NÚMERO 531

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Productivity Shocks, Discount Rate and Incentives

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AGOSTO 2012

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Abstract

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Keywords: Asymmetric information, Principal-Agent Model, Incentives, Pareto Frontier, Evolutionary Algorithms.
JEL Classification Numbers: C63, D61, D82, D86, L14.

Resumen

En este artículo analizamos un modelo repetido de Agente-Principal formulado como un problema de Optimización Multi-objetivo. Aproximamos la Frontera de Pareto de este modelo usando un Algoritmo Evolutivo Multi-objetivo que ha sido propuesto recientemente, llamado RankMOEA. Nos enfocamos en analizar los efectos que generan cambios en la tasa de descuento y la estructura de choques de productividad sobre la Frontera de Pareto y sobre los incentivos del Agente. Nuestros resultados numéricos indican que cuando la tasa de descuento aumenta, la relación Agente-Principal genera mayor valor; la distancia entre la compensación futura (presente) del Agente entre el choque alto y bajo de productividad aumenta (disminuye) y el Agente elige, en general, mayores niveles de esfuerzo. Por otra parte, cuando la estructura de los choques de productividad es tal que el nivel de esfuerzo elegido por el Agente genera mayores (menores) niveles de producción, el Principal (Agente) tiende a beneficiarse porque en dichos casos el Agente (Principal) asume mayores niveles de riesgo.

Palabras clave: Información Asimétrica, Modelo Agente-Principal, Incentivos, Frontera de Pareto, Algoritmos Evolutivos.
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by

Sonia Di Giannatale, Itza T. Q. Curiel, Juan A. Herrera, Katya Rodríguez.*

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1 Introduction

Dynamic models of moral hazard represent situations in which there is a repeated Principal Agent relationship with information asymmetry between the two parties. The risk neutral Principal wishes to delegate the task of managing a production technology of his property to the risk averse Agent. The Agent's effort choices constitute his private information, and those choices are stochastically related to the publicly observed productive outputs. Given this uncertainty about outputs, the Principal has the non trivial task of designing an optimal incentive scheme in order to align the Agent's interests to his interests. Formally, the problem has been formulated as the maximization of the Principal's discounted expected utility subject to two main constraints: the participation constraint and the incentive compatibility constraint, see Spear and Srivastava (1987) and Wang (1997). In this paper, we use a Multi-Objective Optimization (MO) version of the Dynamic Principal Agent Model, see Di Giannatale *et al.* (2010, 2011) and Curiel *et al.* (2012), to capture the idea that the discounted expected utility of the Principal and that of the Agent present conflicting objectives while preserving the situation of information asymmetry between the two parties. Given the nature of this model, we approximate its Pareto Frontier using a recently proposed Multi-Objective Evolutionary Algorithm (MOEA), named RankMOEA (Herrera-Ortiz *et al.*, 2011; and Curiel *et al.*, 2012).

In this paper we focus on the effects of different values in the productivity shocks and discount rates on the Pareto Frontier that results from this model. Our results indicate that as the discount rate β increases, the Principal Agent relationship generates higher values without important changes in the topological characteristics of the contracts. We also observe that when the structure of productivity shocks is such that the Agent's effort yields higher production levels, the Principal tends to benefit because in those cases the Agent assumes more risk than in our benchmark case; while when the structure of the productivity shocks is such that the Agent's effort yields lower production levels, the opposite occurs.

The remaining of this paper is organized as follows: The model is presented in section 2. Section 3 explains the methodology that we use to numerically approximate the model's Pareto Frontier. The numerical results are discussed in section 4. Finally, our concluding remarks are presented in section 5.

2 The model

The Multi-Objective Dynamic Principal Agent model considers the maximization of two objective functions: The lifetime discounted expected utility of a risk neutral Principal, U, and that of a risk averse Agent, W. The Agent's decision variable is the level of effort that he will exert, $a(V)$, which we assume to be a continuous variable; and the Principal's decision variables are the Agent's salary or present compensation, $w(y, V)$, and the Agent's promised discounted expected utility or future compensation, $\overline{V}(y, V)$. The variable $y \in Y$ represents the realizations of the production activity or technology, and it is stochastically related to the Agent's effort decision; where Y is the compact set of the values that y can take. The variable V is the state variable of the problem and represents the continuation value of the Agent's discounted expected utility. Hence, the Multi-Objective Optimization problem that we propose is the following:

$$\max_{a(V), w(y,V), \overline{V}(y,V)} \{U, W\} \tag{1}$$

$$U = \int_{Y} [y - w(y, V) + \beta U(\overline{V}(y, V))] f(y; a^{*}(V)) dy \tag{2}$$

$$W = \int_{Y} [v(w(y, V), a(V)) + \beta \overline{V}(y, V)] f(y; a(V)) dy \tag{3}$$

subject to

$$a(V) \in A \tag{4}$$

$$0 \leq w(y, V) \leq y \qquad \forall y \in Y \tag{5}$$

$$\overline{V}(y, V) \in \mathcal{W} \quad \forall y \in Y \tag{6}$$

where, $\beta \in (0, 1)$ is the Principal and the Agent's common discount rate; $v(w(y, V), a(V))$ is the Agent's period utility function, which is assumed to be bounded and strictly increasing and strictly concave with respect to w, and strictly decreasing with respect to a; and $f(y; a(V) > 0$ is the distribution function that formalizes the stochastic relationship between the output realization and the Agent's effort choice, $\forall y \in Y$ and $\forall a \in A$. We assume that the Monotone Likelihood Ratio Property and the Convexity of the Conditional Distribution hold in order to ensure that the First Order Approach to the Incentive Compatibility Constraint is valid, see Rogerson (1985). On the other hand, equation (4) restricts actions to belong to the compact set A; equation (5) indicates the Agent's temporary inability to borrow; and equation (6) ensures that the Agent's future utility plan is feasible, where $\mathcal{W}$ is the set of the Agent's discounted expected utilities for which the previous two restrictions are satisfied. As it is demonstrated in Di Giannatale *et al.* (2011), this is a valid representation of the problem and it has a solution.

In the next section we propose a methodology to numerically approximate the Pareto Frontier derived from the Multi-Objective Dynamic Principal Agent Model.

3 Numerical Exercise

3.1 Functional Forms and Parameter Values

We assume that the Principal's temporary utility function is: $u(y, w(y, V) = y - w(y, V)$; while the Agent's temporary utility function is: $v(a(V), w(y, V)) = \frac{(w(y,V))^h}{1-h} - a(V)$, where $1 > h > 0$. The Agent's temporary utility function is of the CRRA type and the coefficient of relative risk aversion is h, where higher degrees of relative risk aversion are observed with higher values of h. We assume that the Agent's feasible effort choices are continuous and that they belong to the compact set $A = [0; 10.0]$. The upper bound of this set has been chosen such that it will never be observed in the numerical solution.

Also, we suppose that there are two levels of output: low (L) or high (H), described by the set $Y = \{y_L, y_H\}$. The probability function that formalizes the stochastic relationship between effort and output is:

$$\begin{aligned} f(y_L; a) &= \exp(-a) \\ f(y_H; a) &= 1 - \exp(-a), \end{aligned}$$

and these probabilities capture the idea that the higher the Agent's effort level choice is, the greater the likelihood of the realization of the high output level.

The parameter values we use for our bechmark numerical exercise are the following: $h = \frac{1}{2}$, $\beta = 0.96$, $Y = \{y_L = 2, y_H = 4\}$, $A = [0; 10.0]$.

Further numerical exercises are variations of this benchmark case, as follows: $\beta = \{0.90, 0.98\}$, keeping the rest identical to the bechmark case. Also, we analyze the cases with several output sets: $Y = \{y_L = 3, y_H = 4\}$, $Y = \{y_L = 2, y_H = 3\}$, $Y = \{y_L = 2, y_H = 5\}$, and $Y = \{y_L = 4, y_H = 8\}$, keeping the rest identical to the benchmark case.

3.2 The Computational Approach

Multi-Objective Evolutionary Algorithms (MOEAs) constitute a reliable methodology to achieve the two ideal goals of MO: attaining a good convergence to the Optimal

Pareto Frontier, and maintaining the distribution of the Pareto Frontier approximation as diverse as possible.

Evolutionary Algorithms (EAs) are stochastic methods of search often applied to optimization, see Goldberg (1989). EAs have shown to be a promising approach to deal with MOPs; however, they usually do not guarantee the identification of optimal trade-offs, only that they will find good assessments, *i.e.*, the set of solutions ($Pareto\ Frontier\ Approximation - PF^*_{known}$) whose objective vectors are not too far from the optimal objective vectors. In recent years, several MOEAs have been proposed, but most of them are unable to deal with incommensurable objectives. In this article, we use a recently proposed MOEA, named RankMOEA because of some advantages observed in numerical approximations of the solution of a dynamic model similar to the one proposed here, see Herrera *et al.* (2011).

Now, we describe the algorithm we use to approximate our model's Pareto Frontier:

(i) We set the numerical values of the parameters of the production shocks $Y = \{y_L, y_H\}$, the discount rate β, and the coefficient of relative risk aversion h. We specify that the coding or nature of the genotypes is binary in order to work with the genetic operators whose parameters we specify at this point. The genetic operators are described in step (ix). For details of the coding and the genetic operators' parameters, see Herrera *et al.* (2011).

(ii) We define the two objective functions, namely the Principal's discounted expected utility and the Agent's discounted expected utility, and specify that both of them should be maximized (RankMOEA allows us to choose whether or not every objective function should be maximized).

(iii) Each generation g, $g = 1, ..., G$, where G is a finite number; contains a total of J individuals (solutions), where j is the index of individuals in a generation, $j = 1, ...J$, and J is also a finite number. An individual's chromosome is characterized by 2 substrings of length N, where N is the total number of periods considered in an individual that belongs to generation g. The generation-g individual-j's chromosome has a length of $2N$, and it is defined by the Agent's salary $w_p(y_i, V)$ for every y_i, $i = H, L$; and every period $p = 1, ..., N$. Formally:

$$\begin{bmatrix} w_{gj1}(y_H, V), w_{gj2}(y_H, V), ..., w_{gjN}(y_H, V); \\ w_{gj1}(y_L, V), w_{gj2}(y_L, V), ..., w_{gjN}(y_L, V) \end{bmatrix}.$$

For our numerical exercise, we set the following parameter values: $G = 500,000$; $J = 200$; and $N = 70$.

