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Vorwort

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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

Optimal Investment for Executive Stockholders with Exponential Utility

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November 18, 2010

Abstract

The scope of this paper is to enhance the model for the own-company stockholder (given in Desmettre, Gould and Szimayer (2010)), who can voluntarily performance-link his personal wealth to his management success by acquiring stocks in the own-company whose value he can directly influence via spending work effort. The executive is thereby characterized by a parameter of risk aversion and the two work effectiveness parameters inverse work productivity and disutility stress. We extend the model to a constant absolute risk aversion framework using an exponential utility/disutility set-up. A closed-form solution is given for the optimal work effort an executive will apply and we derive the optimal investment strategies of the executive. Furthermore, we determine an up-front fair cash compensation applying an indifference utility rationale. Our study shows to a large extent that the results previously obtained are robust under the choice of the utility/disutility set-up.

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1 Introduction

It is widely supported that the remuneration of managers should be linked to performance, see, e.g., Ross (1973), Jensen and Meckling (1976), Holmstrom (1979) and others, for the fundamentals of agency theory, and the summaries of Murphy (1999) and Core, Guay and Larcker (2003). Stemming from that theory, many papers dealing with executive compensation have arisen. In recent research, the motivation for individuals in an executive position to voluntarily performance-link their private wealth by acquiring stocks in the own-company was considered. For example, Desmettre, Gould and Szimayer (2010) proposed a model that allows an executive to invest in a riskless asset, a diversified market portfolio and the own-company's stock. Thereby the executive has the possibility to influence the own-company's stock's value by applying work effort. He then maximizes the expected value of the utility of final wealth and the negative utility of integrated work effort over a fixed time horizon. They give closed-form solutions for the optimal investment strategies and the work effort which the executive will apply in a constant relative risk aversion framework. Other technical papers that consider similar dynamic pincipal-agent problems are Cadenillas, Cvitanić and Zapatero (2004) or Ou-Yang (2003), for example.

The scope of this paper is to extend the work of Desmettre, Gould and Szimayer (2010) to a constant absolute risk aversion setting and thus to investigate the robustness of the model proposed by them. We consider an executive who is characterized by an absolute risk aversion parameter (η) and the two work effectiveness parameters inverse work productivity (κ) and disutility stress (α). The executive is endowed with an initial wealth inclusive of his compensation and is allowed to invest in a riskless asset, a diversified market portfolio and the own-company's stock. Furthermore, the executive influences the own-company's stock via his work effort, which is associated to be the choice of his Sharpe ratio control strategy (λ). His aim is then to maximize the expected value of the utility of final wealth and the negative utility of integrated work effort. In contrast to Desmettre, Gould and Szimayer (2010), the executive is characterized by a constant absolute risk aversion utility and disutility function. We derive the executive's optimal investment strategy (Π^*) and work effort (λ^*) in closed form using stochastic control theory and the corresponding Hamilton-Jacobi-Bellman equation, where we have to restrict ourselves to the case when the riskless interest rate is equal to zero. Additionally we derive an up-front fair cash compensation rate of the executive using an indifference utility rationale. Results of past research are confirmed to a large extent. An executive with higher work effectiveness applies a substantially higher work effort and a more productive executive receives a higher up-front fair compensation. These results indicate that the model is robust under the choice of the utility and disutility function. As a technical side aspect, we provide a quite larger class of admissible strategies as in Desmettre, Gould, Szimayer (2010) by reducing a fourth moment condition regarding the proportions invested to a two plus epsilon condition.

The paper is organized as follows. Section 2 introduces the notation and terminology. In Section 3 the Hamilton-Jacobi-Bellman equations characterizing the utility and integrated work effort maximization problem are derived and closed-form solutions for the exponential-utility case are established. The results are illustrated in Section 4 and the fair compensation rate of the executive characterized by the constant absolute risk aversion setting is given. Section 5 concludes. Some proofs are moved to the Appendix.

2 Notation and Set-Up

We look at an optimal investment problem of an executive who is endowed with an initial wealth. He can freely invest in the financial market and can choose the work effort he spends to increase the own-company's performance.

2.1 Financial Market

The executive acts on a given a filtered probability space $(\Omega, \mathcal{F}, P, (\mathcal{F}_t)_{t\geq 0})$ satisfying the usual conditions 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 are a money market account, a diversified market portfolio, and his own-company's stock.

The risk-free money market account has the price process $B = (B_t)_{t\geq 0}$, with dynamics

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

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)

$$\mathrm{d}P_t = P_t\,(\mu_P\, \mathrm{d}t + \sigma_P\, \mathrm{d}W_t^P)\,, \quad P_0 \in \mathbb{R}^+\,, \tag{2}$$

where $\mu_P \in \mathbb{R}$ and $\sigma_P > 0$ are respectively the expected return rate and volatility of the market portfolio. The corresponding Sharpe ratio is then $\lambda_P = (\mu_P - r)/\sigma_P$.

The company's stock price process, $S^\lambda = (S_t^\lambda)_{t\geq 0}$, is a controlled diffusion with SDE

$$\mathrm{d}S_t^\lambda = S_t^\lambda \left([r + \lambda_t\, \sigma]\, \mathrm{d}t + \beta \left[\frac{\mathrm{d}P_t}{P_t} - r\mathrm{d}t \right] + \sigma\, \mathrm{d}W_t \right) , \quad S_0^u \in \mathbb{R}^+ , \tag{3}$$

where $\mu = r + \lambda\, \sigma$ 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), σ is the company's non-systematic volatility, and the Sharpe ratio $\lambda = (\lambda_t)_{t\geq 0}$ of the own-company's stock is controlled by the executive.

2.2 Controls and Wealth Process

The executive invests his initial wealth $V_0 > 0$, which includes also his compensation, in the financial market. For an exogenously given time horizon, $T > 0$, the executive seeks to maximize his total utility by controlling the portfolio holdings and work effort.

The portfolio is determined by a trading strategy in absolute values given by the bivariate control process $\Pi = (\Pi^P, \Pi^S)$, where $\Pi^P = (\pi_t^P\, V_t)_{t\geq 0}$ is the absolute value of wealth invested in the market portfolio and $\Pi^S = (\pi_t^S\, V_t)_{t\geq 0}$ is the absolute value of wealth invested in the company's stock. Thereby the self-financing trading strategy $\pi = (\pi^P, \pi^S)$ represents the proportions invested in the market portfolio and the own-company's stock, respectively.[1] The executive influences the company's stock price process by choice of the control strategy $\lambda = (\lambda_t)_{t\geq 0}$ which is associated with spending work effort for the company. Resulting from that, the executive suffers a disutiliy for the work effort he spends, which is representated by a Markovian disutility rate $c(t, V_t, \lambda_t)$ for control strategy (λ_t), where V_t is the executive's actual wealth. We assume that the disutility rate $c : [0, T] \times \mathbb{R}^+ \times \mathbb{R}_0^+ \to \mathbb{R}_0^+$ is a continuous and suitably differentiable function where T is the executive's time horizon. The control strategy can be conceptualized as deriving from the executive's corporate investment. For example, identifying and initiating positive net

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[1] We choose absolute trading strategies here due to technical reasons, since we will deal with an exponential utility function in the following.

present value projects. Value is added if $\mu = r + \lambda\,\sigma$ is greater than r, indicating excess return compensation for non-systematic risk. To ensure sensible solutions we require $\lambda \geq 0$, which effectively bars him from destroying company value ($\lambda < 0$) and potentially profiting by shorting the company's stock. All controls are collected in the vector process $u = (\Pi^P, \Pi^S, \lambda)$.

