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POLICY UNCERTAINTY AND LONG-RUN INVESTMENT AND OUTPUT ACROSS COUNTRIES*

By Byeongju Jeong[1]

CERGE-EI, Charles University and the Academy of Science, Czech Republic

I present a model economy where policy uncertainty creates short-term bias in investment and leads to a higher capital price and lower long-run investment and output. I conduct a calibration exercise using a set of industry-level investment data across countries. Between the lowest-income and the highest-income countries, policy uncertainty can account for capital price and investment-level differences by a factor of about 3 and for the output-level difference by a factor of about 2.

1. INTRODUCTION

In this article, I explore the view that policy uncertainty lowers long-run investment and output, and thereby it is a major factor for cross-country income differences. I am motivated by the observation that low-income countries have greater (indications of) policy uncertainty, and they invest a lower fraction of their output than high-income countries, if investment is measured by the real amount of capital acquisition. I construct a model economy that features the negative effect of policy uncertainty on long-run investment and output. Based on this model, I assess the quantitative importance of policy uncertainty in cross-country income differences. In the remainder of this section, I lay out the motivations more precisely and outline the content of the article.

One can casually observe indications of policy uncertainty in low-income countries (e.g., the frequent regime changes in many African countries and the recent policy reversals in Russia). Formally, the empirical studies of Barro (1991), Aizenman and Marion (1993), Ramey and Ramey (1995), Alesina and Perotti (1996), and Serven (1998) suggest that low-income countries have greater policy uncertainty than high-income countries and policy uncertainty is an important factor for the lower long-run investment and output in these countries. On the other hand, there are few theories that feature the negative effect of (policy) uncertainty on long-run investment and

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output. In the theory of investment under irreversibility, uncertainty delays investment since investors gain by waiting for more information. Irreversible investment, however, does not imply a negative effect of uncertainty on long-run investment. In Lucas and Prescott (1971), uncertainty has no effect; in Abel and Eberly (1995), it has a positive effect; and in Hopenhayn and Muniagurria (1996), it has a mixed effect. In summary, irreversibility alone is not enough to generate a strong negative effect of uncertainty on long-run investment, and the theory needs an additional corroborating feature.

With this motivation, in Section 2, I present an investment environment that generates a negative effect of policy uncertainty on long-run investment and output. There is ‘‘time to build’’ as in Kydland and Prescott (1982). The key feature is that there are different types of investment projects that differ in duration and in the amount of capital produced at the end of the duration. A project incurs investment costs over its entire duration. For all projects, the one-period (i.e., momentary) investment cost is composed of a constant technical cost and a policy-related cost that follows a two-state Markov chain. Investors are risk neutral. In equilibrium, investors start projects with a low initial policy-related cost, but this low cost may subsequently become high. Since the profile of the expected one-period cost is upward sloping over the duration of a project, shorter-term projects incur a lower policy-related cost on average over the project duration. Thus, policy uncertainty creates a bias toward short-term projects. Further, the investor may abandon a project if the policy-related cost becomes high (and start a project with a low current cost). Thus, policy uncertainty also leads to an abandonment of projects (with the consequent loss of sunk investment under irreversible investment). Bias and abandonment benefit the investors since they reduce the expected cost per unit of capital produced. This saving on costs comes entirely from reducing the expected policy-related cost and, in fact, bias and abandonment increase the expected technical cost: The saving on policy-related costs outweighs the increase in technical costs. A crucial assumption is that the expected policy-related cost as a share of the total (i.e., technical and policy-related) expected cost is held constant *in equilibrium* by appropriately scaling the two possible values of the one-period policy-related cost. In modeling policy uncertainty, this way of fixing the share of policy-related cost in the total cost seems reasonable since policy is presumably set taking into consideration the investors’ response. Given this assumption, policy uncertainty increases the expected cost of producing a unit of capital by increasing technical costs. In competitive investment, this leads to a higher capital price.

In Section 3, I embed this investment environment in a neoclassical aggregate model. The way policy uncertainty affects aggregate investment and output is entirely through the above-mentioned positive effect on the capital price. In steady state (at the aggregate level), policy uncertainty does not alter the amount of resources (as a fraction of aggregate output) channeled to investment in an economy, but reduces capital production due to its effect on the capital price. Consequently, the aggregate output is lower as well. This feature of the model accords well with the empirical finding based on Summers and Heston (1993), as noted by Easterly (1993) and Jones (1994), among others, that low-income countries invest as much as high-income countries, but the acquisition of new capital is less in low-income countries due to the higher capital price relative to the consumption-good price. There are explanations other than policy uncertainty that can account for this empirical pattern. In particular, this pattern would result if low-income countries had a higher *level* of policy-related costs than high-income countries. The level of taxes is not higher in lower-income countries (see Newbery and Stern, 1987), but the level of other policy-related costs such as bribes and regulatory costs may very well be higher in lower-income countries (see De Soto, 1989, for example). In this article, I focus on the uncertainty in policy-related costs holding their level, without denying that the differences in this level may also be a major factor in cross-country income differences.