(iv) We generate our first generation of J individuals, that is a number of J chromosomes as defined above. This generation is created randomly and we specify that the following restrictions must hold:

$$0 \leq w_{1jp}(y_H, V) \leq y_H \qquad \forall p = 1, ..., N$$

$$0 \leq w_{1jp}(y_L, V) \leq y_L \qquad \forall p = 1, ..., N.$$

(v) We define the model's variables, their feasible upper and lower bounds and their level of specification at 10^{-3}. The variables and their bounds are:

Agent's optimal effort level:

$$a_{gjp}(V) = \ln[\frac{(w_{gjp}(y_H, V))^h}{1-h} - \frac{(w_{gjp}(y_L, V))^h}{1-h} + \beta(V_{gjp+1}(y_H, V) - V_{gjp+1}(y_L, V))]$$

Agent's maximal effort level:

$$\overline{a}_{gjp}(V) = \ln[\frac{(y_H)^h}{1-h} - \frac{(0)^h}{1-h} + \beta(V_{gjp+1}(y_H, V) - V_{gjp+1}(y_L, V))]$$

Agent's minimal effort level:

$$\underline{a}_{gjp}(V) = 0$$

Principal's discounted expected utility:

$$\begin{aligned} E[U_{gjp}] &= \exp(-a_{gjp}(V))[y_L - w_{gjp}(y_L, V) + \beta U_{gjp+1}(V_{gjp+1}(y_L, V))] + \\ &\quad (1 - \exp(-a_{gjp}(V)))[y_H - w_{gjp}(y_H, V) + \beta U_{gjp+1}(V_{gjp+1}(y_H, V))] \end{aligned}$$

Maximal Principal's discounted expected utility:

$$\begin{aligned} E[\overline{U}_{gjp}] &= \exp(-\overline{a}_{gjp}(V))[y_L - w_{gjp}(y_L, V) + \beta U_{gjp+1}(V_{gjp+1}(y_L, V))] + \\ &\quad (1 - \exp(-\overline{a}_{gjp}(V)))[y_H - w_{gjp}(y_H, V) + \beta U_{gjp+1}(V_{gjp+1}(y_H, V))] \end{aligned}$$

Minimal Principal's discounted expected utility:

$$\begin{aligned} E[\underline{U}_{gjp}] &= \exp(-\underline{a}_{gjp}(V))[y_L - w_{gjp}(y_L, V) + \beta U_{gjp+1}(V_{gjp+1}(y_L, V))] + \\ &\quad (1 - \exp(-\underline{a}_{gjp}(V)))[y_H - w_{gjp}(y_H, V) + \beta U_{gjp+1}(V_{gjp+1}(y_H, V))] \\ &= [y_L - w_{gjp}(y_L, V) + \beta U_{gjp+1}(V_{gjp+1}(y_L, V))] \end{aligned}$$

Agent's discounted expected utility:

$$\begin{aligned} E[W_{gjp}] &= \exp(-a_{gjp}(V))[\frac{(w_{gjp}(y_L,V))^h}{1-h} - a_{gjp}(V) + \beta V_{gjp+1}(y_L,V)] + \\ & (1-\exp(-a_{gjp}(V)))[\frac{(w_{gjp}(y_H,V))^h}{1-h} - a_{gjp}(V) + \beta V_{gjp+1}(y_H,V)] \end{aligned}$$

Maximal Agent's discounted expected utility:

$$\begin{aligned} E[\overline{W}_{gjp}] &= \exp(-\overline{a}_{gjp}(V))[\frac{(w_{gjp}(y_L,V))^h}{1-h} - \underline{a}_{gjp}(V) + \beta V_{gjp+1}(y_L,V)] + \\ & (1-\exp(-\overline{a}_{gjp}(V)))[\frac{(w_{gjp}(y_H,V))^h}{1-h} - \underline{a}_{gjp}(V) + \beta V_{gjp+1}(y_H,V)] \\ &= \exp(-\overline{a}_{gjp}(V))[\frac{(w_{gjp}(y_L,V))^h}{1-h} + \beta V_{gjp+1}(y_L,V)] + \\ & (1-\exp(-\overline{a}_{gjp}(V)))[\frac{(w_{gjp}(y_H,V))^h}{1-h} + \beta V_{gjp+1}(y_H,V)] \end{aligned}$$

Minimal Agent's discounted expected utility:

$$\begin{aligned} E[\underline{W}_{gjp}] &= \exp(-\underline{a}_{gjp}(V))[\frac{(w_{gjp}(y_L,V))^h}{1-h} - \overline{a}_{gjp}(V) + \beta V_{gjp+1}(y_L,V)] + \\ & (1-\exp(-\underline{a}_{gjp}(V)))[\frac{(w_{gjp}(y_H,V))^h}{1-h} - \overline{a}_{gjp}(V) + \beta V_{gjp+1}(y_H,V)] \\ &= [\frac{(w_{gjp}(y_L,V))^h}{1-h} - \overline{a}_{gjp}(V) + \beta V_{gjp+1}(y_L,V)] \end{aligned}$$

We also set a marker of violated restrictions and all the variables start at zero.

(vi) Each chromosome (solution) is evaluated recursively using backward induction, so that in the last period of every solution in each generation all variables will be zero.

(vii) For each g, j, and p, we evaluate whether the following conditions are satisfied:

$$w_{gjp}(y_L,V) \leq w_{gjp}(y_H,V)$$

$$a_{gjp}(V) \geq 0.$$

When any of the above is not satisfied, a marker of violated restrictions is activated.

(viii) We create a routine to recursively evaluate, using backward induction, each period p of an individual j belonging to generation g. First we evaluate the values of $[a_{gjp}(V), \overline{a}_{gjp}(V), \underline{a}_{gjp}(V), E[U_{gjp}], E[\overline{U}_{gjp}], E[\underline{U}_{gjp}], E[W_{gjp}], E[\overline{W}_{gjp}], E[\underline{W}_{gjp}]]$ at period N of the individual j belonging to generation g. We publish the values $[E[U_{gjp}], E[W_{gjp}]]$ and count the number of violated restrictions. Then, we move to period $N-1$, and so on until we reach period 1 of individual j belonging to generation g. We do the same for all the individuals belonging to generation g, that is for 200 individuals. Then we plot all the values $[E[U_{gjp}], E[W_{gjp}]]$, for $p = 1, ..., 70$ and $j = 1, ..., 200$, given a generation g, to obtain a Pareto Frontier.

(ix) We create the next generation by using the individuals of the previous generation and the genetic operators of cross over, mutation and selection. Cross over involves generating new individuals from individuals from previous generations and its function is to accelerate the new individuals' searching process by using information from previous generations. Mutation provides the population with diversity by exploring new searching areas through the isolated modification of genetic material, as it happens with living beings. Finally, the selection process chooses the individuals that are fitter to survive to form a new generation without compromising the population's diversity, and considering that the two aforementioned objective functions must me maximized.

(x) The new generation is evaluated in step (vii). One can choose from several stopping conditions, defined either by the proximity of the resulting Pareto Frontier of each successive generation or by considering the total number of generations. We use the second criterion and we consider that at the end of $500,000$ generations the final Pareto Frontier is obtained. In Figure 1 we can observe the evolution of our model's Pareto Frontier as the number of generations increases. Notice that both the spread and proximity of the points of the Frontier improve as more generations are considered, and that the difference between the Frontier when $g = 100,000$ and that when $g = 500,000$ is negligible, a result that supports our stopping decision.

4 Results

4.1 The Benchmark Case

In this sub-section, we present our numerical results for the benchmark case. In Figure 2 we show the results of the Principal's most advantageous contract; that is, the point that is located in the right extreme of the Pareto Frontier depicted in the upper-left panel. The Pareto Frontier is decreasing and strictly concave, as expected from related

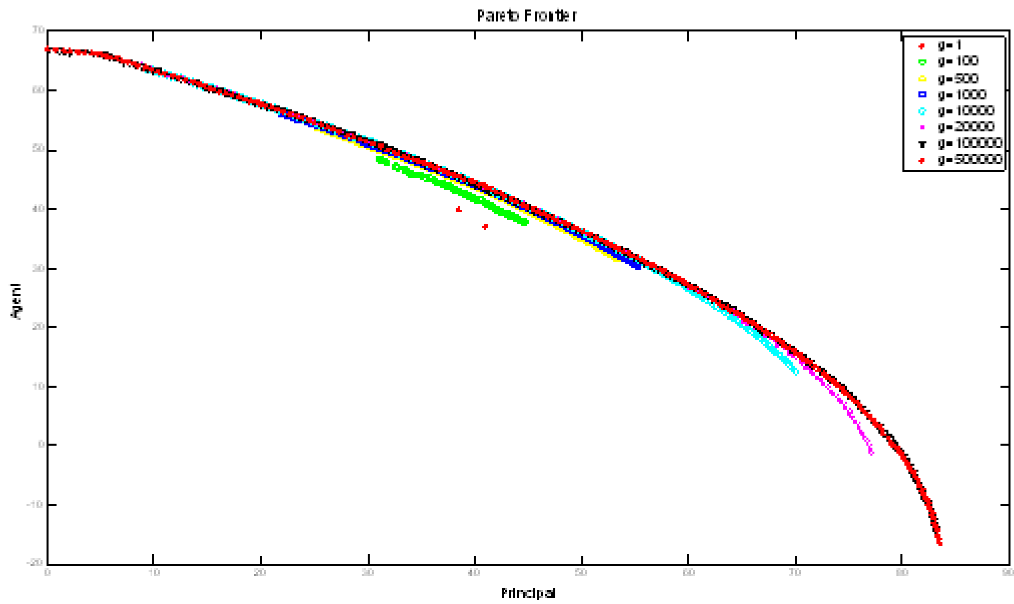

Figure 1: Approximating the Pareto Frontier

literature (Spear and Srivastava, 1987; and Wang, 1997). The Agent's effort schedule is depicted in the upper-right panel and it is decreasing and concave, which means that the probability of the high productivity shock decreases more rapidly as the lifespan of the Agent approaches its end, at $p = 70$. The Agent's discounted expected utilities for the high (H) and low (L) productivity shocks are depicted in the lower-left panel and their spread diminishes as $p \to 70$. The Agent's incentives in future compensation offered by the Principal are very punitive (negative utilities); and only when $p \to 70$ and if there is a high productivity shock, the Principal offers him a positive expected discounted utility. Negative values of the Agent's discounted expected utilities are feasible, because they comply with the restriction of the optimization problem and are a result of the Agent's feasible and high effort choices, and the Agent's positive but low salaries. The Agent's current compensation (salaries) for the low (L) and high (H) productivity shocks are depicted in the lower-right panel. Their spread increases when $p \to 70$, and it is almost zero for many periods. So, in the initial periods, the Principal favours promised discounted expected utility as a tool to provide incentives to the Agent because it is cheaper in terms of the Principal's utility; while in the final periods the Principal favours the Agent's salary to provide incentives to the Agent because promised future utilities become more expensive in terms of the Principal's