For given initial wealth $V_0 = V_0^u > 0$ and control strategy u, the executive's wealth process, $V^u = (V_t^u)_{t\geq 0}$ is then given by

$$\mathrm{d}V_t^u = \left(V_t^u - \Pi_t^P - \Pi_t^S\right)\frac{\mathrm{d}B_t}{B_t} + \Pi_t^P \frac{\mathrm{d}P_t}{P_t} + \Pi_t^S \frac{\mathrm{d}S_t^\lambda}{S_t^\lambda}\,, \quad V_0^u \in \mathbb{R}^+\,, \tag{4}$$

which can be rewritten using the equations (1), (2) and (3) as

$$\begin{aligned} \mathrm{d}V_t^u = {} & \left[r\,V_t^u + (\Pi_t^P + \beta\,\Pi_t^S)\lambda^P\sigma^P + \Pi_t^S\lambda_t\,\sigma\right]\mathrm{d}t \\ & + \left[\Pi_t^P + \beta\,\Pi_t^S\right]\sigma^P\mathrm{d}W_t^P + \Pi_t^S\,\sigma\,\mathrm{d}W_t\,, \quad V_0^u \in \mathbb{R}^+\,. \end{aligned} \tag{5}$$

2.3 Stochastic Control Problem

The executive maximizes the expected value of the terminal utility of his wealth for time horizon T, subject to some utility function U. The disutility for work effort is quantified by the cost function c. The utility function and the cost function will be specified when deriving a closed-form solution.

The executive's *optimal investment and control decision including work effort* is then the solution of

$$\Phi(t,v) = \sup_{u\in A(t,v)} \mathbb{E}^{t,v}\left[U\left(V_T^u\right) - \int_t^T c\left(s, V_s^u, \lambda_s\right)\mathrm{d}s\right]\,,\ (t,v) \in [0,T]\times\mathbb{R}^+\,, \tag{6}$$

where $A(t,v)$ is given in Def. 2.1.

Definition 2.1 *Let $0 \leq t \leq T$, t fixed, and let further λ take values in $[0,\infty)$. Then we denote by $A(t,v)$ the set of admissible strategies $u = \left(\Pi^P, \Pi^S, \lambda\right)$ corresponding to portfolio value $v = V_t^u > 0$ at time t, which are $\{\mathcal{F}_s\,;\, t \leq s \leq T\}$-predictable processes, such that*

(i) the company's stock price process

$$\mathrm{d}S_s^\lambda = S_s^\lambda\left(\left[r + \lambda_s\sigma\right]\mathrm{d}s + \beta\left[\frac{\mathrm{d}P_s}{P_s} - r\mathrm{d}s\right] + \sigma\,\mathrm{d}W_s\right)\,, \quad S_t^\lambda \in \mathbb{R}^+\,,$$

has a unique non-negative solution and satisfies

$$\int_t^T (S_s^\lambda)^2 \left((\beta\sigma^P)^2 + \sigma^2\right) \mathrm{d}s \;<\; \infty \quad P - a.s.\,;$$

(ii) the wealth equation

$$\mathrm{d}V_s^u = \left(V_s^u - \Pi_s^P - \Pi_s^S\right) \frac{\mathrm{d}B_s}{B_s} + \Pi_s^P \frac{\mathrm{d}P_s}{P_s} + \Pi_s^S \frac{\mathrm{d}S_s^\lambda}{S_s^\lambda}\,,\; V_t^u \in \mathbb{R}^+\,,$$

has a unique non-negative solution and satisfies

$$\int_t^T \left((\Pi_s^P + \beta\,\Pi_s^S)^2(\sigma^P)^2 + (\Pi_s^S\sigma)^2\right) \mathrm{d}s \;<\; \infty \quad P - a.s.\,;$$

(iii) and the utility of wealth and the minimized disutility of control satisfy

$$\mathbb{E}\left[U(V_T^u)^- + \int_t^T c(s, V_s^u, \lambda_s)\,\mathrm{d}s\right] \;<\; \infty\,.$$

3 Optimal Strategies

In this section we give a closed-form solution for the optimal investment and control problem in (11) for an exponential utility/disutility set-up.

We specify the utility and disutility function in a constant absolute risk aversion (CARA) set-up. In particular, for the absolute risk aversion parameter $\eta > 0$, the utility function U is

$$U(v) = 1 - e^{-\eta\, v}\,, \tag{7}$$

and the disutility of control (i.e. work effort) c is

$$c(t, v, \lambda) = \kappa\, e^{-\eta\, v}\, \frac{\lambda^\alpha}{\alpha}\,, \tag{8}$$

where $\kappa > 0$ and $\alpha > 2$ are the executive's work effectiveness parameters, termed 'inverse work productivity' and 'disutility stress'. The constant κ

directly relates his work effort disutility to the quality of his control decision as indicated by the non-systematic Sharpe ratio λ, and α indicates how rapidly his work effort disutility will rise for the sake of an improved λ. The requirement $\alpha > 2$ is a consequence of our set-up that ensures the executive's disutility grows with work effort, i.e. λ, at a rate that offsets (at some level of λ) the rate of his utility gain due to the flow-on from his work effort to the value of his own-company stockholding. A higher quality executive is able to achieve a given λ with lower disutility, and is able to improve λ with lower incremental disutility. That is, higher individual quality (i.e. higher work effectiveness) is implied by lower values of κ and α. In (8), the scaling factor $e^{-\eta v}$ relates the executive's disutility of work effort to his wealth (v) with a formulation based on the constant absolute risk aversion formulation of the utility function in (7). Given a positive value of the absolute risk aversion parameter, $\eta > 0$, the executive's disutility of work effort decreases with his wealth.

To guarantee that the candidates we will derive for the executive's optimal investment and control strategy as well as the value function are indeed optimal, we restrict the class of admissible strategies now as follows:

Definition 3.1 *Let $0 \leq t \leq T$, t fixed, and let λ take values in $[0, \infty)$. Then for some $\tilde{\epsilon} > 0$ we denote by $A_\eta(t, v)$the set of admissible strategies $u \in A(t, v)$, such that we have for $\eta > 0$:*

$$\int_t^T (\Pi_s^P + \beta\, \Pi_s^S)^{2+\tilde{\epsilon}} (\sigma^P)^{2+\tilde{\epsilon}} + \left(\Pi_s^S \sigma\right)^{2+\tilde{\epsilon}} \mathrm{d}s \leq C_1 < \infty, \text{ for some } C_1 \in \mathbb{R}_0^+, \tag{9}$$

$$\int_t^T \Pi_s^S \sigma \lambda_s \,\mathrm{d}u \geq C_2 > -\infty\,, \text{ for some } C_2 \in \mathbb{R}_0^+\,. \tag{10}$$

The optimal investment and control problem stated w.r.t. this more restrictive class is given by

$$\Phi(t, v) = \sup_{u \in A_\eta(t,v)} \mathbb{E}^{t,v} \left[U(V_T^u) - \int_t^T c(s, V_s^u, \lambda_s)\,\mathrm{d}s \right] , \tag{11}$$

where $(t, v) \in [0, T] \times \mathbb{R}^+$.

