^P + \int_t^T (V_u^\pi)^{1-\gamma}\pi_u^S\sigma_u^\star\,\mathrm{d}W_u\\ &- 1/2\int_t^T \gamma f(u)(V_u^\pi)^{1-\gamma}\left[(\pi_u^P\sigma^P)^2 + (\pi_u^S\sigma_u^\star)^2\right]\,du\\ &= \Phi(t,v) + M_T^t + \int_t^T \frac{(V_u^\pi)^{1-\gamma}}{1-\gamma}\Big\{\dot f(u) + f(u)\big[(1-\gamma)\left(r + \pi_u^P\lambda\sigma^P + \pi_u^S\lambda\sigma_u^\star\right)\\ &\qquad - \frac{\gamma}{2}(1-\gamma)\left((\pi_u^P\sigma^P)^2 + (\pi_u^S\sigma_u^\star)^2\right)\big]\Big\}\,du\,.\end{aligned}$$

Now recalling that

$$\dot f = f\left[-(1-\gamma)\left(r + \frac{1}{2}\frac{\lambda_P^2}{\gamma}\right)\right] + f^{\frac{\alpha}{\alpha-2}}\left[-(1-\gamma)\,\frac{\kappa}{2}\,\frac{\alpha-2}{\alpha}\,\left(\frac{1}{\kappa\,\gamma}\right)^{\frac{\alpha}{\alpha-2}}\right]$$

and keeping in mind that $\lambda_u^\star = \left(\frac{1}{\kappa\gamma}f(u)\right)^{\frac{1}{\alpha-2}}$ we get:

$$\begin{aligned}\Phi(T, V_T^\pi) = \Phi(t,v) + M_T^t + \int_t^T (V_u^\pi)^{1-\gamma} f(u)\big[&-\frac{1}{2\gamma}\lambda_P^2 - \frac{1}{2\gamma}(\lambda_u^\star)^2\frac{\alpha-2}{\alpha} + \pi_u^P\lambda_P\sigma^P\\ &+ \pi_u^S\lambda_u\sigma_u^\star - 1/2\,\gamma(\pi_u^P\sigma^P)^2 - 1/2\,\gamma(\pi_u^S\sigma_u^\star)^2\big]\,du\,.\end{aligned}$$

Some side calculations including completing the square then yield:

$$\begin{aligned}M_T^t = \underbrace{\Phi(T,V_T^\pi)}_{(1)} - \underbrace{\Phi(t,v)}_{(2)} &+ \underbrace{\frac{\lambda_P^2}{2\gamma}\int_t^T (V_u^\pi)^{1-\gamma} f(u)\,du}_{\geq 0} + \underbrace{\frac{1}{2\gamma}\frac{\alpha-2}{\alpha}\int_t^T (V_u^\pi)^{1-\gamma} f(u)(\lambda_u^\star)^2\,du}_{\geq 0}\\ &+ \underbrace{\frac{\gamma}{2}\int_t^T (\sigma_u^\star)^2\left(\pi_u^S - \frac{\lambda_u}{\gamma\sigma_u^\star}\right)^2 + \sigma_P^2\left(\pi_u^P - \frac{\lambda_P}{\gamma\sigma_P}\right)^2\,du}_{\geq 0} - \underbrace{\frac{1}{2\gamma}\int_t^T \lambda_u^2\,du}_{(3)} - \frac{\lambda_P^2}{2\gamma}(T-t)\,.\end{aligned}$$

For $0 < \gamma < 1$, we have that $(1) > 0$, (2) is $\mathcal{F}_t$-measurable an thus deterministic at time t. Due to condition (3.3), (3) is $\mathcal{F}_t$-measurable too for all t and bounded by the real constant C. Thus, M_T^t is a local martingale which is bounded from below, i.e.

$$M_T^t \geq -\Phi(t,v) - \frac{1}{2\gamma}\left(C + \lambda_P^2(T-t)\right)\,.$$

This implies that M_T^t is a supermartingale and therefore equation (3.27) simplifies to

$$\Phi(T, V_T^\pi) - \int_t^T \kappa\,(V_u^\pi)^{1-\gamma}\,\frac{\lambda_u^\alpha}{\alpha}\,\mathrm{d}u \,\leq\, \Phi(t,v)\,.$$

Taking the expectation on both sides then yields equation (3.25) which finishes the proof for the case $0 < \gamma < 1$.
Part 1.2: $\gamma > 1$.
To verify equation (3.25) for the case $\gamma > 1$ we will impose conditions under which the local martingale M_T^t is a martingale. The straightforward condition for this is

$$\mathbb{E}\left[\int_t^T (V_u^\pi)^{2(1-\gamma)} f^2(u) \left((\pi_u \sigma^P)^2 + (\sigma_u^\star \pi_u^S)^2\right) du\right] < \infty . \tag{3.28}$$

But this condition is not handsome enough for our purposes. In what follows we will derive conditions which are independent from the wealth process.
For the integrand of (3.28) the following estimate is valid:

$$(V_u^\pi)^{2(1-\gamma)} f^2(u) \left((\pi_u \sigma^P)^2 + (\sigma_u^\star \pi_u^S)^2\right) \leq \underbrace{\frac{1}{2} f^4(u) \, (V_u^\pi)^{4(1-\gamma)}}_{(1)} + \underbrace{\frac{1}{2} \left((\pi_u \sigma^P)^2 + (\sigma_u^\star \pi_u^S)^2\right)^2}_{(2)}$$

From this equation one directly obtains that condition (3.5) in Def. 3.1 ensures that

$$\frac{1}{2} \mathbb{E}\left[\int_t^T \left((\pi_u \sigma^P)^2 + (\sigma_u^\star \pi_u^S)^2\right)^2 du\right] < \infty . \tag{3.29}$$

Note that in expression (1), f is a deterministic function on the compact set $[0, T]$ and therefore $\sup\limits_{t \leq u \leq T} f^4(u) < \infty$. So what is left, is to ensure that

$$\frac{1}{2} \mathbb{E}\left[\int_t^T (V_u^\pi)^{4(1-\gamma)} du\right] < \infty . \tag{3.30}$$