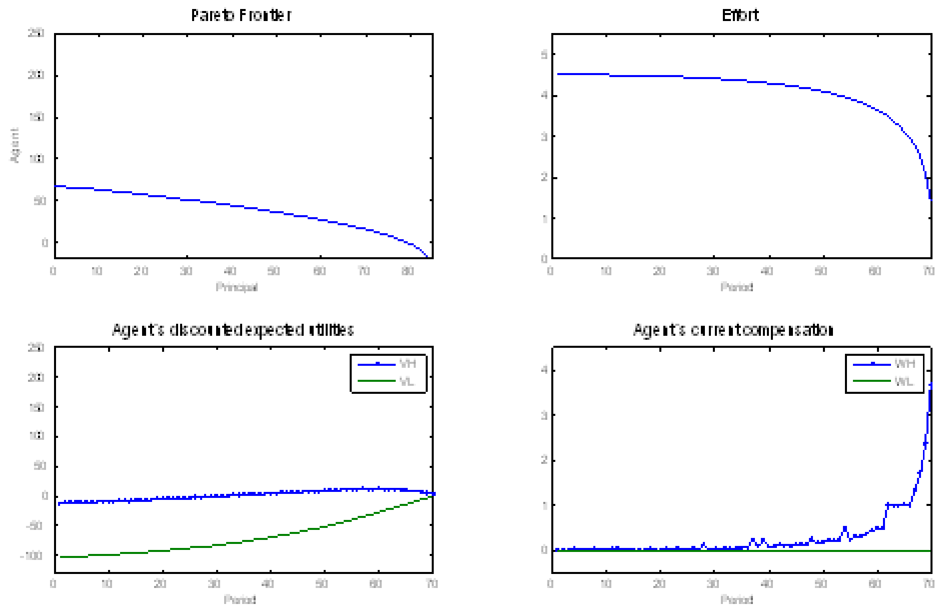

Figure 2: Principal's most advantageous contract, benchmark case.

utility as $p \to 70$.

In Figure 3 we show the results of the most advantageous contract for the Agent; that is, the point that is located in the left extreme of the same Pareto Frontier depicted in the previous graph. The Agent's effort schedule has the same topological characteristics as in the previous figure; but, at the beginning the Agent chooses higher effort levels and towards the end the Agent chooses lower effort levels compared to those in Figure 2. The spread between the Agent´s expected discounted utilities for the low (L) productivity shock and the high (H) productivity shock is decreasing, indicating that this incentive tool is favoured by the Principal in the initial periods of the relationship. The difference with respect to the previous graph is that the Agent is able to obtain higher levels of expected discounted utilities under the this contract, and that the schedule for the high productivity shock displays a non-increasing behavior while that of Figure 2 displays a non-decreasing behavior. Notice that this last result is linked with the behavior of the optimal effort schedule because while in Figure 2 we observe that only when $p \to 70$ the Agent's optimal effort decreases significantly, this behavior can be observed in Figure 3 at a much earlier period. This triggers a response from the Principal of lowering the promises he makes to the Agent in terms of future utility. On the other hand, the Principal uses

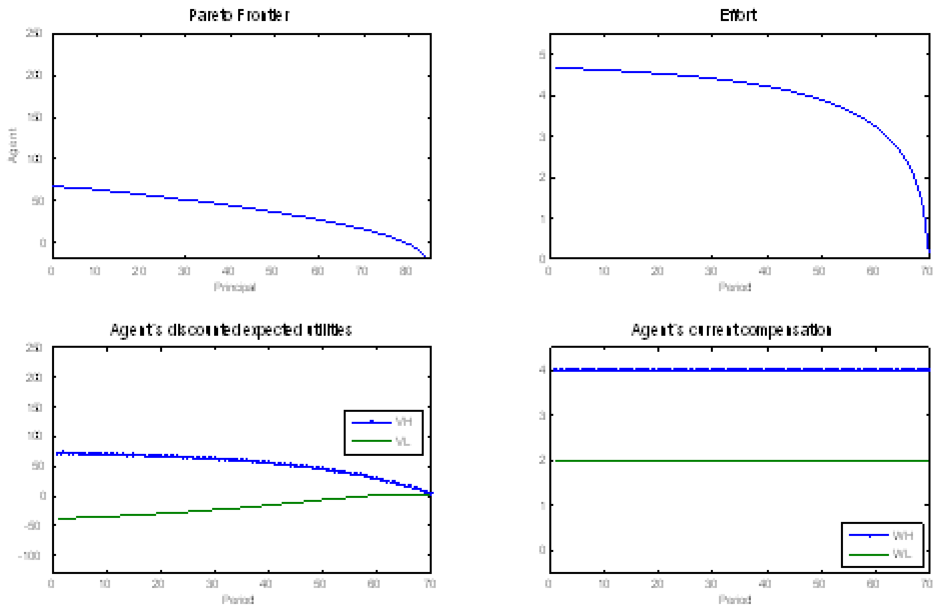

Figure 3: Agent's most advantageous contract, benchmark case.

the Agent's current compensation uniformly across periods as an incentive tool, given that there is a difference for the realization of the high or low productivity shock; but this difference is constant. This means that the Agent is assuming little of the risk inherent to the productive activity and only faces variability in the compensation scheme through future compensation.

In Figure 4 we show the results of what we label as the social contract; that is, the point that is located at the middle of the same Pareto Frontier depicted in previous two graphs. The Agent's effort schedule has the same shape as in the two previous figures; but, the Agent chooses higher effort levels compared to those in Figure 3 at the beginning and the decline of the Agent´s optimal effort beings earlier than in Figure 2 but later than in Figure 3. The behavior of the spread between the Agent´s expected discounted utilities for the low (L) and high (H) productivity shocks is similar to what is observed in Figure 3, but the decline in the Agent´s expected discounted utility for the high productivity shock is less pronounced than in Figure 3. This is due to the aforementioned observation about the Agent's optimal effort decline happening at a latter period than in Figure 3. The behavior of the Agent's current compensation schedules for the low and high productivity levels is similar to that in Figure 2; but, the spread between the two is higher and with richer dynamics

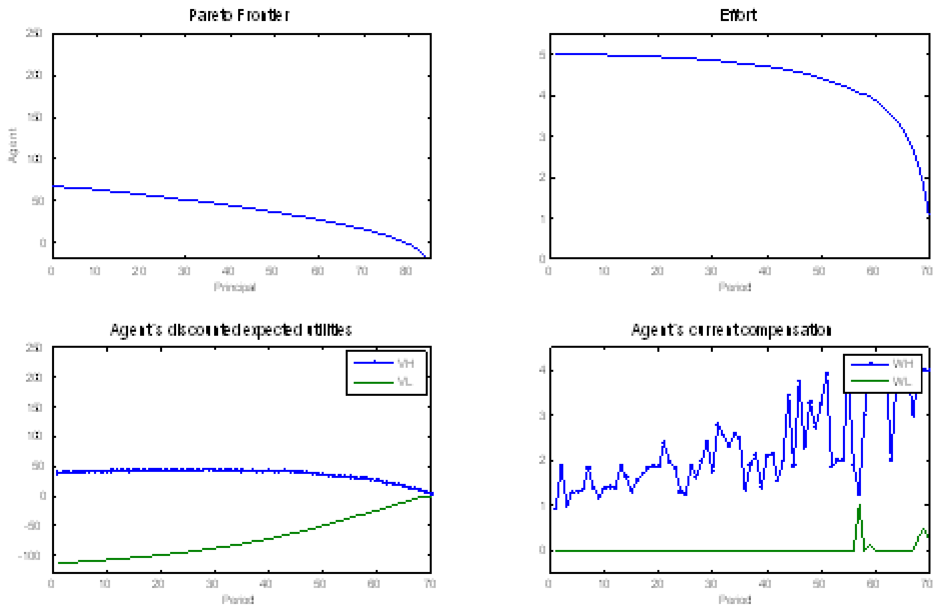

Figure 4: Social contract, benchmark case.

than that observed in Figure 3. This incentive tool is actively used by the Principal from the beginning, but it seems to be more intensively used as $p \to 70$.

4.2 Changes in the Discount Rate

We now present our numerical results when the value of the discount rate β changes. The discount rate tells us how patient the principal and the agent are, meaning that a higher value of β implies that both of them are more patient and more willing to defer consumption.