As alluded to above, the policy-related investment cost is meant to capture a broad spectrum of costs: It includes not only direct taxes and subsidies on investment, but also indirect costs such as bribes and the costs of following regulations. Thus, policy uncertainty stems not only from uncertain taxes and subsidies, but also from (unexpected) changes in regulations, in their enforcement, and in required bribes due to a replacement of officials. Many of these costs are not measured, especially in low-income countries, so we cannot directly assess the merits of the model. However, some indirect evidence for the model can be found in investment data across countries. In the model, aside from the effect on capital price, investment, and output, policy uncertainty also affects industry-level investment dynamics. Generally speaking, policy uncertainty increases the ''volatility'' of investment. Thus, the model implies a negative relationship between the output level and the volatility of industry investment across countries. In Section 4, I investigate the industry-level investment sequences from 1967 to 1988 across 27 manufacturing industries and across 16 countries of diverse output levels. I find that investment in lower-income countries is indeed more volatile: In lower-income countries, the industry investment sequence is more dispersed, less persistent, and skewed downward.

In Section 5, I assess the quantitative importance of policy uncertainty in accounting for cross-country differences in the capital price and long-run investment and output. My approach is to calibrate the model using the model's implication for investment dynamics: I simulate industry investment sequences for various model parameter values and select the ones that generate the actual investment dynamics, with different values corresponding to different income levels. The implicit assumption here is that all industry-level investment fluctuations are due to policy uncertainty of the type modeled here. This is, of course, a crude assumption and ignores other sources of fluctuation. Therefore, the quantitative results from this exercise should be considered tentative. With this qualification, the exercise shows that policy uncertainty can account for a large portion of the observed cross-country differences: Between the lowest-income and the highest-income countries, policy uncertainty can account for the capital price and investment-level differences by a factor of about 3 and the output-level difference by a factor of about 2.

In Section 6, I summarize and evaluate the results of the article.

2. INVESTMENT UNDER POLICY UNCERTAINTY

In this section, I present an investor's problem under the uncertainty of policy-related investment costs. I characterize the optimal investment rule and show that under competition, the effect of uncertainty is to increase the equilibrium capital price.

2.1. *The Investor's Problem.* Consider an investor who is risk neutral and discounts the future costs and returns by one-period discount rate $\beta < 1$. At any date, the investor can choose one of three activities: to start an investment project, to continue an unfinished project if there is one, or to remain idle. There are many types of projects. A project of type $j \in \{1, 2, \ldots\}$ requires j consecutive periods of investment to be completed. The one-period cost of investment, denoted as ϕ, is composed of 1 unit of technical cost and $\phi - 1$ units of policy-related cost. The policy-related cost is project-specific and its future values are uncertain. Thus, ϕ is project-specific and uncertain as well. The value of ϕ can be either ϕ_1 or ϕ_2, where $\phi_1 < \phi_2$, and evolves according to a Markov chain: If the current-period cost is ϕ_q, $q = 1, 2$, the probability that the next-period cost will be ϕ_q is π_q. I assume that $\pi_1 + \pi_2 > 1$, which implies some persistence in the one-period cost: For $q = 1, 2$, the probability of the next-period cost being ϕ_q is greater if the current-period cost is ϕ_q. I also assume that at each date and for each type of project, there are some new projects with the low current cost ϕ_1. This implies that there is no "value of waiting to invest," which is an important feature of models with irreversible investment. As mentioned earlier, the value of waiting to invest, aside from its effect on the timing of investment, is unlikely to have a robust effect on the long-run investment, which is the concern of this article. A project of type j, once completed, yields $h(j)$ units of new capital. I call $h(j)$ the capital return function and assume that a unique finite j solves the problem $\max_j\{(\beta^{j-1}h(j))/\sum_{n=0}^{j-1}\beta^n\}$.[2] This assumption ensures that the investor's problem is well defined and has a unique solution in the absence of policy uncertainty (see Proposition 2). Let P denote the capital price, which is assumed to be fixed for now. The value of the completed project is then $Ph(j)$. An unfinished project can be abandoned, but once it is abandoned, the costs of investment already incurred cannot be recovered (i.e., investment is irreversible) and the project cannot be continued later.