For the remainder of the paper we assume that the optimal investment and control problem (11) admits a value function $\Phi \in C^{1,2}$.

Remark 3.1 *Condition* (9) *is very close to the minimum requirement of the existence of second moments, which are in any case necessary since this results from the quadratic variation of the wealth process* (5)*. In Desmettre, Gould and Szimayer (2010), fourth moments were still required. That theses conditions are sufficient is proved in Theorem 3.2.*

3.1 Hamilton-Jacobi-Bellman Equation

Having formulated the optimal investment and control decision problem with respect to the parameter set $u = (\Pi^P, \Pi^S, \lambda)$ as given by (11), we can write down the corresponding Hamilton-Jacobi-Bellman equation (HJB). Note that we formulate this equation with respect to a general utility function U and a general disutility function c.

$$\begin{aligned} 0 &= \sup_{u \in \mathbb{R}^2 \times [0,\infty)} \left[(L^u\, \Phi)(t,v) - c(t,v,\lambda) \right] \,, \text{ for } (t,v) \in [0,T) \times \mathbb{R}^+, \\ U(v) &= \Phi(T,v)\,, \quad \text{for } v \in \mathbb{R}^+\,, \end{aligned} \tag{12}$$

where the differential operator L^u is given by

$$\begin{aligned} (L^u g)(t,v) = \frac{\partial g}{\partial t}(t,v) + \frac{\partial g}{\partial v}(t,v) \left(r\, v + \Pi^S \lambda\, \sigma + (\Pi^P + \beta\, \Pi^S)\lambda^P \sigma^P \right) \\ + \frac{1}{2} \frac{\partial^2 g}{\partial v^2}(t,v) \left(\left[\Pi^S \sigma\right]^2 + \left[(\Pi^P + \beta\, \Pi^S)\sigma^P\right]^2 \right) . \end{aligned} \tag{13}$$

Potential maximizers $\Pi^{P^\star}$, $\Pi^{S^\star}$ and $\lambda^\star$ of the HJB (12) can be calculated by establishing the first order conditions:

$$\begin{aligned} \Pi^{P^\star}(t,v) &= -\frac{(\mu^P - r)}{(\sigma^P)^2} \frac{\Phi_v(t,v)}{\Phi_{vv}(t,v)} - \beta\, \Pi^{S^\star}(t,v) \quad , \\ \Pi^{S^\star}(t,v) &= -\frac{\lambda^\star(t,v)}{\sigma} \frac{\Phi_v(t,v)}{\Phi_{vv}(t,v)} \quad , \end{aligned} \tag{14}$$

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

$$\lambda \frac{\Phi_v^2(t,v)}{\Phi_{vv}(t,v)} + \frac{\partial c}{\partial \lambda}(t,v,\lambda) = 0 \quad \text{for all } (t,v) \in [0,T] \times \mathbb{R}^+\,, \tag{15}$$

where we have already used (14) to simplify the equation.

Substitung the candidates (14) in the Hamilton-Jacobi-Bellman equation (12) yields:

$$0 = \Phi_t(t,v) + \Phi_v(t,v)\, v\, r - \frac{1}{2}(\lambda^\star(t,v))^2 \frac{\Phi_v^2(t,v)}{\Phi_{vv}(t,v)} - \frac{1}{2}\lambda_P^2 \frac{\Phi_v^2(t,v)}{\Phi_{vv}(t,v)} - c(t,v,\lambda)\,. \tag{16}$$

In the following section we derive a solution of this equation which then solves our optimal control problem.

3.2 Closed-Form Solution

A closed-form solution is derived for the control problem (11) using the utility and disutility functions (7) and (8), for $\eta > 0$, where we have to restrict ouselves to the case when the riskless interest rate r is equal to zero to obtain solvability of the problem. Nevertheless the class of control problems that we will solve in this setting is still sufficiently large. On the one hand, we repeat that we have enhanced the notion of admissibility for this problem as stated in Remark 3.1. And on the other hand, the assumption of zero interest rates corresponds to discounting the portfolio value by the riskless interest rate, i.e. we consider the utility function of the form $\tilde{U}(v) = 1 - e^{-\eta(T)\, v}$ with $\eta(T) := \eta/B(T)$ and the disutility function of the form $\tilde{c}(t,v) = \kappa e^{-\eta(t)\, v} \frac{\lambda^\alpha}{\alpha}$ with $\eta(t) := \eta/B(t)$, for $0 \le t \le T$. The advantages of assuming zero interest rates is are a closed-form solution and less tedious calculations.

Theorem 3.1 *The full solution of the maximization problem (11) assuming that the risk-fre interest rate fullfills $r = 0$ can be summarized by the strategy*

$$\begin{aligned} \lambda^\star(t,v) &= \left(\frac{1}{\kappa}\, f(t)\right)^{\frac{1}{\alpha-2}}\,, \\ \Pi^{P\star}(t,v) &= \frac{\mu^P}{\eta\,(\sigma^P)^2} - \beta\, \Pi^{S\star}(t,v)\,, \quad \Pi^{S\star}(t,v) = \frac{\lambda^\star(t,v)}{\eta\,\sigma}\,, \end{aligned} \tag{17}$$

and value function

$$\Phi(t,v) = 1 - f(t)\, e^{-\eta\, v}\,, \tag{18}$$

where

$$\begin{aligned} f(t) &= e^{-\frac{1}{2}\left(\mu^P/\sigma^P\right)^2 (T-t)} \\ &\quad \times \left(1 - \frac{(\alpha-2)\,\left(\sigma^P\right)^2\, \kappa^{-\frac{2}{\alpha-2}}}{\alpha\,\left(\mu^P\right)^2} \left(e^{-\frac{1}{\alpha-2}\left(\mu^P/\sigma^P\right)^2 (T-t)} - 1\right)\right)^{-\frac{\alpha-2}{2}}\,. \end{aligned} \tag{19}$$

Proof. Using the representation (8) of the disutility function, the first order condition for $\lambda^\star$ in (15) is now solved:

$$\lambda^\star = \left(\frac{e^{\eta\,v}}{\kappa}\,\frac{\Phi_v^2}{-\Phi_{vv}}\right)^{\frac{1}{\alpha-2}}\,. \tag{20}$$

Now (16) reads

$$0 = \Phi_t + \Phi_v\,v\,r + \frac{1}{2}\,\frac{\Phi_v^2}{-\Phi_{vv}}\,\left(\lambda^P\right)^2 + \frac{\alpha-2}{2\,\alpha}\,\left(\frac{e^{\eta\,v}}{\kappa}\right)^{\frac{2}{\alpha-2}}\,\left(\frac{\Phi_v^2}{-\Phi_{vv}}\right)^{\frac{\alpha}{\alpha-2}}\,. \tag{21}$$