The solution of the wealth equation (2.4) expressed w.r.t. to the parameter λ applying variation of constants is:

$$V_t^\pi = V_0^\pi \, e^{rt + \int_0^t \pi_u^P \lambda^P \sigma^P + \pi_u^S \lambda_u \sigma_u^\star \, du} \, e^{L_t - \frac{1}{2} \langle L \rangle_t} ,$$

where $L_t = \int_0^t \pi_u^P \sigma^P dW_u^P + \int_0^t \pi_u^S \sigma_u^\star dW_u$ and $\langle L \rangle_t = \int_0^t (\pi_u^P \sigma^P)^2 + (\pi_u^S \sigma_u^\star)^2 du$.
Using this we have that

$$\begin{aligned}
(V_t^\pi)^{4(1-\gamma)} &= (V_0^\pi)^{4(1-\gamma)} \, e^{4(1-\gamma)[rt + \int_0^t \pi_u^P \lambda^P \sigma^P + \pi_u^S \lambda_u \sigma_u^\star \, du]} \, e^{4(1-\gamma) L_t - \frac{1}{2} 4(1-\gamma) \langle L \rangle_t} \\
&= (V_0^\pi)^{4(1-\gamma)} \, e^{4(1-\gamma)[rt + \int_0^t \pi_u^P \lambda^P \sigma^P + \pi_u^S \lambda_u \sigma_u^\star \, du]} \\
&\quad \cdot e^{4(1-\gamma) L_t - \frac{1}{2} 16 (1-\gamma)^2 \langle L \rangle_t} \, e^{\frac{1}{2} 16 (1-\gamma)^2 \langle L \rangle_t - \frac{1}{2} 4(1-\gamma) \langle L \rangle_t} \\
&= (V_0^\pi)^{4(1-\gamma)} \, e^{4(1-\gamma) L_t - \frac{1}{2} 16 (1-\gamma)^2 \langle L \rangle_t} \, e^{4(1-\gamma)[(2(1-\gamma) - \frac{1}{2}) + rt + \int_0^t \pi_u^P \lambda^P \sigma^P + \pi_u^S \lambda_u \sigma_u^\star \, du]} .
\end{aligned}$$

Condition (3.30) is fullfilled, if for example we have that

$$Z_t := e^{4(1-\gamma) L_t - \frac{1}{2} 16 (1-\gamma)^2 \langle L \rangle_t} \in L^2(P) ,$$

and that

$$R_t := e^{4(1-\gamma)\left[(2(1-\gamma)-\frac{1}{2})+rt+\int_0^t \pi_u^P \lambda^P \sigma^P + \pi_u^S \lambda_u \sigma_u^\star \, du\right]} \in L^2(P)\,.$$

We consider the square of Z_t:

$$\begin{aligned} Z_t^2 &= e^{8(1-\gamma)L_t - \frac{1}{2}32(1-\gamma)^2 \langle L \rangle_t} \\ &= e^{8(1-\gamma)L_t - 64(1-\gamma)^2\langle L \rangle_t} e^{48(1-\gamma)^2\langle L \rangle_t} \\ &\le \underbrace{\frac{1}{2}\, e^{16(1-\gamma)L_t - \frac{1}{2}256(1-\gamma)^2\langle L \rangle_t}}_{(1)} + \underbrace{\frac{1}{2} e^{96(1-\gamma)^2\langle L \rangle_t}}_{(2)}\,. \end{aligned}$$

Condition (3.5) of Def. 3.1 then implies the Novikov condition for expression (1) and at the same time that expression (2) belongs to $L^1(P)$. So we have that $Z_t \in L^2(P)$.
To guarantee that $R_t \in L^2(P)$, we need that

$$\mathbb{E}\left[\int_t^T e^{8(1-\gamma)\left[(2(1-\gamma)-\frac{1}{2})+rs+\int_0^s \pi_u^P \lambda^P \sigma^P \, du + \int_0^s \pi_u^S \lambda_u \sigma_u^\star \, du\right]} \, ds\right] < \infty\,.$$

This condition is then implied by conditions (3.5) and (3.6) of Def. 3.1, where we note that $8(1-\gamma) < 0$ for $\gamma > 1$.
Now (3.30) is proved and since (3.29) holds, we have finally fullfilled condition (3.28).
Part 2: $\gamma = 1$.
Just using analogous arguments as in the power utility case we arrive at

$$\mathbb{E}^{t,v}\left[\log(V_T^{\pi^\star})\right] - \mathbb{E}^{t,v}\left[\int_t^T \kappa \frac{(\lambda_u^\star)^\alpha}{\alpha}\,\mathrm{d}u\right] = J'(t,v;\pi^\star,\lambda^\star) = \Phi(t,v)\,.$$

The equation corresponding to (3.27) for the log utility case then reads:

$$\Phi(T, V_T^\pi) - \int_t^T \kappa \frac{\lambda_u^\alpha}{\alpha}\,\mathrm{d}u \;\le\; \Phi(t,v) + \int_t^T \pi_u^P \sigma^P \, dW_u^P + \int_t^T \pi_u^S \sigma_u^\star \,\mathrm{d}W_u\,,$$

where we have used that $\Phi_v(t,v) = 1/v$. Taking the expectation on both both sides and keeping in mind that $\Phi(t,v) = \log(v)$ then yields

$$\begin{aligned} \mathbb{E}^{t,v}\left[\log(V_T^\pi)\right] - \mathbb{E}^{t,v}\left[\int_t^T \kappa \frac{(\lambda_u)^\alpha}{\alpha}\,\mathrm{d}u\right] &= J'(t,v;\pi,\lambda) \\ &\le \Phi(t,v) + \underbrace{\mathbb{E}^{t,v}\left[\int_t^T \pi_u^P \sigma^P \, dW_u^P + \int_t^T \pi_u^S \sigma_u^\star \,\mathrm{d}W_u\right]}_{=0,\ by\ (3.4)}\,. \end{aligned}$$

□

4 Discussion and Implications of Results

Our results in Theorem 3.1, Theorem 3.2, and Theorem 3.3 indicate the unconstrained executive's maximized utility and his behavior regarding personal portfolio selection and choice of work effort in the constant relative risk aversion setup. Subsequently we investigate the sensitivity of these optimal strategies when varying the characteristics of the executive: risk aversion, productivity, and disutility stress. Additionally, we derive the fair compensation for the work effort of the executive in an indifference utility framework, see, e.g., Lambert, Larcker and Verecchia (1991) for a related approach.