4.2.1 $\beta = 0.90$

In Figure 5, the results of the most advantageous contract for the Principal are depicted. The Pareto Frontier is decreasing and strictly concave, and both the Principal and the Agent achieve lower maximal values in discounted expected utility with respect to Figure 2. The Agent's effort schedule is increasing at the initial periods, and after $p = 60$, approximately, becomes decreasing. The values of the Agent's effort levels are overall lower in this case than in Figure 2, which means that the probabil-

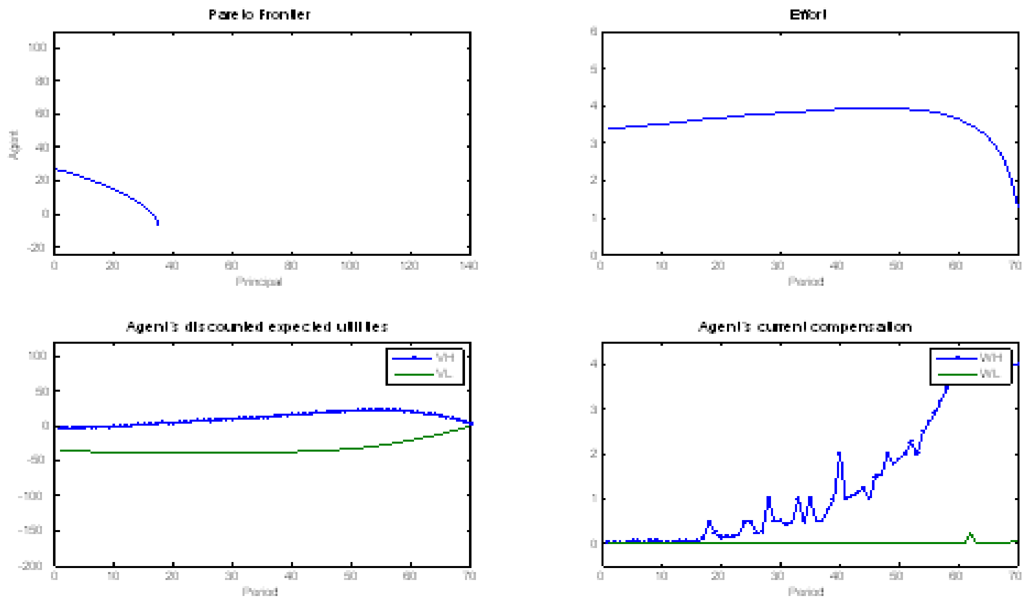

Figure 5: Principal's most advantageous contract, $\beta = 0.90$.

ity of the high productivity shock is lower in this case. The spread of the Agent´s discounted expected utilities for the low (L) and high (H) productivity levels is, in general, lower, and that the Agent receives higher levels of discounted expected utility in this case than when $\beta = 0.96$. It must be noticed that in this case the schedule of the Agent's discounted expected utilities for the high productivity shock exhibits a decreasing behavior after $p = 60$ while this is not observed in the corresponding schedule of Figure 2. The Agent's current compensation schedules for the low and high productivity levels are similar to those in Figure 2; but, here the spread between the two starts at a much earlier period and it is, in general, higher. Hence, the incentive provision mechanism works similarly as when $\beta = 0.96$; but given a higher level of impatience of both the Agent and the Principal, the value that the relationship attains is much lower, and the Agent is less willing to assume risk.

In Figure 6 we show the results of the most advantageous contract for the Agent. The Agent's effort schedule, the Agent´s expected discounted utilities for the low (L) and high (H) productivity levels, and the Agent's current compensation schedules for the low and high productivity levels are very similar to those in Figure 3. Hence, the incentive provision mechanism works similarly; but, again, given that the value of β

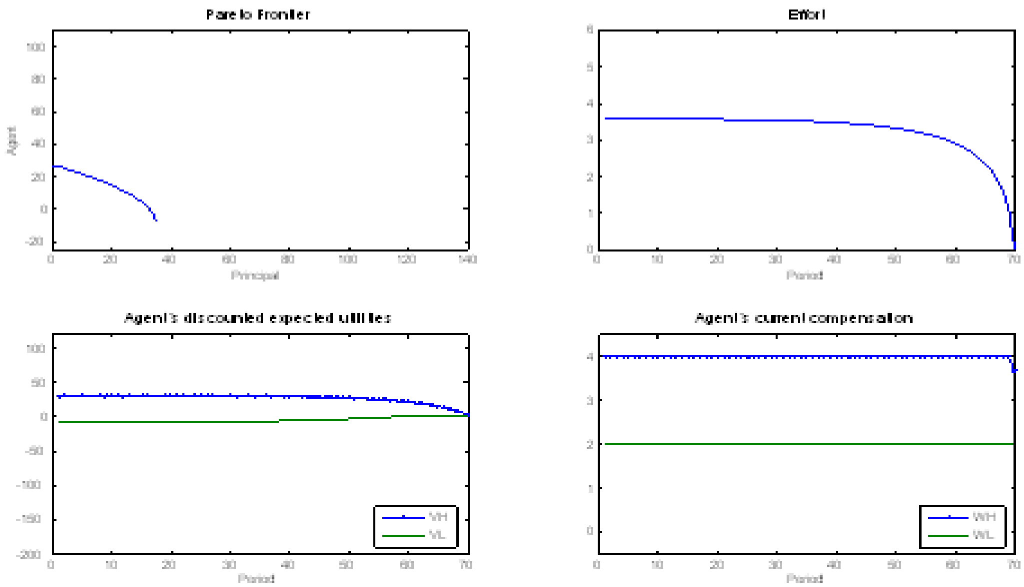

Figure 6: Agent's most advantageous contract, $\beta = 0.90$.

is lower in this case, the Principal-Agent relationship generates a lower value, and the Agent assumes less risk.

In Figure 7 we show the results of the social contract. The Agent's current compensation schedule for the high (H) productivity level is similar to that in Figure 5 for $p < 25$, and it behaves similarly to that in Figure 6 for $p > 25$. The Agent's current compensation schedule for the low (L) productivity level is similar to that in Figure 5 for all p. The rest of the results are similar to the social contract depicted in Figure 4. Hence, the incentive provision mechanism accounts for the higher impatience of both the Principal and the Agent causing that the value their relationship generates is lower with a lower willingness to assume risk on the part of the Agent.

4.2.2 $\beta = 0.98$

In Figures 8, 9 and 10 we show the results of the contract that gives priority to the Principal's expected discounted utility, of the contract that gives priority to the Agent's discounted expected utility and of the social contract, respectively. The Pareto Frontier is decreasing and concave, and both the Principal and the Agent

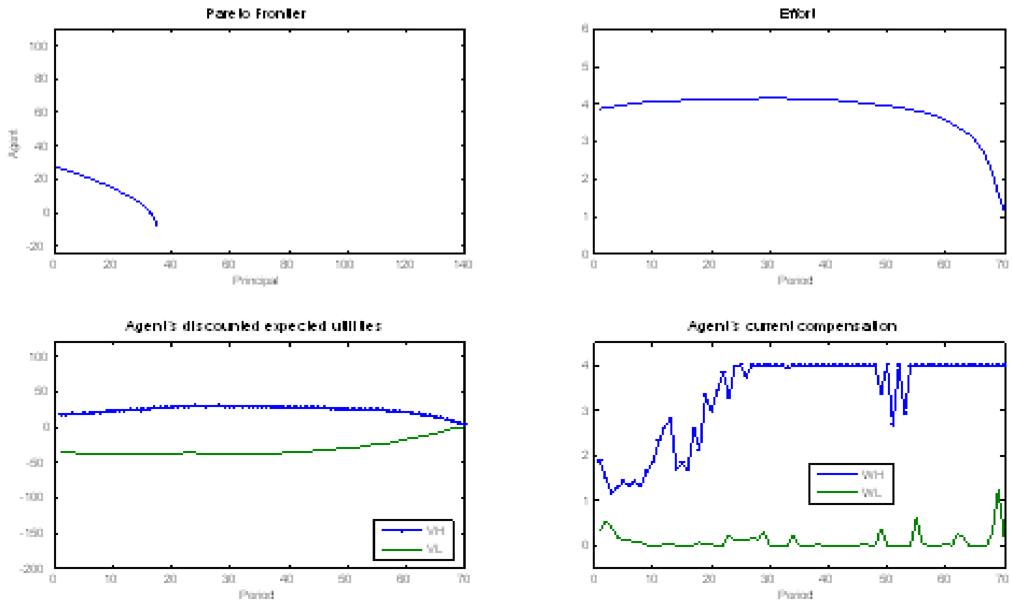

Figure 7: Social contract, $\beta = 0.90$.

achieve higher maximal values in discounted expected utility than those observed in the previous corresponding figures. The interpretation of the rest of the results is similar to that given above; however, given that both the Principal and the Agent are more patient, their relationship generates a higher value than in the two aforementioned cases with the Agent assuming more risk.

4.3 Changes in the Productivity Shocks

In this subsection, we present our numerical results from changing the possible output sets. The interesting point of this numerical exercise is to see how changing the productivity shocks affects the incentive schemes derived from the Principal-Agent relationship.

4.3.1 $Y = \{y_L = 3, y_H = 4\}$

In this case, the distance between the low and high productivity shocks decreases by means of a higher output level associated with the low productivity shock with respect to the benchmark case. In Figure 11, we show the results of the Principal's

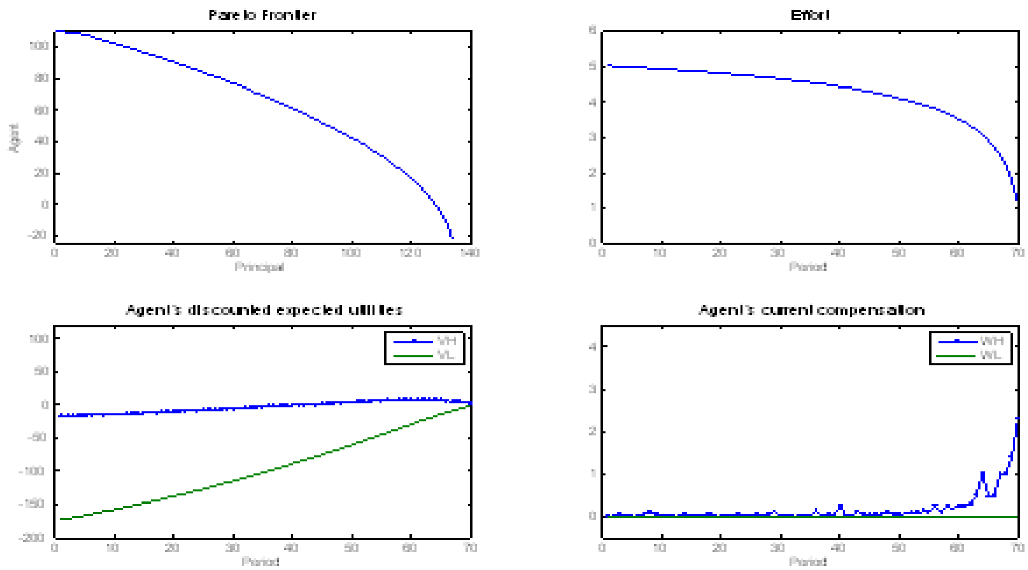

Figure 8: Principal's most advantageous contract, $\beta = 0.98$.