Using the separation ansatz $\Phi(t,v) = 1 - f(t)\,e^{-\eta\,v}$ with $f(T) = 1$ results in

$$\Phi_t = -\dot{f}\,e^{-\eta\,v}\,,\ \ \Phi_v = \eta\,f\,e^{-\eta\,v}\,,\ \ \Phi_{vv} = -\eta^2\,f\,e^{-\eta\,v}\,,\ \ \text{and}\ \ \frac{\Phi_v^2}{-\Phi_{vv}} = f(t)\,e^{-\eta\,v}\,.$$

Thus (21) becomes

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

Simplifying gives

$$-e^{-\eta\,v}\left\{\dot{f} - f\,\left[\eta\,v\,r + \frac{1}{2}\lambda_P^2\right] + f^{\frac{\alpha}{\alpha-2}}\,\left[-\frac{\alpha-2}{2\alpha}\,\kappa^{-\frac{2}{\alpha-2}}\right]\right\} = 0\,. \tag{22}$$

From (22), we see that the separation approach as given above only works if we have that $r = 0$. From (22) with $r = 0$ we see, that we have to solve the ordinary differential equation (ODE) of Bernoulli type

$$\dot{f} = f\,\frac{1}{2}\left(\frac{\mu^P}{\sigma^P}\right)^2 + f^{\frac{\alpha}{\alpha-2}}\,\frac{\alpha-2}{2\alpha}\,\kappa^{-\frac{2}{\alpha-2}}\,, \tag{23}$$

where we keep in mind that $(\lambda^P)^2 \overset{r=0}{=} (\mu^P/\sigma^P)^2$. An ODE of Bernoulli-type $\dot{f} = a_1\,f + a_\nu\,f^\nu$, has the solution

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

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

$$a_1 = \frac{1}{2}\left(\frac{\mu_P}{\sigma^P}\right)^2 \quad , \quad a_\nu = \frac{\alpha-2}{2\alpha}\,\kappa^{\frac{-\alpha}{\alpha-2}} \, .$$

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

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

then

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

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

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

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

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

Substituting for a_1 and a_ν then yields the result for $f(t)$. Using $\frac{\Phi_v}{\Phi_{vv}} = -\frac{1}{\eta}$ and the first order conditions in (14) and (20) we obtain the claimed optimal strategies $\lambda^\star$, $\Pi^{P\star}$ and $\Pi^{S\star}$. Finally note that our claimed optimal strategies are admissible, i.e. $u^\star \in A_\eta(t,v)$. A sufficient condition for admissibility is that $\lambda^\star$, $\Pi^{P\star}\,\sigma^P$, and $\Pi^{S\star}\,\sigma$ are uniformly bounded (see Def. 3.1); because these expressions are deterministic and continuous functions in s on $[t,T]$, they are hence uniformly bounded. □

Remark 3.2 *In the classical set-up without disutility of work effort the executive's optimal investment decision w.r.t. absolute investment strategies can be solved for an exponential utility function using the ansatz* $\Phi(t,v) = e^{-\eta[f(t)\,v+g(t)]}$ *with* $f(T)=1$ *and* $g(T)=0$*. However in our set-up including a disutility of work effort, this technique does not work, since the additional term arising from the disutility in* (21) *causes problems when applying the ansatz stated above in order to reduce equation* (21) *to ordinary differential equations w.r.t.* f *and* g*.*

3.3 Verification Theorem

The solutions of the maximization problem given in Theorem 3.1 are candidates for the optimal investment and control choices for the problem in (11) for the case $r = 0$. In this section we verify that under sufficient assumptions these solutions are indeed optimal. The proof of the following Theorem is provided in the Appendix and can also be found in Desmettre (2010).

Theorem 3.2 (Verification Result) *Let $\kappa > 0$ and $\alpha > 2$; further let $r = 0$. Assume the executive's utility and disutility functions are given by (7) and (8). Then the candidates given in (17) - (19) are the optimal investment and control strategy (i.e. own-company stockholding, market portfolio holding and non-systematic Sharpe ratio strategy) and value function of the optimal control problem (11).*

4 Discussion and Implications of the Results

Theorems 3.1 and 3.2 indicate our unconstrained executive's maximized utility and associated optimal behavior in terms of personal portfolio selection and choice of work effort, subject to the constant absolute risk aversion set-up. In what follows, we investigate the sensitivity of the executive's optimal control choice $\lambda^\star$ to variation of the executive's risk aversion η and work effectiveness characteristics $1/\kappa$ and α. We apply an utility indifference rationale to determine the fair compensation of the executive characterized by the exponential utility/disutility set-up. Furthermore, we comment on the differences (or similarities) between the constant absolute risk aversion set-up examined in this work and the constant relative risk aversion set-up given in Desmettre, Gould and Szimayer (2010).

The executive is characterized by the constant absolute risk aversion coefficient ($\eta > 0$) and the two work effectiveness parameters work productivity ($1/\kappa$, with $\kappa > 0$) and disutility stress ($\alpha > 2$). In order to produce results that are relative to a base-level of work effort, as indicated by a base-level non-systematic Sharpe ratio control decision $\lambda_0 > 0$, the disutility c given by (8) is reparameterized by choosing

$$\tilde{\kappa} := \kappa \left(\lambda_0\right)^{\alpha}, \tag{24}$$

which results in the reparametrized disutility rate

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

Assuming that the work productivity fulfills $1/\tilde{\kappa}>\lambda_0^{-2}\,f(0)^{-1}$, we can then ensure that the optimal work effort is not less than the base-level λ_0.

Regarding the executive's optimal personal investment decisions $\Pi^{\star}$, the optimal own-company stockholding $\Pi^{S^{\star}}$ is a function of the optimal work effort choice and the associated volatility σ. The optimal market portfolio allocation $\Pi^{P^{\star}}$ considered in conjunction with the systematic risk exposure associated with $\Pi^{S^{\star}}$ coincides with the classical Merton proportion in a CARA utility set-up. We point out that we deal with absolute investment strategies in contrast to relative weights given in Desmettre, Gould and Szimayer (2010), which is a consequence of the usage of an exponential utility function.

Note that the optimal work effort $\lambda^{\star}$ does not depend on the risk aversion parameter η, which is caused by assuming $r=0$ in equation (22) in the proof of Theorem 3.1 in order to make the separation approach. In contrast to that, the optimal work effort in a constant relative risk aversion setting is dependent on the relative risk aversion parameter γ because that setting is solvable for the general case $r\neq 0$. As a consequence, we have to limit the graphical representations here to the behaviour w.r.t. the work effectiveness parameters and time.