The executive is characterized by the relative risk aversion coefficient ($\gamma > 0$), and two work effectiveness parameters: productivity ($1/\kappa$, with $\kappa > 0$), and disutility stress (α, with $\alpha > 2$). To produce results that have relativity to a base-level of work effort (i.e. a base-level control strategy specified by the Sharpe ratio λ_0), the disutility $c^\star$ is reparameterized so that the set-up becomes

$$U(v) = \begin{cases} \dfrac{v^{1-\gamma}}{1-\gamma}\,, & \text{for } \gamma > 0 \text{ and } \gamma \neq 1 \\ \log(v)\,, & \text{for } \gamma = 1 \end{cases}$$

and

$$c^\star(t,v,\lambda) = \frac{\kappa}{\alpha}\, v^{1-\gamma} \left(\frac{\lambda}{\lambda_0}\right)^{\alpha}, \quad \text{for } \lambda \geq 0\,, \quad \gamma > 0.$$

For most parts of this section we focus on the optimal effort choice ($\lambda^\star$), and pass over the optimal portfolio strategy ($\pi^\star$). The optimal own-company stockholding ($\pi^{S^\star}$) is a function of the optimal effort choice and of the optimized volatility ($\sigma^\star$, derived in Lemma 2.1), that is not explicitly specified. The optimal holdings in the market portfolio ($\pi^{P^\star}$) coincides with the result from classical utility maximization in the constant relative risk aversion setting, and is therefore of limited interest.

4.1 The Log-Utility Case

The optimal choice of effort in the new parameterizations is $\lambda^\star = \lambda_0^{\frac{\alpha}{\alpha-2}}\, \kappa^{-\frac{1}{\alpha-2}}$ (see Theorem 3.2 for the optimal solution in the original parametrization). We require a minimal productive efficiency, that is $\kappa^{-1} > \lambda_0^{-2}$, to ensure that the optimal work effort is greater than the corresponding base level, i.e. $\lambda^\star \geq \lambda_0$. Under this assumption we can formulate the optimal work effort as a function of productivity and disutility stress, $\lambda^\star = \lambda^\star(\kappa, \alpha)$, and calculate the sensitivities

$$\frac{\partial \lambda^\star}{\partial (1/\kappa)} = \frac{1/\kappa}{\alpha - 2}\, \lambda^\star > 0\,, \quad \text{and} \quad \frac{\partial \lambda^\star}{\partial \alpha} = \lambda^\star\, \frac{\ln \kappa/\lambda_0^2}{(\alpha-2)^2} < 0\,, \quad \text{for } \alpha > 2, \text{ and } \kappa^{-1} > \lambda_0^{-2}\,.$$

The executive's optimal work effort choice is positively related to his work productivity parameter ($\frac{\partial \lambda^\star}{\partial(1/\kappa)} > 0$), and negatively related to his disutility stress parameter ($\frac{\partial \lambda^\star}{\partial \alpha} < 0$).

Figure 1 depicts the optimal effort choice ($\lambda^\star$) as a function of work productivity ($1/\kappa$) and disutility stress (α), with $\lambda_0 = 0.10$. As predicted, the optimal effort choice, the idiosyncratic Sharpe ratio ($\lambda^\star$), increases with work productivity ($1/\kappa$) and decreases with disutility stress (α). For moderate and large values of disutility stress, the optimal effort appears to be mainly driven by the executive's productivity where we observe a higher sensitivity for the productivity ($1/\kappa$) being close to the designated boundary value ($1/\lambda_0^2 = 100$).

Interesting limiting cases are:

$$\lim_{\kappa \nearrow \lambda_0^2} \lambda^\star(\kappa, \alpha) = \lambda_0 \quad \text{and} \quad \lim_{\kappa \searrow 0} \lambda^\star(\kappa, \alpha) = +\infty \,, \quad \text{for all } \alpha > 2 \,,$$

indicating that the limit for deteriorating work productivity is base-level work effort (λ_0), and ever increasing work productivity yields ever increasing effort (to infinity). Taking the disutility stress parameter to its boundary cases gives

$$\lim_{\alpha \searrow 2} \lambda^\star(\kappa, \alpha) = +\infty \quad \text{and} \quad \lim_{\alpha \nearrow \infty} \lambda^\star(\kappa, \alpha) = \lambda_0 \,, \quad \text{for all } \kappa^{-1} > \lambda_0^{-2} \,,$$

indicating that the executive will deliver ever increasing work effort as disutility stress diminishes ($\alpha \searrow 2$), and the totally stressed executive ($\alpha \nearrow \infty$) will deliver base-level effort.

The executive's maximized utility from his optimal personal investment and work effort decision can be written as difference of the utility from investment and disutility from effort:

$$\Phi(v, 0) = \underbrace{\log v + \left[r + \frac{1}{2} (\lambda^P)^2 + \frac{1}{2} (\lambda^\star)^2 \right] T}_{= \mathbb{E}^{0,v}[U(V_T^{\pi^\star})]} - \underbrace{\frac{1}{\alpha} (\lambda^\star)^2 \, T}_{\mathbb{E}^{0,v} \int_0^T c(\lambda^\star(t, V_t^{\pi^\star}) \, \mathrm{d}t} \,.$$

Applying indifference utility arguments, the executive's fair compensation for the cost of effort can be paid as an upfront cash compensation (Δv). Then the fair compensation is a cash upfront payment (Δv) that is the solution of:

$$\Phi(v + \Delta v, 0) = \Phi(v, 0) + \mathbb{E}^{0,v} \left[\int_0^T c(\lambda^\star(t, V_t^{\pi^\star}) \, \mathrm{d}t \right] \tag{4.1}$$

The solution is

$$\Delta v = v \left(e^{\frac{(\lambda^\star)^2 \, T}{\alpha}} - 1 \right) = v \left(e^{\frac{\lambda_0^2 \, T}{\alpha} \left(\frac{\lambda_0^2}{\kappa} \right)^{\frac{2}{\alpha - 2}}} - 1 \right) \,.$$

The sensitivities of the compensation ($\Delta v(\kappa, \alpha)$) with respect to changes in the work productivity and disutility stress parameters are as expected:

$$\frac{\partial \Delta v}{\partial (1/\kappa)} = \frac{2}{\alpha - 2} \frac{1}{\kappa} \frac{(\lambda^\star)^2}{\alpha} \Delta v \quad > \quad 0 \,, \quad \text{for } \alpha > 2 \text{ and } \kappa^{-1} > \lambda_0^{-2} \,.$$

and

$$\frac{\partial \Delta v}{\partial \alpha} = -\left(\frac{1}{\alpha} + \frac{2\,\ln \lambda_0^2/\kappa}{(\alpha-2)^2}\right)\frac{(\lambda^\star)^2}{\alpha}\,\Delta v \quad < \quad 0\,, \quad \text{for } \alpha > 2 \text{ and } \kappa^{-1} > \lambda_0^{-2}\,.$$

The executive's indifference utility compensation therefore increases with his work productivity and decreases with his disutility stress.