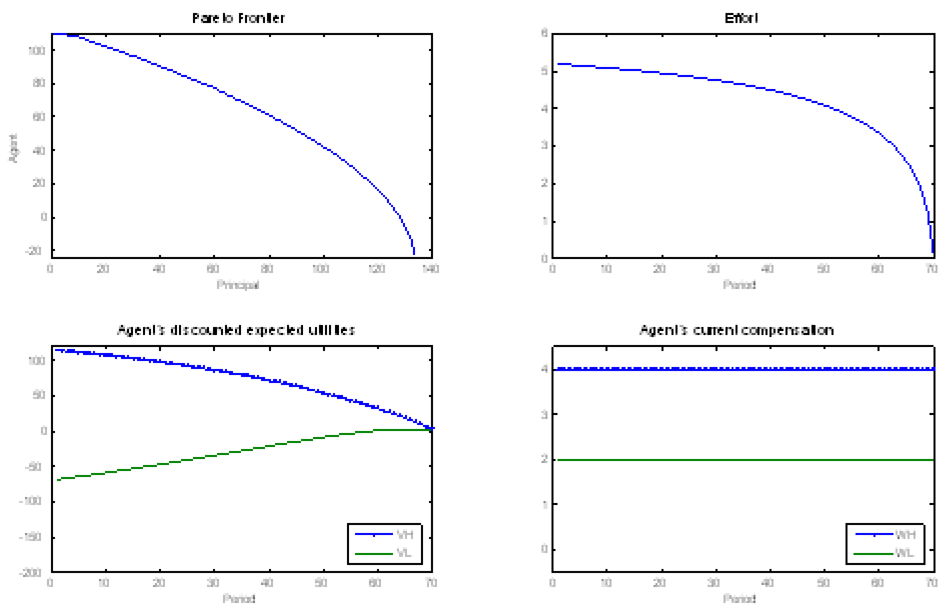

Figure 9: Agent's most advantageous contract, $\beta = 0.98$.

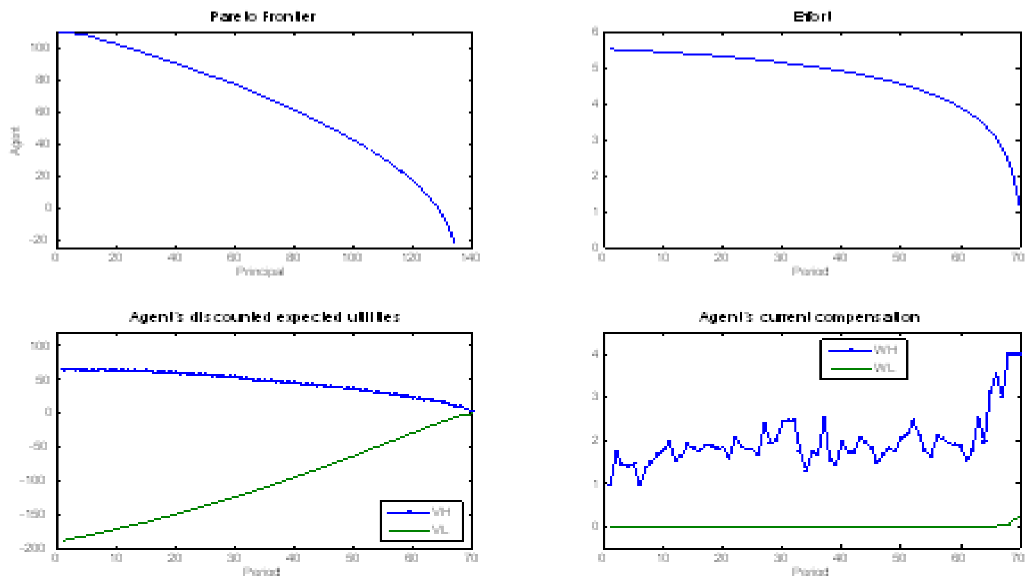

Figure 10: Social contract, $\beta = 0.98$.

most advantageous contract. The main difference with respect to the results of Figure 2 is that salary is actively used as an incentive tool at all periods; but still persists the result that future utility is more intensely used in the initial periods of the relationship while present compensation is more intensely used in the final periods of the relationship.

In Figure 12 we show the results of the most advantageous contract for the Agent. The main differences with respect to the results depicted in Figure 11 are that the Agent's promised discounted expected utilities are higher in this case and that the Principal uses the Agent's current compensation uniformly across periods as an incentive tool, given that there is a difference for the realization of the high or low productivity shock; but the difference between them is constant. This means that the Agent is assuming little of the risk inherent to the productive activity and only faces variability in the compensation scheme through future compensation. A difference with respect to the results of Figure 3 is that in the present case, given that the low productivity shock is higher than and the high productivity shock is equal to those of the benchmark case, the Agent is able to achieve higher levels of promised expected discounted utility and of salary in the low productivity case. The schedule of the Agent's discounted expected utility for the high productivity shock displays a similar

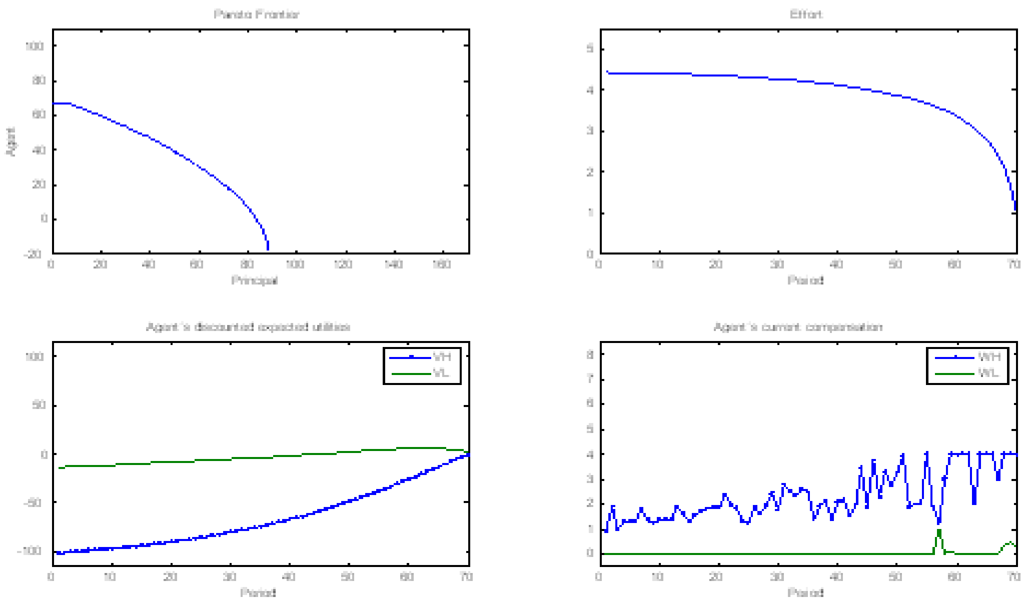

Figure 11: Principal's most advantageous contract, $Y = \{3, 4\}$

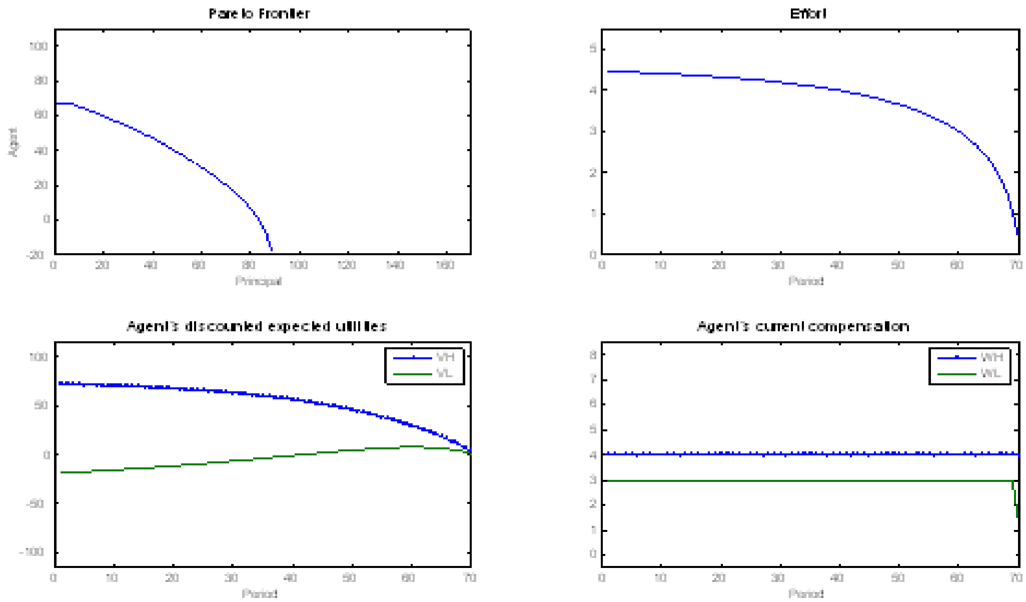

Figure 12: Agent's most advantageous contract, $Y = \{3, 4\}$

behavior of that of Figure 3; however, the decreasing behavior is more pronounced in the current Figure as well as the decreasing behavior in the schedule of the Agent's optimal effort.

In Figure 13 we show the results of what we label as the social contract. The Agent chooses higher effort levels compared to those in the previous two figures. We notice that around $p = 50$, both the behavior of the spread between the Agent´s expected discounted utilities for the low (L) and high (H) productivity shocks and that of the Agent's salaries for the low (L) and high (H) productivity shocks experience a change. Before that period, we observe that the behavior of the spread between those utilities and salaries is similar to that observed in the Principal's most advantageous contract for the same periods. For $p > 50$, the behavior of the spread between those utilities and salaries becomes more similar to that observed in the Agent's most advantageous contract; however, we observe a richer dynamics in the Agent's salary in the case of the low productivity shock in this contract than that observed in the corresponding schedule in the Agent's most advantageous contract. It must be noted that this result is different than that obtained in the social contract of the bechmark model. So, we can say that the higher value of the low productivity shock allows the Principal to assume more risk in the social contract in later periods compared to what is observed

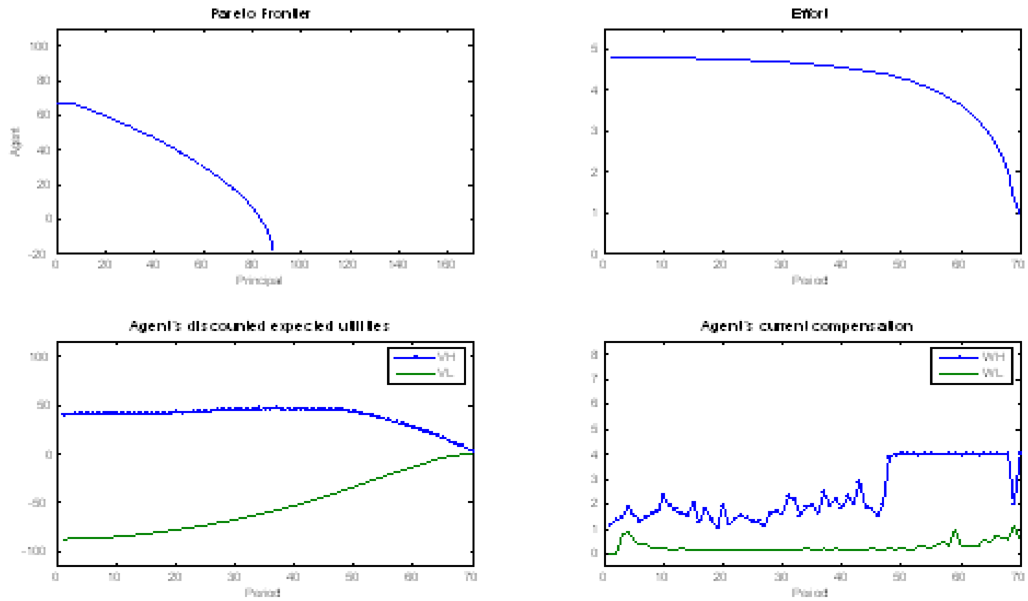

Figure 13: Social contract, $Y = \{3, 4\}$

in the social contract of the benchmark model, where the principal seems to share more risk with the Agent.