The value function specifying the executive's maximized utility can be written as the difference between the utility from his optimal personal investment decision and the disutility from his optimal work effort, i.e.

$$\Phi(0,v)=\mathbb{E}^{0,v}\left[U(V_T^{u^{\star}})\right]-\mathbb{E}^{0,v}\left[\int_0^T c(t,V_t^{u^{\star}},\lambda^{\star}(t,V_t^{u^{\star}}))\,\mathrm{d}t\right]\,.$$

We assume that the executive's fair compensation for the disutility of work effort is paid up-front with cash or marketable (unconstrained) securities of value Δv. Applying a utility indifference argument, the fair level of compensation satisfies

$$\Phi(0,v+\Delta v)=\Phi(0,v)+\mathbb{E}^{0,v}\left[\int_0^T c(t,V_t^{u^{\star}},\lambda^{\star}(t,V_t^{u^{\star}}))\,\mathrm{d}t\right]\,,\tag{25}$$

which gives the fair compensation rate of the executive who is characterized by the CARA utility/disutility set-up as follows:

Proposition 4.1 *The exponential-utility executive's utility indifference (fair) up-front compensation* $\Delta\, v$ *is*

$$\Delta\, v = \frac{1}{2\,\eta} \int_0^T (\lambda^*(s))^2 \mathrm{d}s$$
$$+ \frac{\alpha - 2}{\alpha\,\eta} \log \left(1 - \frac{(\alpha-2)\,(\sigma^P)^2 \left(\frac{\lambda_0^\alpha}{\tilde{\kappa}}\right)^{\frac{2}{\alpha-2}}}{2\alpha\,(\mu^P)^2} \left(e^{-\frac{1}{\alpha-2}\,(\mu^P/\sigma^P)^2\, T} - 1 \right) \right).$$

The proof of Proposition 4.1 can be found in the Appendix or in Desmettre (2010).

Remark 4.1 *The fair compensation* $\Delta\, v$ *depends in contrast to the optimal work effort* $\lambda^\star$ *on the risk aversion* η*, which is caused by the representation of the value function (compare equation* (18)*). Furthermore,* $\Delta\, v$ *is independent of the initial wealth* v *of the executive. This is a consequence of the CARA set-up and the fact that already the optimal investment strategies* $\Pi^{P^\star}$ *and* $\Pi^{S^\star}$ *are independent of the actual wealth.*

The sensitivities of the executive's optimal work effort $\lambda^\star$ and fair compensation Δv with respect to variations in his work effectiveness parameters cannot be shown with compact expressions. Instead we limit ourselves to graphical representations of the relationships, with additional consideration of the executive's parameter η of constant absolute risk aversion for the fair compensation.

Figures 1 and 2 show optimal work effort over time for varying work effectiveness parameters (i.e. respectively $\lambda^\star$ versus t and $1/\tilde{\kappa}$, and $\lambda^\star$ versus t and α). The executive's work effort increases with increasing work productivity and with increasing time (see Figure 1), and the executive's work effort increases with decreasing disutility stress and increasing time (see Figure 2), i.e. work effort is positively related to work productivity $1/\tilde{\kappa}$, and negatively related to disutility stress α. The increase of the executive's optimal work effort with a higher work productivity confirms the behaviour of an executive characterized by a constant relative risk aversion set-up. But given that the optimal work effort does not depend on the risk aversion η, it is an (at first sight) unexpected fact that the optimal work effort increases with time since we know from the constant relative risk-aversion set-up (see Desmettre, Gould, Szimayer (2010)) that the optimal work effort of an executive characterized by a power-utility/disutility set-up does only increase in time for a rather high level of the relative risk aversion parameter γ. This can be interpreted as the exponential-utility executive with zero interest rates is in general of a risk-averse nature, which may stem from the fact that in a financial market with zero interest rates a loss in a risky asset would cause more damage to the executive than in an environment with higher interest rates, since the investment in the money market account will deliver no return when $r = 0$.

Figures 3 and 4 show the exponential utility executive's fair compensation versus pairings of risk aversion with each of work productivity and disutility stress (i.e. respectively Δv versus η and $1/\tilde{\kappa}$, and Δv versus α and η). Any combination of decreasing risk aversion, increasing work productivity, and decreasing disutility stress leads to higher work effort and commensurately higher fair compensation. We repeat that the fair compensation in the exponential utility/disutility set-up does not depend on the initial wealth v implying that the illustrations are true for any initial wealth of the executive. The level of fair compensation is particularly prominently dependent on risk aversion: fair compensation sensitivity to work productivity and disutility stress is highest when risk aversion is low ($\eta \approx 0.5$ or lower), which is emphasized by Figures 3 and 4. This result stems from the fact that the company can only benefit from the executive's control decision when he has a rather low risk aversion leading to a substantial own-company stockholding followed by a higher incentive to apply substantial work effort. This behaviour is qualitatively the same as in the constant relative risk aversion set-up and thus supports the results given in Desmettre, Gould and Szimayer (2010).

In summary, the results obtained in this work w.r.t. a constant absolute risk aversion set-up show to a large extend that the model is robust under the choice of the utility and disutility functions. The differences in the results in contrast to the constant relative risk aversion set-up given in Desmettre, Gould and Szimayer (2010) are either caused by the need to restrict ourselves to the case of zero interest rates or the usage of absolute investment strategies and an exponential utility function.

5 Conclusion

In this paper, we picked up the model for the own-company stockholding and work effort preferences of an unconstrained executive who can voluntarily link his personal wealth to his management success and influence the value of the own-company's stock via spending work effort as given in Desmettre, Gould and Szimayer (2010). The executive maximizes the expected value of the utility of final wealth and the negative utility of integrated work effort. We give a closed-form solution of this stochastic control problem using an exponential utility/disutility set-up in the case of zero interest rates. Furthermore, we determine an up-front fair cash compensation. We confirm that a more productive executive applies a substantial higher work effort and receives a higher cash compensation. Thus, our study shows that the model is robust under the choice of the utility/disutilty set-up. As a technical side aspect, we have enhanced the class of admissible strategies in contrast to Desmettre, Gould and Szimayer (2010) by reducing integrability conditions from a fourth moment condition to a two plus epsilon condition.

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Appendix

Proof of Theorem 3.2. Define the performance functional of our optimal investment and control decision by

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

where $(t, v) \in [0, T] \times \mathbb{R}^+$ and $u = (\Pi^P, \Pi^S, \lambda) \in A'_\eta(t, v)$. First note that the wealth process (5) for $r = 0$ reads

$$\begin{aligned}
\mathrm{d}V_t^u = {} & \left[(\Pi_t^P + \beta\, \Pi_t^S)\, \mu^P + \Pi_t^S\, \lambda_t\, \sigma\right] \mathrm{d}t \\
& + \left[\Pi_t^P + \beta\, \Pi_t^S\right] \sigma^P \mathrm{d}W_t^P + \Pi_t^S\, \sigma\, \mathrm{d}W_t\,, \quad V_0^u \in \mathbb{R}^+\,.
\end{aligned} \tag{26}$$