Figure 2 displays a graph of the the fair cash up-front compensation based on the indifference utility rationale. The fair compensation (Δv) depends on the executive's initial wealth (v), the specific time horizon (T), and the base-level Sharpe ration (λ_0). For the present case we have chosen $v = \$5$ Mio, $T = 10$ years, and $\lambda_0 = 0.10$. Interesting limiting cases are:

$$\lim_{\kappa \nearrow \lambda_0^2} \Delta v(\kappa,\alpha) = v\left(e^{\frac{\lambda_0^2 T}{\alpha}} - 1\right)\,, \quad \text{and} \quad \lim_{\kappa \searrow 0} \Delta v(\kappa,\alpha) = +\infty\,, \quad \text{for all } \alpha > 2\,,$$

indicating that the limit for deteriorating work productivity to base-level work effort ($1/\lambda_0^2$) is the corresponding fair compensation, and ever increasing work productivity yields ever increasing fair compensation (to infinity). Taking the disutility stress parameter to its boundary cases gives

$$\lim_{\alpha \searrow 2} \Delta v(\kappa,\alpha) = +\infty\,, \quad \text{and} \quad \lim_{\alpha \nearrow \infty} \Delta v(\kappa,\alpha) = v\left(e^{\frac{\lambda_0^2 T}{\alpha}} - 1\right)\,, \quad \text{for all } \kappa < \lambda_0^2\,,$$

indicating that the executive will receive ever increasing fair compensation as disutility stress diminishes ($\alpha \searrow 2$), and the totally stressed executive ($\alpha \nearrow \infty$) will receive the base-level compensation (case: $\lambda^\star = \lambda_0$).

4.2 The Power-Utility Case

The optimal effort in the new parametrization reads $\lambda^\star(t) = \lambda_0^{\frac{\alpha}{\alpha-2}}\,(\kappa\gamma)^{-\frac{1}{\alpha-2}}\,f(t)^{\frac{1}{\alpha-2}}$, where we have dropped the dependence on the variable v. To ensure that the optimal effort is greater than the base effort we assume $r > -\frac{1}{2}\frac{\lambda_P^2}{\gamma}$ and

$$\kappa^{-1} \geq \begin{cases} \gamma\,\lambda_0^{-2}\,, & \text{for } \; 0 < \gamma < 1\,, \\ \gamma\,\lambda_0^{-2}\,f(0)^{-1}\,, & \text{for } \gamma > 1\,. \end{cases}$$

The conditions above follow from properties of the function f that is a solution of an ordinary differential equation of Bernoulli-type. Also note that in the new parametrization $f(0)$ reads

$$f(0) = e^{(1-\gamma)\left(r+\frac{1}{2}\frac{\lambda_P^2}{\gamma}\right)T}\left(1 - \frac{(\alpha-2)\left(\frac{\lambda_0^\alpha}{\kappa\,\gamma}\right)^{\frac{2}{\alpha-2}}}{\alpha\,(2\,\gamma\,r + \lambda_P^2)}\left(e^{\frac{1-\gamma}{\alpha-2}\left(2\,r+\frac{\lambda_P^2}{\gamma}\right)T} - 1\right)\right)^{-\frac{\alpha-2}{2}}.$$

The executive's fair compensation is derived from Equation (4.1). The cash upfront payment Δv is

$$\Delta v = v \left(e^{\frac{1}{2\gamma}\int_0^T \lambda^\star(t)^2\,\mathrm{d}t} \left[1 - \frac{(\alpha-2)\left(\frac{\lambda_0^\alpha}{\kappa\,\gamma}\right)^{\frac{2}{\alpha-2}}}{\alpha\,\left(2\,\gamma\, r + \lambda_P^2\right)} \left(e^{\frac{1-\gamma}{\alpha-2}\left(2\,r + \frac{\lambda_P^2}{\gamma}\right)T} - 1 \right) \right]^{\frac{(\alpha-2)}{2(1-\gamma)}} - 1 \right).$$

Remark 4.1. *The presented solution Δv is derived by using structural properties of the optimal portfolio strategies. The optimal portfolio strategy $\pi^\star$ is identical to that of an outsider investor $\widehat{\pi}^\star$ with knowledge of the effort exercised by the executive, that is, the outside investor knows $\lambda^\star$. Denote $\widehat{\Phi}(v,0)$ the maximized utility of the outside investor, then it follows that $\widehat{\Phi}(v,0) = \Phi(v,0) + \mathbb{E}[\int_0^T c^\star(\lambda^\star(t))\,\mathrm{d}t]$. Further, we can calculate*

$$\widehat{\Phi}(0,v) = \frac{v^{1-\gamma}}{1-\gamma}\, e^{(1-\gamma)\left[\left(r+\frac{1}{2}\frac{\lambda_P^2}{\gamma}\right)T + \frac{1}{2\gamma}\int_0^T \lambda^\star(t)^2\,\mathrm{d}t\right]},$$

and then solve $\widehat{\Phi}(v,0) = \Phi(v+\Delta,0)$, the indifference utility principle as given in Equation (4.1)*, for Δv.*

In contrast to the log-utility case, the sensitivities of the optimal effort $\lambda^\star$ and the fair compensation Δv with respect to variations in the parameters describing the executive cannot be given in a compact expression.

First the sensitivities of the optimal work effort ($\lambda^\star$) is investigated. Figure 3 displays the optimal effort ($\lambda^\star$) over time for varying risk aversion γ. It is notable that an executive with a rather low risk aversion ($0 < \gamma < 1$) starts at a high effort level and then decreases over time. For an executive with a rather high risk aversion ($\gamma > 1$) the effort starts at a lower level and increases over time. Observing the executive's effort over time therefore potentially reveals his risk aversion. Figure 4 is in line with the previous observation. The risk aversion is fixed at a rather low value ($\gamma = 0.5$), hence the executive's effort decreases over time. The executive's effort ($\lambda^\star$) increases with his productivity (κ^{-1}) indicating that a more productive executive will work harder in order to benefit from the company's stock price growth through his investment decision of own-company stockholding. Figure 5 is similar to the previous setting, but now the disutility stress (α) is varied, with productivity being fixed ($\kappa^{-1} = 2000$). Increasing susceptibility to stress leads to decreasing effort.