4.3.2 $Y = \{y_L = 2, y_H = 3\}$

In this case, the distance between the low and high productivity shocks decreases by means of a lower output level associated with the high productivity shock with respect to the benchmark case. In Figure 14, we show the results of the Principal's most advantageous contract. The main difference with respect to the results of Figure 2 is that salary is less intensely used as an incentive tool even as $p \to 70$, because the Agent's salary in the high productivity shock is consistently lower in this case than in the benchmark case.

In Figure 15 we show the results of the most advantageous contract for the Agent. The interpretation of the results depicted in this figure is similar to that of Figure 12; however, as the high productivity shock in this case is lower than that of the benchmark case and that of Figure 12, the Agent's compensation in terms of salary and in terms of promised discounted expected utility is lower. The differences between this and the previous figure are essentially the same as those of figures 2 and 3.

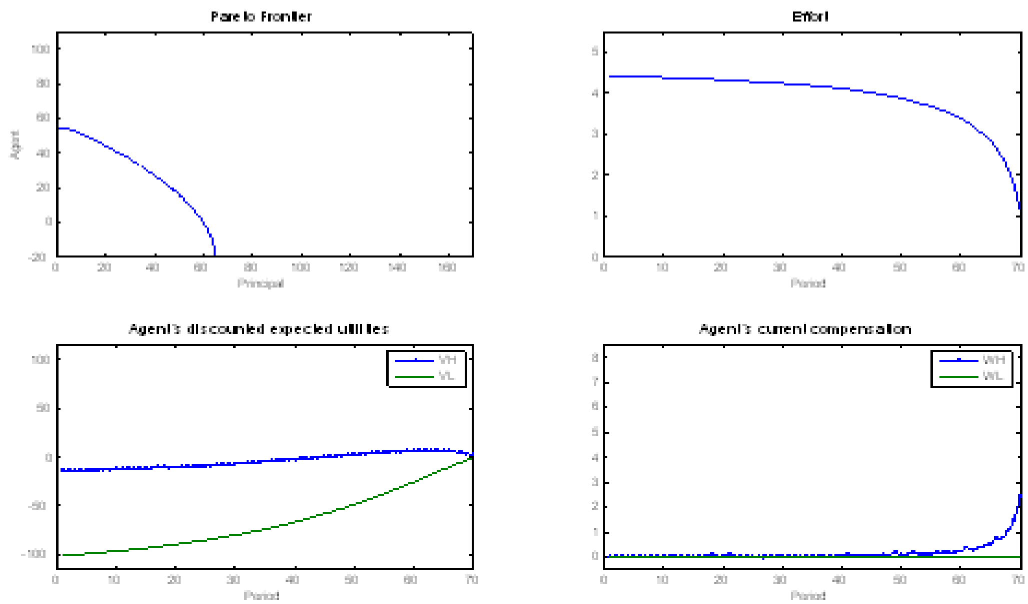

Figure 14: Principal's most advantageous contract, $Y = \{2, 3\}$

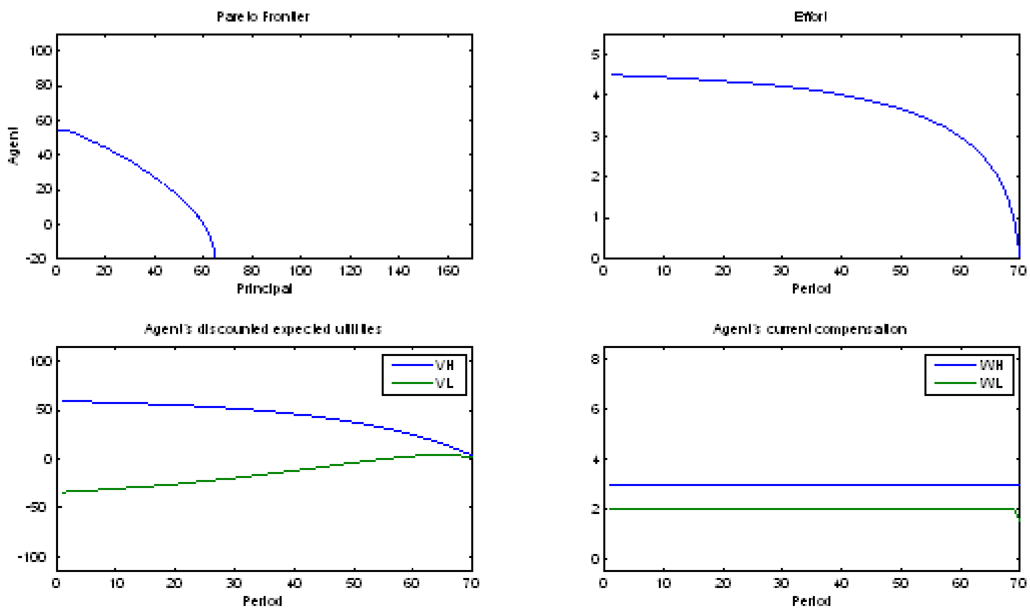

Figure 15: Agent's most advantageous contract, $Y = \{2, 3\}$

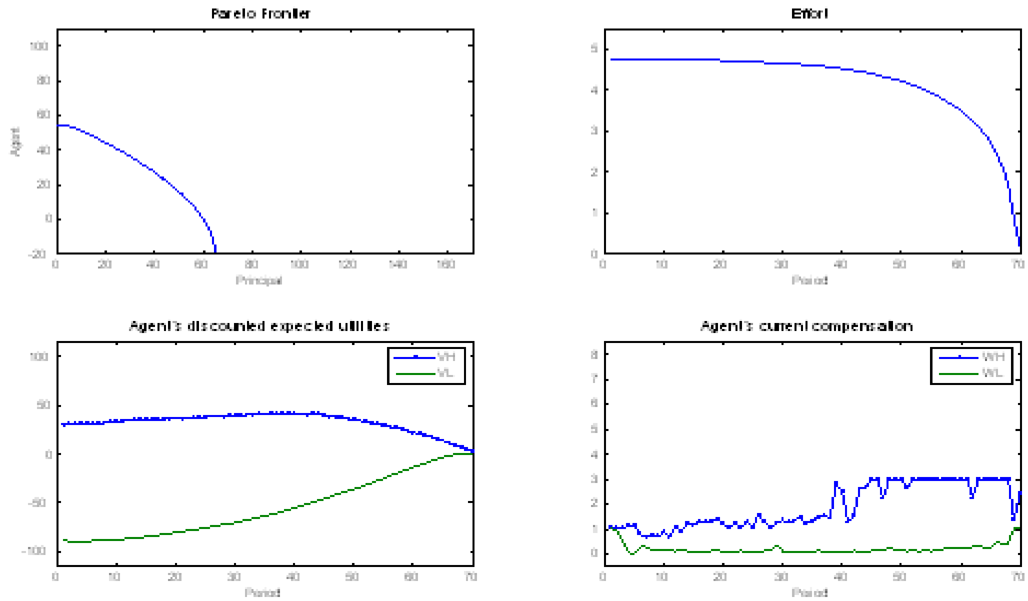

Figure 16: Social contract, $Y = \{2, 3\}$

In Figure 16 we show the results of what we label as the social contract. The Agent exerts higher effort levels compared to those in the previous two figures. The behavior of the spread between the Agent´s expected discounted utilities for the low (L) and high (H) productivity shocks and that between the Agent's salaries for the low (L) and high (H) productivity shocks is similar to what is observed in Figure 13, and hence, the interpretation is similar. The difference is that in the current figure the change observed in both spreads, similar to that reported in Figure 13, occurs at an earlier period; that is, around $p = 40$. So, the Principal seems to be assuming more of the risk at earlier periods in this case compared to what is observed in Figure 13.

4.3.3 $Y = \{y_L = 2, y_H = 5\}$

In this case, the distance between the low and high productivity shocks increases by means of a higher output level associated with the high productivity shock with respect to the benchmark case. In Figure 17 and 18, we show the results of the Principal's and the Agent's most advantageous contracts, which are similar to those of Figure 2 and 3, respectively.