Recall that the claimed optimal value function $\Phi \in C^{1,2}$ and apply Ito's formula for $\eta > 0$ to obtain:

$$\begin{aligned}
& U\left(V_T^u\right) - \int_t^T c(s, V_s^u, \lambda_s)\, \mathrm{d}s = \Phi(T, V_T^u) - \int_t^T \kappa e^{-\eta V_s^u} \frac{\lambda_s^\alpha}{\alpha}\, \mathrm{d}s = \Phi(t, v) \\
& + \int_t^T \Big(\Phi_t(s, V_s^u) + \Phi_v(s, V_s^u) \left[\Pi_u^S\, \lambda_s\, \sigma + (\Pi_s^P + \beta\, \Pi_s^S)\, \mu^P\right] \\
& + 1/2\, \Phi_{vv}(s, V_s^u) \left[((\Pi_s^P + \beta\, \Pi_s^S)\sigma^P)^2 + (\Pi_s^S \sigma)^2\right] - \kappa e^{-\eta V_s^u} \frac{\lambda_s^\alpha}{\alpha} \Big)\, \mathrm{d}s \\
& + \int_t^T \Phi_v(s, V_s^u)\, (\Pi_s^P + \beta\, \Pi_s^S) \sigma^P\, \mathrm{d}W_s^P + \int_t^T \Phi_v(s, V_s^u)\, \Pi_s^S \sigma\, \mathrm{d}W_s\,.
\end{aligned} \tag{27}$$

The remainder of the proof is divided into two parts. Part (a) establishes that the value function Φ coincides with the performance functional J evaluated at the claimed maximizers $u^\star = (\Pi^{P\star}, \Pi^{S\star}, \lambda^\star)$, $\eta > 0$. Part (b) shows the optimality of the candidate $u^\star$, i.e.: $J(t, v; u) \leq \Phi(t, v)$, for $u = (\Pi^P, \Pi^S, \lambda) \in A_\eta(t, v)$.

Part (a): We establish that $J(t, v; u^\star) = \Phi(t, v)$. To do this we show that in the right hand side (RHS) of (27) the drift vanishes by the HJB (12) and that the local martingale component is a true martingale and hence disappears in expectation. And finally, it is verified that indeed $u^\star \in A_\eta(t, v)$.

By construction, Φ with control $u^\star$ satisfies the HJB-PDE in (12), that is for $r = 0$,

$$\begin{aligned}
0 \;=\; & \Phi_t + \Phi_v\, \left(\Pi^{S\star}\, \lambda^\star\, \sigma + (\Pi^{P\star} + \beta\, \Pi^{S\star})\, \mu^P\right) \\
& + (1/2)\, \Phi_{vv}\, \left([\Pi^{S\star}\, \sigma]^2 + [(\Pi^{P\star} + \beta\, \Pi^{S\star})\, \sigma^P]^2\right) - c\,.
\end{aligned}$$

This eliminates the drift (Lebesgue integral) in (27) and we obtain

$$\begin{aligned}
& U\left(V_T^{u^\star}\right) - \int_t^T c(s, V_s^{u^\star}, \lambda_s^\star)\, \mathrm{d}s = \Phi(t, v) + \\
& \int_t^T \Phi_v(s, V_s^{u^\star})\, (\Pi_s^{P\star} + \beta\, \Pi_s^{S\star}) \sigma^P\, \mathrm{d}W_s^P + \int_t^T \Phi_v(s, V_s^{u^\star})\, \Pi_s^{S\star} \sigma\, \mathrm{d}W_s\,.
\end{aligned}$$

For $J(t,v;u^\star) = \Phi(t,v)$, it remains to prove that the local martingale component disappears in expectation. A sufficient condition is the square-integrability of the local martingale component

$$\mathbb{E}\left[\int_t^T \left(\Phi_v(s, V_s^{u^\star})\right)^2 \left([\Pi_s^{P\star} + \beta\,\Pi_s^{S\star}]^2(\sigma^P)^2 + [\Pi_s^{S\star}\sigma]^2\right)\,\mathrm{d}s\right] < \infty\,.$$

Using the explicit form of the candidates in (17) and $\Phi_v = \eta\, f(t)\, e^{-\eta\, v}$, for $\eta > 0$, gives

$$\begin{aligned}\left(\Phi_v(s, V_s^{u^\star})\right)^2 &\left([\Pi_s^{P\star} + \beta\,\Pi_s^{S\star}]^2(\sigma^P)^2 + [\Pi_s^{S\star}\sigma]^2\right)\\ &= f(s)^2\, e^{-2\,\eta\, V_s^{u^\star}} \left[\left(\frac{\mu^P}{\sigma^P}\right)^2 + \left(\frac{1}{\kappa} f(s)\right)^{\frac{2}{\alpha-2}}\right].\end{aligned}$$

The RHS is $e^{-2\,\eta\, V_s^{u^\star}}$ times a deterministic and continuous function on the compact set $[t,T]$. The deterministic part is uniformly bounded. Therefore, it is sufficient to focus on the stochastic component: $V^{u^\star}$ satisfies

$$\mathrm{d}V_s^{u^\star} = \Big[\frac{(\mu^P)^2}{\eta\,(\sigma^P)^2} + \frac{(\lambda^\star(s, V_s^{u^\star}))^2}{\eta}\Big]\,\mathrm{d}s + \frac{\mu^P}{\eta\,\sigma^P}\,\mathrm{d}W_s^P + \frac{\lambda^\star(s, V_s^{u^\star})}{\eta}\,\mathrm{d}W_s.$$

The solution of the above inhomogeneous wealth equation w.r.t. the optimal strategies $u^\star$ starting at t with initial wealth $V_t^{u^\star} = v$ applying variation of constants is

$$V_s^{u^\star} = v + \int_t^s \left(\frac{(\mu^P)^2}{\eta\,(\sigma^P)^2} + \frac{(\lambda_{\tilde{s}}^\star)^2}{\eta}\right)\mathrm{d}\tilde{\mathrm{s}} + \int_{\mathrm{t}}^{\mathrm{s}} \frac{\mu^{\mathrm{P}}}{\eta\,\sigma^{\mathrm{P}}}\,\mathrm{dW}_{\tilde{\mathrm{s}}}^{\mathrm{P}} + \int_{\mathrm{t}}^{\mathrm{s}} \frac{\lambda_{\tilde{\mathrm{s}}}^\star}{\eta}\,\mathrm{dW}_{\tilde{\mathrm{s}}}\,.$$

Recalling that $\lambda^\star(\tilde{s}, v)$ is a continuous function in s and does not depend on v, we see that $V_s^{u^\star}$ follows a normal distribution. Since all moments of a log-normally distributed random variable exist, it follows that $e^{-2\,\eta\, V_s^{u^\star}}$ exists and thus the local martingale is a square-integrable martingale. This establishes $J(t,v;u^\star) = \Phi(t,v)$. Finally, $u^\star \in A_\eta(t,v)$ follows from the fact that $\Pi^{P\star}$, $\Pi^{S\star}\sigma^\star$, and $\lambda^\star$ are uniformly bounded on $[t,T]$, for each $\eta > 0$.

Part (b): Now we show the optimality, i.e. $J(t,v;u) \leq \Phi(t,v)$, for $u \in A_\eta(t,v)$. As in (a), this is also based on the analysis of (27). The HJB (12) is applied to show that the drift component is bounded from above by zero. Then it is shown that the conditions in Def. 3.1 are sufficient for the local martingale component on the RHS of (27) to vanish in expectation.