The executive's fair compensation is now analyzed. The sensitivities of the upfront cash payment (Δv) is studied with respect to variations in the parameters describing the executive. Figure 6 shows the fair compensation graphed against productivity (κ^{-1}) and risk aversion (γ), disutility stress fixed ($\alpha = 5$). Decreasing risk aversion and increasing productivity leads to an increasing compensation. This effect becomes more notable for executives with a rather low risk aversion ($\gamma \approx 0.5$ and below). In Figure 7 the executives risk aversion is fixed ($\gamma = 0.5$) and the other parameters vary. Increasing productivity (κ^{-1}) and decreasing disutility stress (α) leads to an increasing fair compensation, where the relationship is more sensitive for small values of disutility stress (α). In Figure 8 the executive's productivity is fixed ($\kappa^{-1} = 2000$), and risk aversion (γ) and disutility stress (α) are varied. The sensitivities are as observed before, and the effect becomes more pronounced for a rather low risk aversion ($\gamma \approx 0.5$ and below) and a rather low disutility stress ($\alpha \approx 4.5$). For even lower disutility stress ($\alpha \approx 4$ and below) the fair compensation (Δv) increases rapidly (what cannot be shown in the present figure).

In our framework the executive's effort choice ($\lambda^\star$) and fair compensation (Δv) depend sensibly on the executive's characteristics, risk aversion (γ), work productivity (κ^{-1}), and disutility stress (α). Consequential observations are that the executive's risk aversion can be backed out from the exercised effort monitored over time, and that a better qualified executive (more productivity κ^{-1} and less disutility stress α) leads not only to a better performance but also to a higher indifference utility compensation (Δv). Thus the unconstrained executive is rewarded twice for talent. First he receives a higher compensation as a direct reward. Second, he benefits from investing in his own-company stock what can be termed an indirect reward.

5 Conclusion and Outlook

We establish a model framework that gives insight into an unconstrained executive's own-company stockholding and work effort preferences. The executive is characterized by risk aversion and work effectiveness parameters. We demonstrate that an executive with superior work effectiveness (i.e. higher quality) will undertake more work effort for his company. Furthermore, depending on any change in the company's non-systematic volatility associated with the executive's work effort (i.e. control strategy), due to risk aversion a higher quality executive will not necessarily undertake a higher own-company stockholding.

For application to empirical data, our framework allows an executive quality measure to be backed-out from the observed own-company stockholdings of unconstrained executives (assuming knowledge of non-systematic company volatility). Alternatively, with assumption of executive quality and risk aversion, our framework allows identification of the deviation in own-company stockholding that results from constraining an executive with performance contracting. A future extension for our framework is to specify a constrained executive subject to an imposed own-company stockholding representative of performance contracting, and to contrast his work effort strategy with that of our unconstrained executive.

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Figures

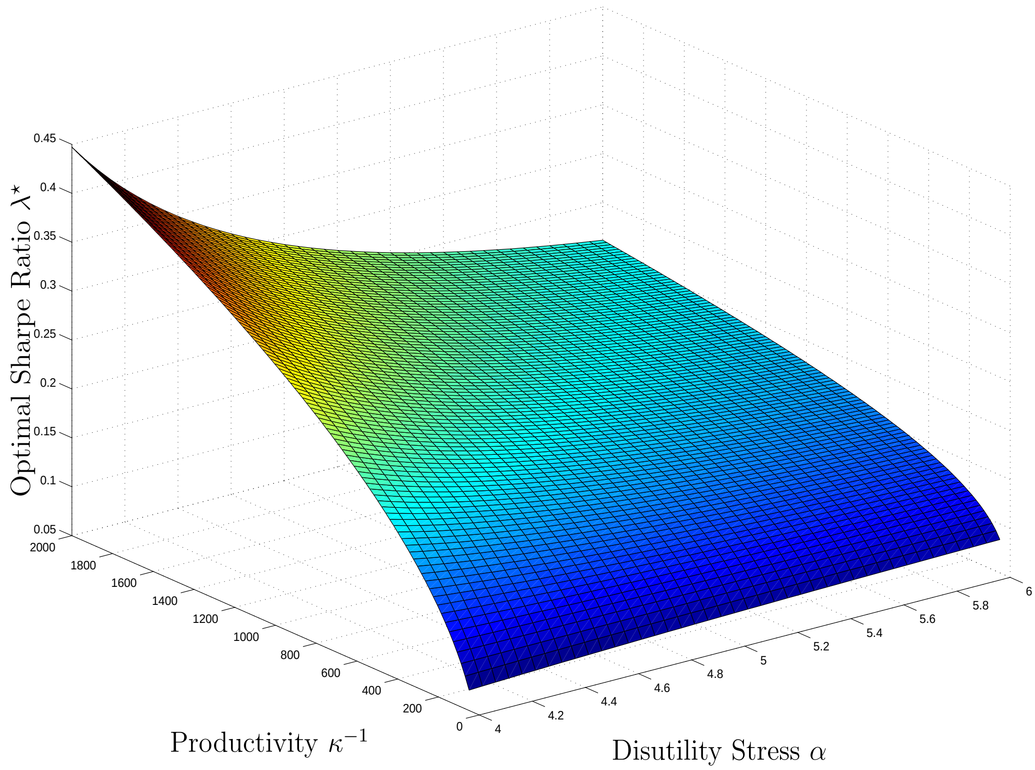

Figure 1: The optimal choice of the executive's effort $\lambda^\star$ is graphed against executive's characteristics work productivity κ^{-1} and disutility stress α; with fixed base-level Sharpe ratio $\lambda_0 = 0.10$.