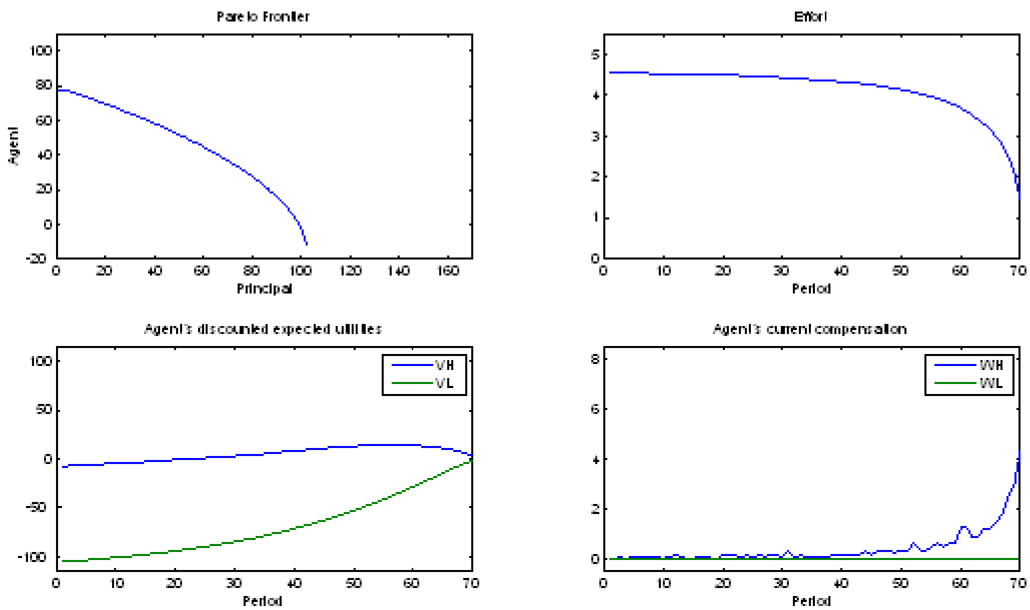

Figure 17: Principal's most advantageous contract, $Y = \{2, 5\}$

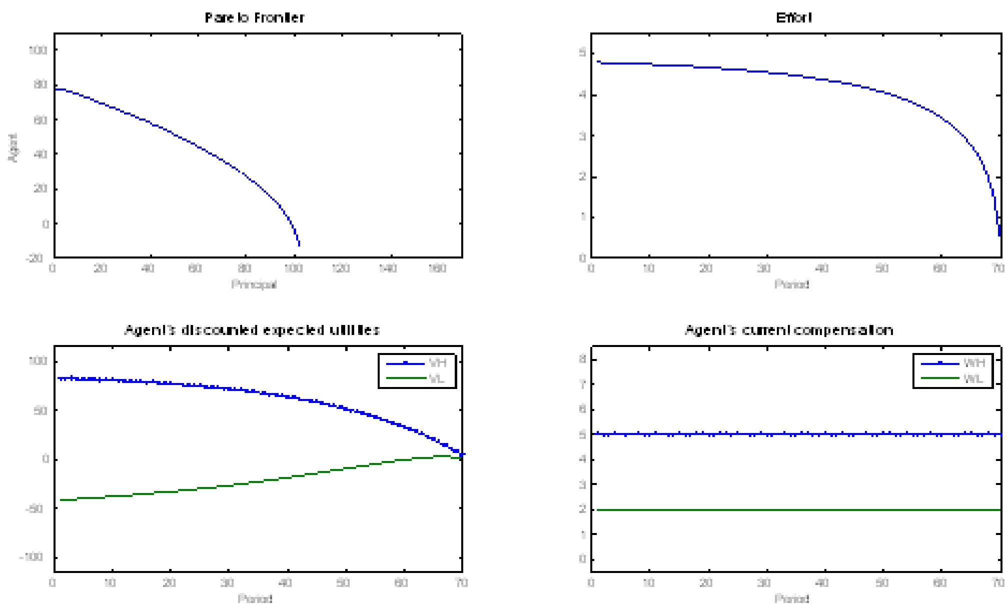

Figure 18: Agent's most advantageous contract, $Y = \{2, 5\}$

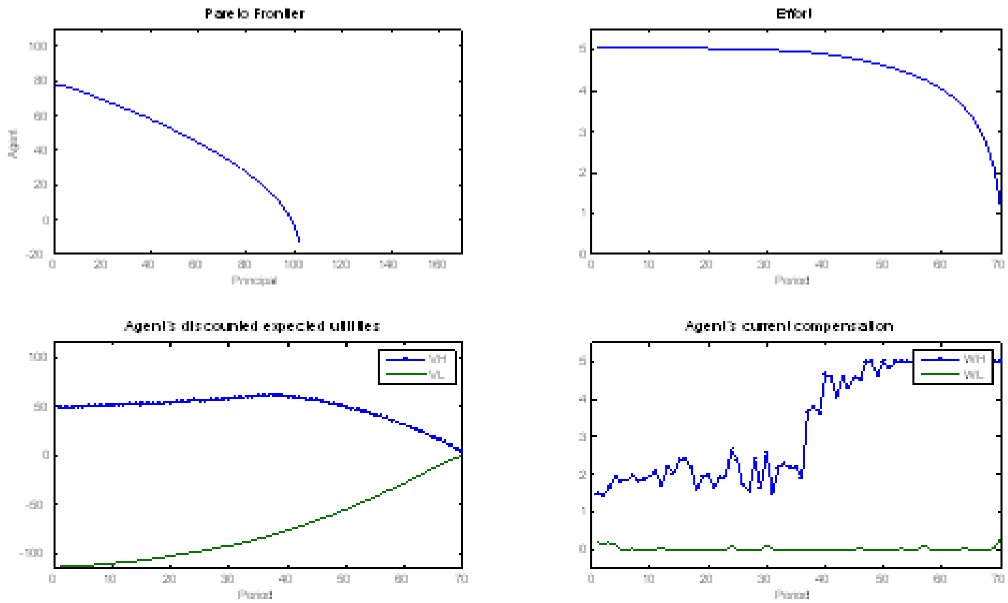

Figure 19: Social Contract, $Y = \{2, 5\}$

In Figure 19 we show the results of what we label as the social contract. The results are similar to those reported in Figure 16; but with a higher spread in both the Agent's promised future utilities and salaries, a result derived from the higher level of the high productivity shock.

4.3.4 $Y = \{y_L = 4, y_H = 8\}$

In this case, the distance between the low and high productivity shocks increases, and both productivity shocks are higher than those of the benchmark case. In Figure 20, we show the results of the Principal's most advantageous contract, with similar results to those reported in Figure 2.

In Figure 21 we show the results of the most advantageous contract for the Agent, with similar results to those reported in Figure 3.

In Figure 22 we show the results of what we label as the social contract, with similar results to those reported in Figure 19, but the beginning of the similarity of the behavior of the Agent's current compensation schedule of the high productivity shock to the case of the Agent's most advantageous contract beginning a a later period, at around $p = 60$. So, from observing the structure of the social contract