By the HJB (12), Φ with arbitrary $u = (\Pi^P, \Pi^S, \lambda) \in \mathbb{R} \times \mathbb{R} \times \mathbb{R}_0^+$ with $r = 0$ satisfies

$$\begin{aligned} 0 \;\; \geq \;\; & \Phi_t + \Phi_v \left(\Pi^S \, \lambda \, \sigma + (\Pi^P + \beta \, \Pi^S) \, \mu^P\right) \\ & + (1/2) \, \Phi_{vv} \left([\Pi^S \, \sigma]^2 + [(\Pi^P + \beta \, \Pi^S) \, \sigma^P]^2\right) - c \, , \end{aligned}$$

for $(s, v) \in [t, T] \times \mathbb{R}^+$. This provides the point-wise upper bound zero for the drift in (27) and we obtain

$$\begin{aligned} & U\left(V_T^u\right) - \int_t^T c(s, V_s^u, \lambda_s) \, \mathrm{d}s \leq \Phi(t, v) + \\ & \underbrace{\int_t^T \Phi_v(s, V_s^u) \, (\Pi_s^P + \beta \, \Pi_s^S) \sigma^P \, \mathrm{d}W_s^P + \int_t^T \Phi_v(s, V_s^u) \, \Pi_s^S \sigma \, \mathrm{d}W_s}_{=: M_T^t} \; . \end{aligned} \tag{28}$$

Now recall $\Phi_v(t, v) = \eta \, f(t) \, e^{-\eta \, v}$ and calculate the quadratic variation of M^t:

$$\begin{aligned} \langle M^t \rangle_T &= \int_t^T \eta^2 \, e^{-2\eta \, V_s^u} f^2(s) \left([\Pi_s + \beta \, \Pi_s^S]^2 (\sigma^P)^2 + [\sigma \Pi_s^S]^2\right) \, \mathrm{d}s \\ &\leq \frac{1}{1 + \epsilon} \eta^2 \sup_{0 \leq s \leq T} f(s)^2 \Big[\epsilon \int_t^T e^{-2 \, \eta \, V_s^u \left(1 + \frac{1}{\epsilon}\right)} \, \mathrm{d}s \\ & \qquad + \int_t^T \left([\Pi_s + \beta \, \Pi_s^S]^2 (\sigma^P)^2 + [\sigma \Pi_s^S]^2\right)^{1+\epsilon} \, \mathrm{d}s \Big] \; , \; \epsilon > 0 \; , \end{aligned} \tag{29}$$

where the upper bound in the second line was achieved using Young's inequality. We show that M^t is a martingale by deriving the integrability of the quadratic variation $\langle M^t \rangle_T$. First we use once more that f is a continuous function on the compact set $[t, T]$ and is uniformly bounded, and thus $\sup_{0 \leq s \leq T} f(s)^2$ is finite. We are left to deal with the two expressions in the brackets of (29). The second expression is bounded in expectation by assumption, see (9) in Def. 3.1, setting $\epsilon = \frac{1}{2} \tilde{\epsilon}$. In what follows we establish that the first expression is finite by showing that

$$\mathbb{E}^{t,v}[e^{\xi \, V_s^u}] < \infty \quad \text{uniformly in } s \in [t, T] \, , \tag{30}$$

with $\xi = -2 \, \eta \, \left(1 + \frac{1}{\epsilon}\right)$, where $\xi < 0$ since $\eta > 0$ and we note that $|\xi| < \infty$ since $\epsilon > 0$.

The solution of the inhomogeneous wealth equation (26) starting at t with initial wealth $v = V_t^u$ applying variation of constants is

$$V_s^u = v + \int_t^s \left((\Pi_{\tilde{s}}^P + \beta\, \Pi_{\tilde{s}}^S)\, \mu^P + \Pi_{\tilde{s}}^S \lambda_{\tilde{s}} \sigma \right) \mathrm{d}\tilde{s} \\ + \int_t^s (\Pi_{\tilde{s}}^P + \beta\, \Pi_{\tilde{s}}^S)\, \sigma^P \,\mathrm{d}W_{\tilde{s}}^P + \int_t^s \Pi_{\tilde{s}}^S\, \sigma \,\mathrm{d}W_{\tilde{s}}\,.$$

With

$$L_s^t := \int_t^s (\Pi_{\tilde{s}}^P + \beta\, \Pi_{\tilde{s}}^S)\, \sigma^P \,\mathrm{d}W_{\tilde{s}}^P + \int_t^s \Pi_{\tilde{s}}^S\, \sigma \,\mathrm{d}W_{\tilde{s}}\,,$$
$$\left\langle L^t \right\rangle_s := \int_t^s \left((\Pi_{\tilde{s}}^P + \beta\, \Pi_{\tilde{s}}^S)^2\, (\sigma^P)^2 + (\Pi_{\tilde{s}}^S\, \sigma)^2 \right) \mathrm{d}\tilde{s}\,,$$

we have

$$e^{\xi\, V_s^u} = e^{\xi\, v} e^{\xi\, \left[\xi\, \left\langle L^t \right\rangle_s + \int_t^s \left((\Pi_{\tilde{s}}^P + \beta\, \Pi_{\tilde{s}}^S)\, \mu^P + \Pi_{\tilde{s}}^S \lambda_{\tilde{s}} \sigma \right) \mathrm{d}\tilde{s} \right]} \times e^{\xi\, L_s^t - \xi^2 \left\langle L^t \right\rangle_s}\,.$$

The first factor is uniformly bounded by a constant, see Def. 3.1, (9) and (10), and noting that $\xi < 0$ for $\eta > 0$ and $|\xi| < \infty$ since $\epsilon > 0$.

It remains to prove that the second factor $Z_s^t = e^{\xi\, L_s^t - \frac{1}{2}\xi^2 \left\langle L^t \right\rangle_s}$, $t \le s \le T$, is integrable. However, Z^t is a strictly positive local martingale since it is the stochastic exponential of the local martingale $\xi\, L^t$. The Novikov condition holds by (9), i.e. $\mathbb{E}^{t,v}(e^{\frac{1}{2}\xi^2 \left\langle L^t \right\rangle_T}) < \infty$, and hence Z^t is a true martingale and $\mathbb{E}^{t,v}(\tilde{Z}_s^t) = 1$, $t \le s \le T$. In summary, the local martingale M^t is therefore a martingale vanishing in expectation in (28), and taking the conditional expectation of (28) gives the desired result

$$J(t,v;u) = \mathbb{E}^{t,v}\left[U(V_T^u) - \int_t^T c(s, V_s^u, \lambda_s)\,\mathrm{d}s \right] \;\le\; \Phi(t,v)\,, u \in A_\eta(t,v).$$

$\square$

Proof of Proposition 4.1. An outside investor with knowledge of the work effort exercised by the executive (i.e. with knowledge of $\lambda^\star$) and his optimal investment strategies $\Pi^{P^\star}$ and $\Pi^{S^\star}$, will choose a control vector $\widehat{u}^\star = (\widehat{\Pi}^{P^\star}, \widehat{\Pi}^{S^\star}, \widehat{\lambda}^\star)$ identical to the executive's control vector $u^\star$. Denote $\widehat{\Phi}(0,v)$ to be the maximized utility of the outside investor, then it follows that