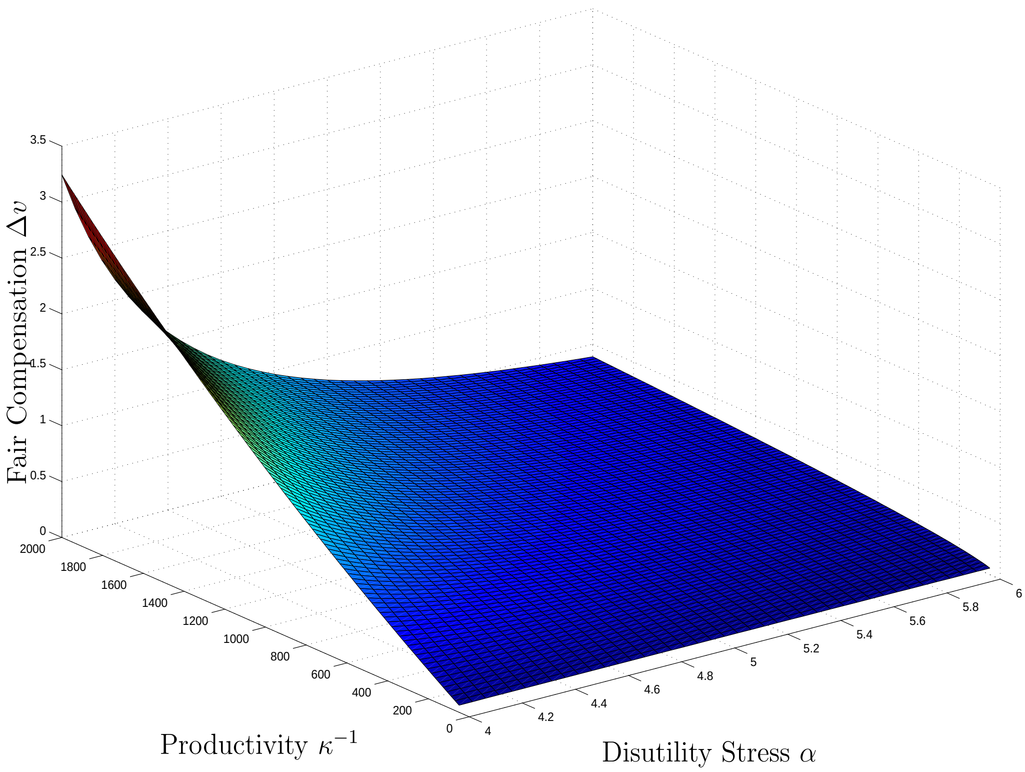

Figure 2: The executive's fair up-front cash compensation Δv (based on indifference utility) is graphed against executive's characteristics work productivity κ^{-1} and disutility stress α; with fixed base-level Sharpe ratio $\lambda_0 = 0.10$, initial wealth $v = \$5$ Mio., and $T = 10$.).

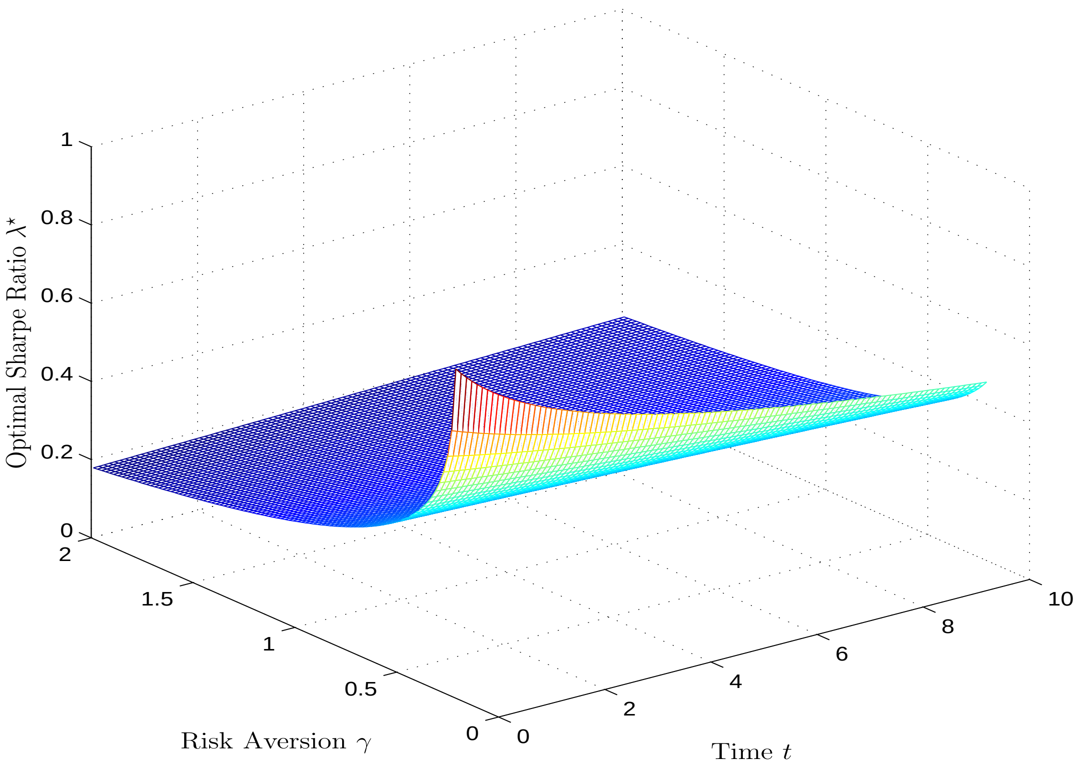

Figure 3: The optimal choice of the executive's effort $\lambda^\star$ is graphed against time t and risk-aversion γ; with fixed base-level Sharpe ratio $\lambda_0 = 0.10$, disutility stress $\alpha = 5$, work productivity $\kappa^{-1} = 2000$.