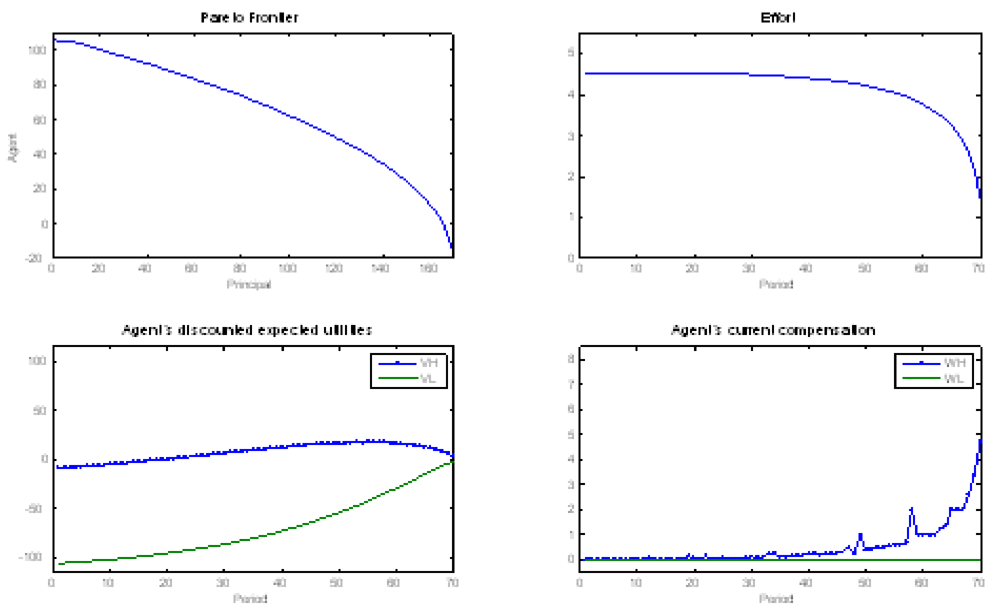

Figure 20: Principal's most advantageous contract, $Y = \{4, 8\}$

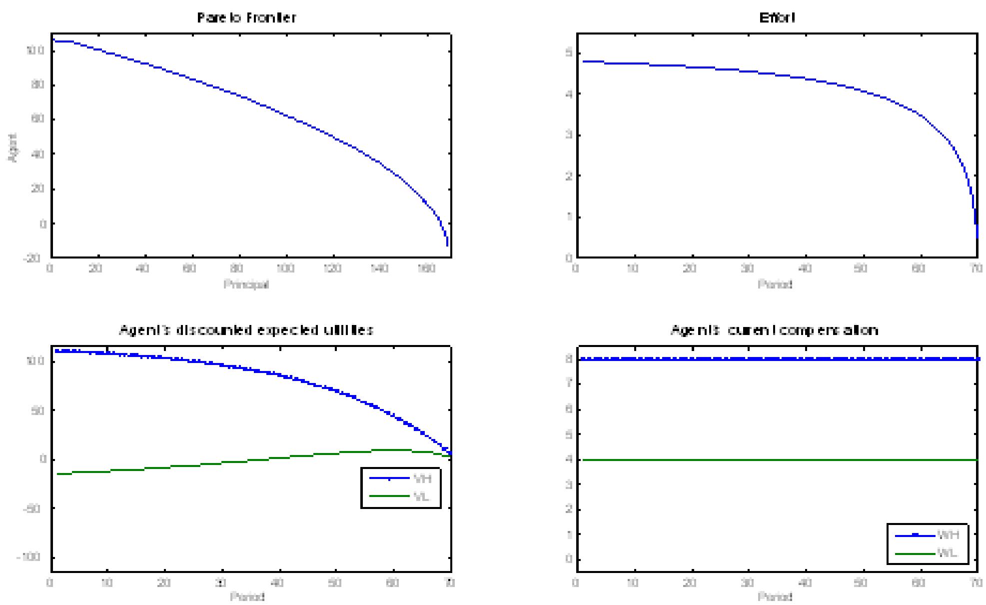

Figure 21: Agent's most advantageous contract, $Y = \{4, 8\}$

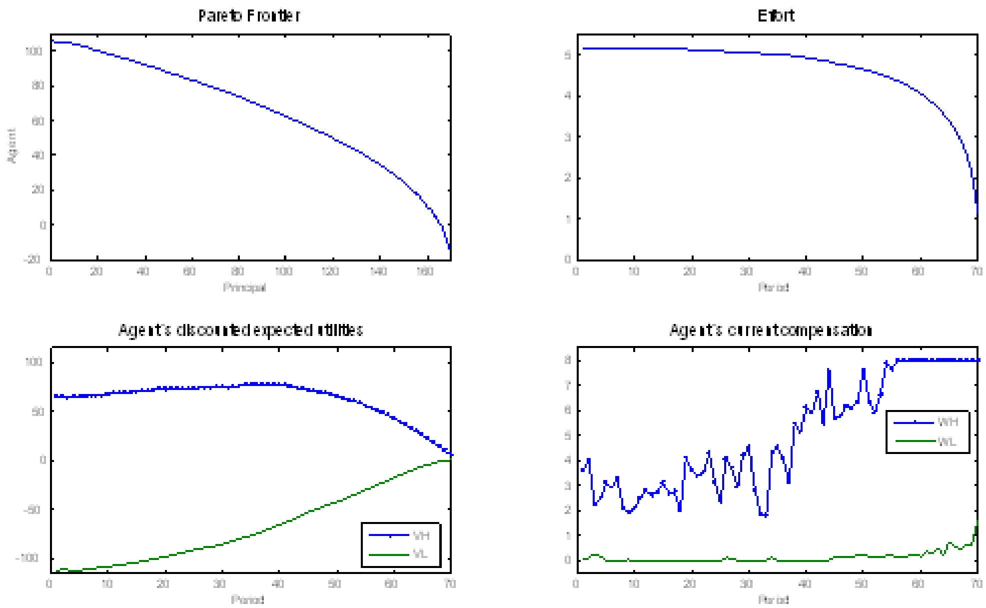

Figure 22: Social contract, $Y = \{4, 8\}$

of all the cases of productivity shocks considered here, one can conclude that this contract is a mixture of the other two contracts, at least with respect to the behavior of the schedules of the Agent's current compensation for the high and low productivity shocks. In the initial periods, the Principal provides incentives that are similar to the Principal's most advantageous contract and then after a certain point, the Principal shifts to an incentive structure that is more similar to that of the Agent's most advantageous contract. That tipping point seems to be related to the structure of the productivity shocks, because when those shocks are such that there are higher levels of production and resources, the Principal tends to let the Agent take more risk and the shift to a more flat incentive structure occurs at later periods.

4.3.5 How are gains from changes in productivity shocks shared?

We assess how gains/losses derived from changes in productivity shocks are shared between the Principal and the Agent. In order to do that, for every pair of productivity shocks considered above, we measure the distance from the Principal's maximal utility in his most advantageous contract and his utility in the Agent's most advantageous contract, $\Delta PP = |U_P - U_A|$. We also measure the distance from the Principal's

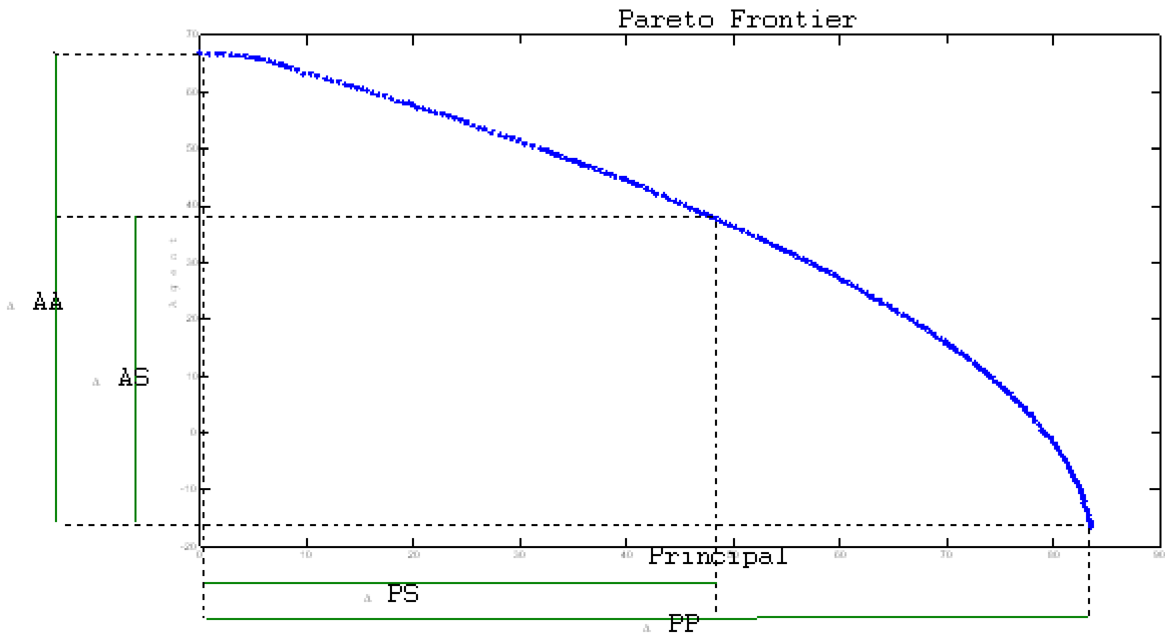

Figure 23: Measuring ΔAA, ΔAS, ΔPP, and ΔPS on the Pareto Frontier, benchmark case.

utility in the social contract and his utility in the Agent's most advantageous contract, $\Delta PS = |U_S - U_A|$. For the case of the Agent, for every pair of productivity shocks considered above, we measure the distance from the Agent's maximal utility in his most advantageous contract and his utility in the Principal's most advantageous contract, $\Delta AA = |V_A - V_P|$. We also measure the distance from the Agent's utility in the social contract and his utility in the Principal's most advantageous contract, $\Delta AS = |V_S - V_P|$. We show the aforementioned measures on the Pareto Frontier in Figure 23, and the numerical values of those measures in Table 1.

Table 1

	$\{2,4\}$	$\{3,4\}$	$\{2,3\}$	$\{2,5\}$	$\{4,8\}$
ΔPP	83.53029382	88.37666718	64.90066374	102.0904546	168.8769348
ΔAA	83.45872312	85.37478526	73.48293183	89.83868206	119.3997101
ΔPS	52.30366428	53.93391853	40.89641844	61.05970618	103.2953663
ΔAS	50.87562358	53.6345627	44.95816443	55.82544316	73.97713028

Then, we construct the following relative measures to determine who is favoured when moving from the productivity shocks of the benchmark case to any other set of productivity shocks, where i is the subindex for any new set of productivity shocks, as follows: $i = 1$ means that $Y = \{3, 4\}$, $i = 2$ means that $Y = \{2, 3\}$, $i = 3$ means that $Y = \{2, 5\}$, and $i = 4$ means that $Y = \{4, 8\}$; B is the subindex of the productivity shocks of the benchmark case, $Y = \{2, 4\}$; and R stands for "relative":

$$\begin{aligned}
\Delta PPR_i &= \frac{\Delta PP_i - \Delta PP_B}{\Delta PP_B} = \frac{\Delta PP_i}{\Delta PP_B} - 1 \\
\Delta PSR_i &= \frac{\Delta PS_i - \Delta PS_B}{\Delta PS_B} = \frac{\Delta PS_i}{\Delta PS_B} - 1 \\
\Delta AAR_i &= \frac{\Delta AA_i - \Delta AA_B}{\Delta AA_B} = \frac{\Delta AA_i}{\Delta AA_B} - 1 \\
\Delta ASR_i &= \frac{\Delta AS_i - \Delta AS_B}{\Delta AS_B} = \frac{\Delta AS_i}{\Delta AS_B} - 1
\end{aligned}$$

The numerical values we obtain are reported in Table 2, and must be understood as results from moving from the benchmark case $Y = \{2, 4\}$ to the cases reported in Table 2.

Table 2

	$\{3,4\}$	$\{2,3\}$	$\{2,5\}$	$\{4,8\}$
ΔPPR	0.05801935	-0.223028428	0.222196762	1.021744771
ΔAAR	0.022958201	-0.119529642	0.076444483	0.430643864
ΔPSR	0.031169026	-0.218096495	0.16740781	0.974916436
ΔASR	0.054229097	-0.116312268	0.097292559	0.454078104

From these results, we conclude that: (i) Moving from $Y = \{2, 4\}$ to $Y = \{3, 4\}$ favors the Principal because he obtains a higher relative gain in utility when his most advantegeous contract is implemented than the Agent when his most advantageous contract is implemented; while it favors the Agent when implementing the social contract. (ii) Moving from $Y = \{2, 4\}$ to $Y = \{2, 3\}$ favors the Agent overall. (iii) Moving from $Y = \{2, 4\}$ to $Y = \{2, 5\}$, and also to $Y = \{4, 8\}$, favors the Principal overall. So, it seems that when the structure of productivity shocks is such that the Agent's effort yields higher production levels, the Principal tends to benefit because in those cases the Agent assumes more risk than in the benchmark case, as it can be seen in the previous sub-sections through the behavior or the Agent's current and future compensation; while when the structure of the productivity shocks is such that the Agent's effort yields lower production levels, the opposite occurs. So, how risk is shared between the Principal and the Agent determines who benefits when the structure of the productivity shocks changes.

5 Conclusions

In this paper we study the effects of variability of productivity shocks and of the discount rate on the optimal contracts' structure derived from a repeated Principal Agent model, formulated as a Multi-Objective Optimization problem. We numerically approximate this model's Pareto Frontier using a Multi-Objective Optimization Evolutionary Algorithm for different parameter value setups.

From our numerical results, we conclude that as the discount rate β increases, the Principal Agent relationship generates higher values; the spread in the Agent's future (current) compensation between the low and high productivity shocks increases (decreases); and the Agent chooses, in general, higher effort levels. On the other hand, the social contract is the contract that experiences higher changes when the value of the parameter β changes. This contract is a mixture of the Principal's most advantageous contract and the Agent's most advantageous contract, and it can be observed in this contract that as β increases, the Agent assumes more of the risk associated with the production process through the short and long term incentives.

We can also conclude that when the structure of productivity shocks is such that the Agent's effort yields higher production levels, the Principal tends to benefit because in those cases the Agent assumes more risk; while when the structure of the productivity shocks is such that the Agent's effort yields lower production levels, the opposite occurs. So, risk sharing between the Principal and the Agent determines who benefits when the structure of the productivity shocks changes. On the other hand, the social contract is again the contract that is more changeable when the structure of productivity shocks changes. The behavior of this contract puts into evidence that the Agent tends to bear more risk associated with the production process when his effort yields higher outcomes thorugh the short and long term incentives.

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