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

Applying the indifference utility principle (25), we obtain $\Delta\, v$ by solving

$$\widehat{\Phi}(0,v) = \Phi(0, v + \Delta v)\,. \tag{31}$$

An outside investor with knowledge of the optimal control vector $u^\star$ does not suffer from disutility and is characterized by the following HJB equation (where we note that $r = 0$):

$$0 = \widehat{\Phi}_t(t,v) - \frac{1}{2}(\lambda^\star(t))^2\,\frac{\widehat{\Phi}_v^2(t,v)}{\widehat{\Phi}_{vv}(t,v)} - \frac{(\mu^P)^2}{2\,(\sigma^P)^2}\,\frac{\widehat{\Phi}_v^2(t,v)}{\widehat{\Phi}_{vv}(t,v)}\,,$$

where we have set $\lambda^\star(t,v) = \lambda^\star(t)$, since we already know from (17) that the optimal work effort does not depend on v.
Applying the ansatz $\widehat{\Phi}(t,v) = \widehat{f}(t)\,e^{-\eta\, v}$ with $\widehat{f}(T) = 1$ results in the ODE

$$\dot{\widehat{f}} = \left[\frac{1}{2}\,(\lambda^\star(t))^2 + \frac{(\mu^P)^2}{2\,(\sigma^P)^2}\right]\widehat{f} \quad , \quad \widehat{f}(T) = 1\,,$$

which has the solution

$$\widehat{f}(t) = e^{-\frac{(\mu^P)^2}{2\,(\sigma^P)^2}(T-t) - \frac{1}{2}\int_t^T(\lambda^\star(s))^2\mathrm{d}s}\,.$$

From (31) we then get that

$$1 - \widehat{f}(0)\,e^{-\eta\, v} = 1 - f(0)\,e^{-\eta\,(v+\Delta\, v)} \quad \Leftrightarrow \quad \Delta\, v = -\frac{1}{\eta}\,\log\left(\frac{\widehat{f}(0)}{f(0)}\right)\,.$$

Plugging in the representations of $\widehat{f}$ and f, respectively, and simplifying gives the result. □

Figures

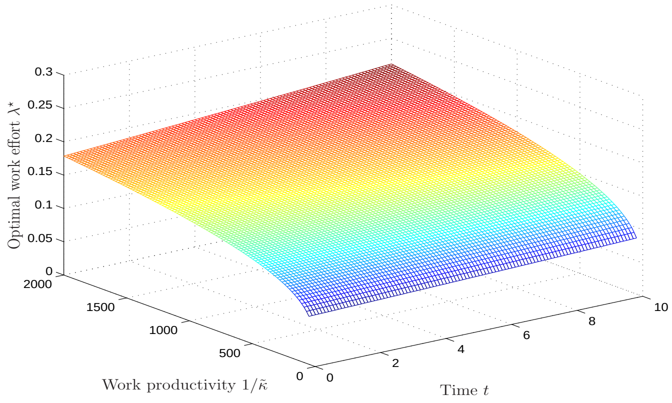

Figure 1: The exponential-utility executive's optimal work effort/control choice, in terms of optimal non-systematic Sharpe ratio $\lambda^\star$, w.r.t. time t, for varying work productivity $1/\tilde{\kappa}$; given disutility stress $\alpha = 5$, and base-level work effort $\lambda_0 = 0.10$.

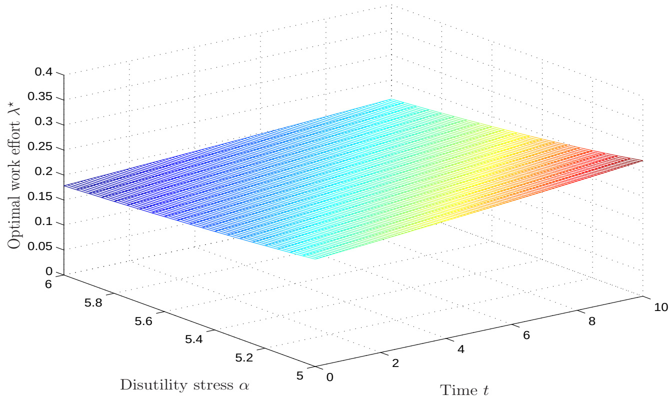

Figure 2: The exponential-utility executive's optimal work effort/control choice, in terms of optimal non-systematic Sharpe ratio $\lambda^\star$, w.r.t. time t, for varying disutility stress α; given work productivity $1/\tilde{\kappa} = 2000$, and base-level work effort $\lambda_0 = 0.10$.

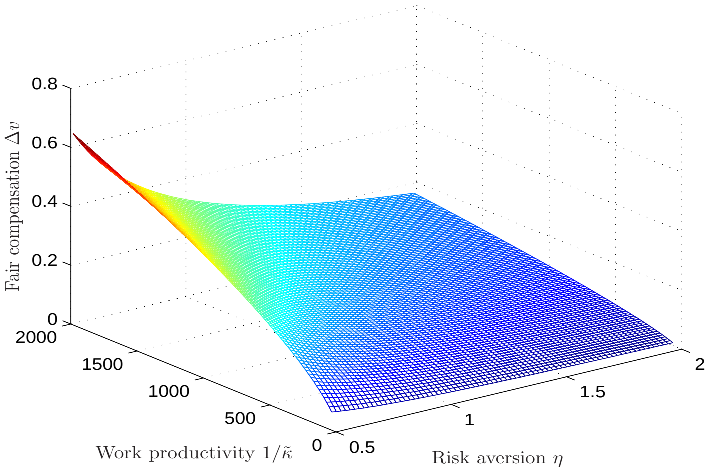

Figure 3: The exponential-utility executive's fair up-front compensation Δv, based on utility indifference, w.r.t. his work productivity $1/\tilde{\kappa}$ and risk aversion η; given disutility stress $\alpha = 5$, time horizon $T = 10$ years, and base-level work effort $\lambda_0 = 0.10$.

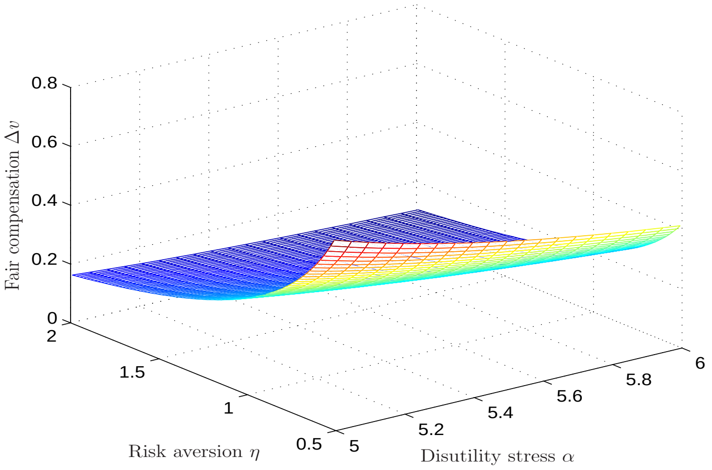

Figure 4: The exponential-utility executive's fair up-front compensation Δv, based on utility indifference, w.r.t. his risk aversion η and disutility stress α; given work productivity $1/\tilde{\kappa} = 2000$, time horizon $T = 10$ years, and base-level work effort $\lambda_0 = 0.10$.

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