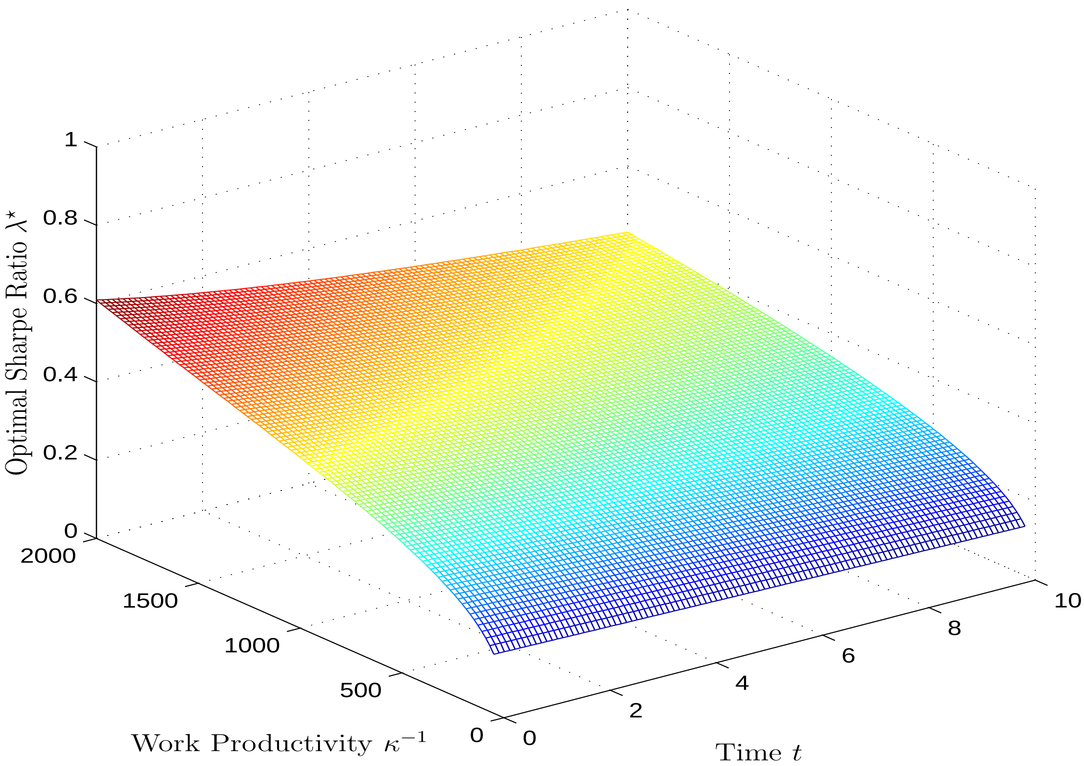

Figure 4: The optimal choice of the executive's effort $\lambda^\star$ is graphed against time t and work productivity κ^{-1}; with fixed base-level Sharpe ratio $\lambda_0 = 0.10$, disutility stress $\alpha = 5$, risk aversion $\gamma = 0.25$.

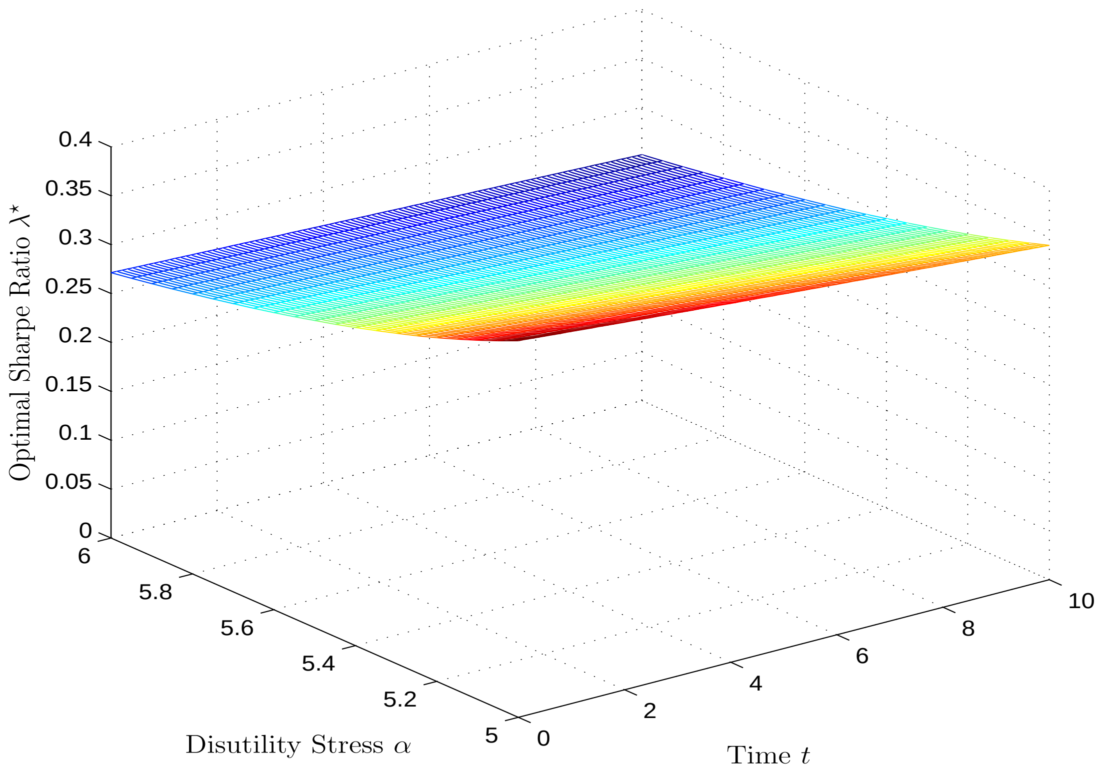

Figure 5: The optimal choice of the executive's effort $\lambda^\star$ is graphed against time t and disutility stress α; with fixed base-level Sharpe ratio $\lambda_0 = 0.10$, work productivity $\kappa^{-1} = 2000$, risk aversion $\gamma = 0.5$.

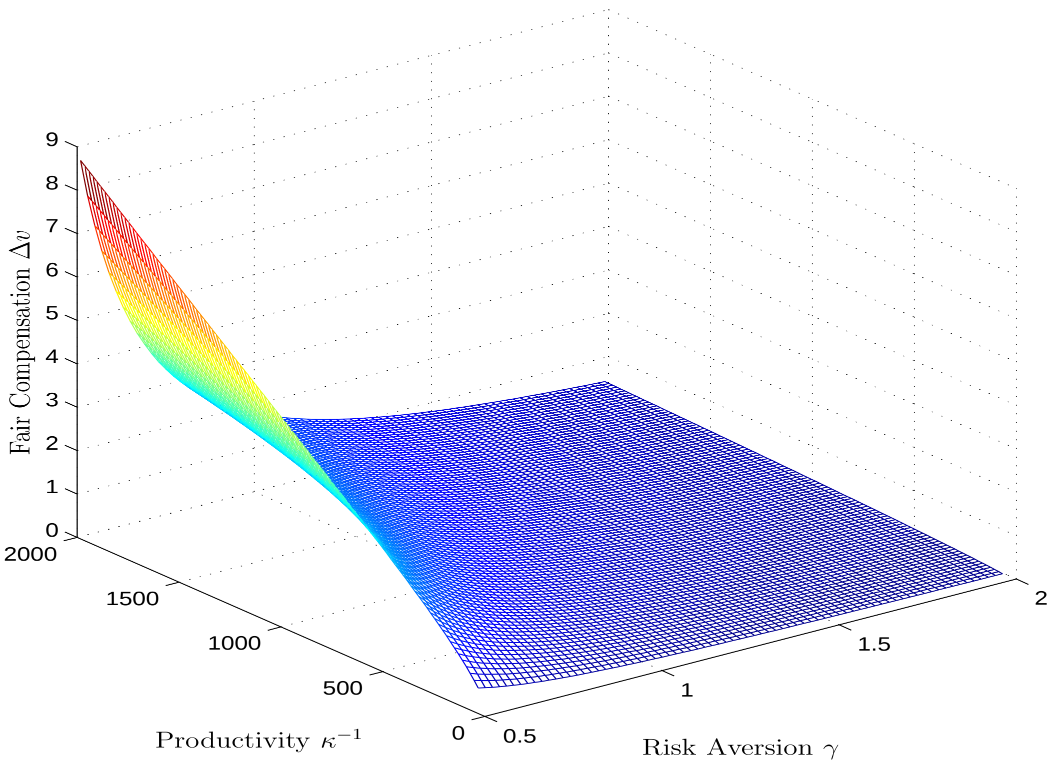

Figure 6: The executive's fair up-front cash compensation Δv (based on indifference utility) is graphed against the executive's characteristics work productivity κ^{-1} and risk aversion γ; with fixed base-level Sharpe ratio $\lambda_0 = 0.10$, initial wealth $v = \$5$ Mio., $T = 10$, and disutility stress $\alpha = 5$.

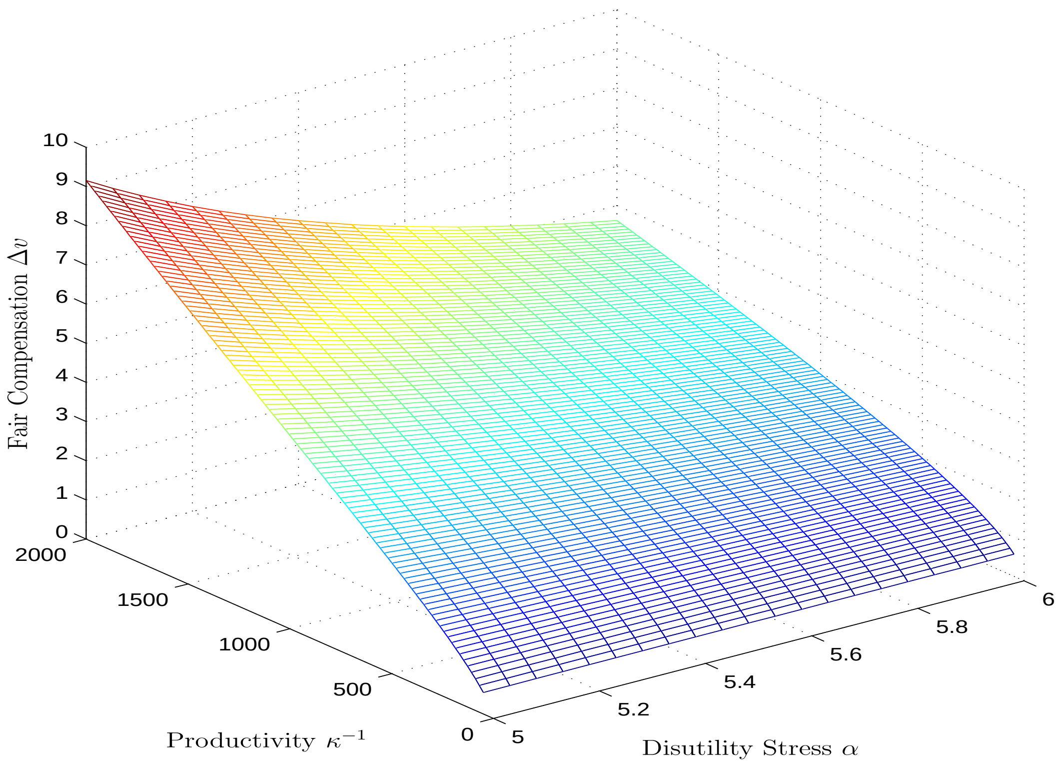

Figure 7: The executive's fair up-front cash compensation Δv (based on indifference utility) is graphed against the executive's characteristics work productivity κ^{-1} and disutility stress α; with fixed base-level Sharpe ratio $\lambda_0 = 0.10$, initial wealth $v = \$5$ Mio., $T = 10$, and risk aversion $\gamma = 0.5$.

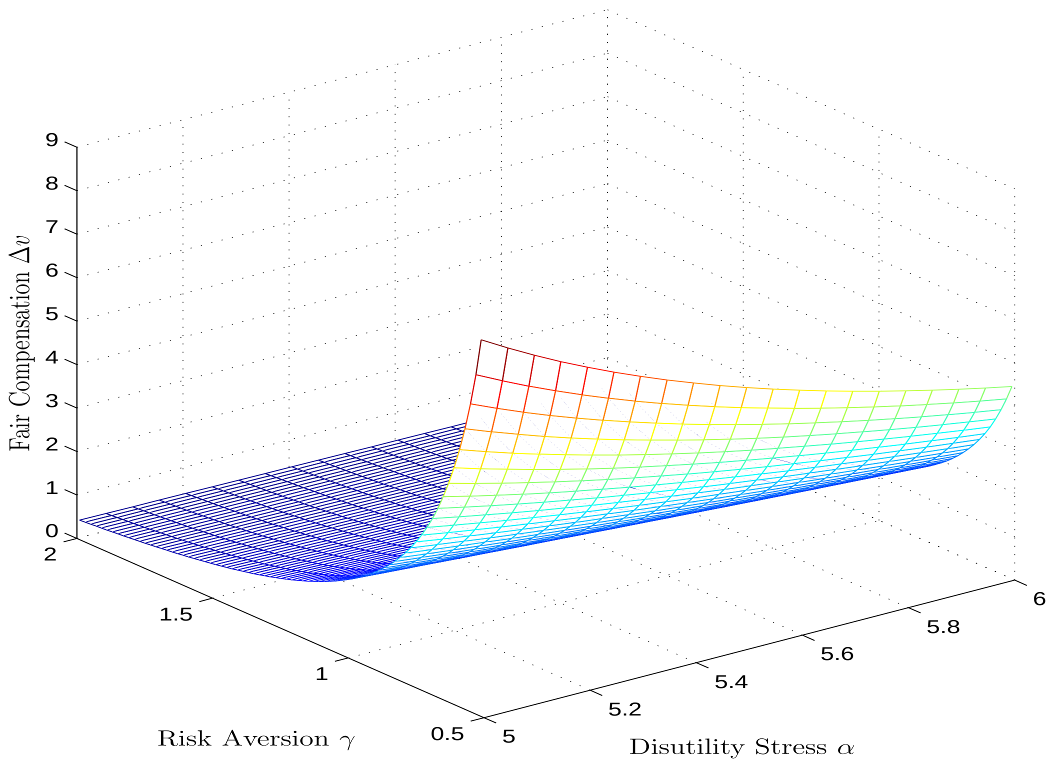

Figure 8: The executive's fair up-front cash compensation Δv (based on indifference utility) is graphed against the executive's characteristics risk aversion γ and disutility stress α; with fixed base-level Sharpe ratio $\lambda_0 = 0.10$, initial wealth $v = \$5$ Mio., $T = 10$, and work productivity $\kappa^{-1} = 2000$.

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