In this environment, the investor's decision problem at each date is as follows: If he has an unfinished project carried over from the previous date, he decides whether to continue the project or to abandon it, given the current cost of the project. If he does not have an unfinished project or if he decides to abandon an unfinished project, he decides whether to start a new project and, if he decides to, chooses the type of project and the initial one-period cost. To formalize this problem, let $v(j, n, q)$ denote the value of managing (i.e., starting or continuing) a project of type j, aged n, and with the current cost ϕ_q. Then,

$$v(j, n, q) = -\phi_q + \pi_q\beta\tilde{v}(j, n+1, q) + (1 - \pi_q)\beta\tilde{v}(j, n+1, q') \tag{2.1}$$

for $n \in \{0, 1, \ldots, j-2\}$;

$$v(j, j-1, q) = -\phi_q + Ph(j) \tag{2.2}$$

[2] Sufficient for this assumption to hold is the condition that h is increasing and, loosely speaking, concave enough.

and

$$\tilde{v}(j, n, q) = \max\{v(j, n, q) - \xi, 0\} \tag{2.3}$$

where in each equation $q' = 1$ if $q = 2$, and $q' = 2$ if $q = 1$. The term $\tilde{v}(\cdot)$ is the value of the option to manage the project. The term ξ is the opportunity cost of managing the project, that is, the value of the best alternative to managing the project. Since the alternatives are starting a new project or being idle, we have

$$\xi = \max\{\max_{j,q}\{v(j, 0, q)\}, 0\} \tag{2.4}$$

If the value of managing a project is greater than the opportunity cost, the investor will choose to manage the project. If it is less than the opportunity cost, he will not manage the project and instead opt for the best alternative.

If the values of all new projects are negative ($\max_{j,q}\{v(j, 0, q)\} < 0$), the investor will be idle at all dates. On the other hand, if the values of some new projects are positive ($\max_{j,q}\{v(j, 0, q)\} > 0$), the investor will manage projects at all dates. In the middle case ($\max_{j,q}\{v(j, 0, q)\} = 0$), the investor will be indifferent between managing projects and being idle. The following proposition characterizes the investor's behavior when he manages projects ($\max_{j,q}\{v(j, 0, q)\} \geq 0$).

Proposition 1. *If there is investment* ($\max_{j,q}\{v(j, 0, q)\} \geq 0$), *the investor's behavior is characterized by the optimal investment rule* (J, N): *Start a project of type J with low current cost; continue the project as long as its cost stays low; and if the cost becomes high, abandon the project if it is younger than N periods, and continue the project if it is as old or older than N periods.*

Proof. See the Appendix.

This proposition can be intuitively explained as follows: Given the minimum persistence in the cost, the value of a project with a low current cost is greater than that of an identical project except for its high current cost, and so the investor would start a project with a low current cost. As for the type of project, he will select the one that has the maximum value: $J = \arg\max_j v(j, 0, 1)$.[3] As for the continuation rule, the value of an older project is greater than that of an identical project except for its younger age since an older project requires less investment to be completed and the return is sooner. Given this monotonicity of the value of a project over its age, once the investor has started a project, he will continue it as long as the cost remains low. If the cost becomes high, he will continue the project only if it is old enough to compensate for the loss of its value due to the increase in cost, and abandon the project if it is not old enough.

2.2. *Capital Price in Competitive Equilibrium.* In Section 2.1, the capital price was assumed to be fixed. Now let us consider an environment where the capital price

[3] There is such finite J given the assumption for h (see Proposition 2). However, J may not be unique.

is determined under competitive investment. In this environment, there are many investors who are identical to the one we considered and who competitively produce capital by managing investment projects. Further, the underlying demand for capital is price-elastic so that the capital price responds to the changes in supply of capital. In this environment, if the value of an optimal project $v(J, 0, 1)$ is positive, more projects will be started and capital production will increase. This will in turn decrease the capital price, which will then decrease the value of the project. On the other hand, if the value of the optimal project is negative, no projects would be undertaken, thereby increasing the capital price and the value of the project. Considering these scenarios, we can conclude that there is an equilibrium price P under which the value of any optimal project is zero:

$$v(J, 0, 1) = \xi = 0 \tag{2.5}$$

Formally, given ϕ_1, ϕ_2, π_1, and π_2, an equilibrium is a capital price P and an optimal investment rule (J, N) such that under $P, (J, N)$ is a solution to the investor's problem of Equations (2.1)–(2.4) and Equation (2.5) is satisfied.

2.3. *The Effect of Policy Uncertainty on Capital Price.* In the investment environment considered in the previous subsections, there is uncertainty in investment cost due to uncertain policy-related cost, and this uncertainty is governed by the possible one-period costs, ϕ_1 and ϕ_2, and the transition probabilities, π_1 and π_2. To consider the effect of policy uncertainty on investment in a meaningful context, I will first clarify the meaning of uncertainty in this environment by transforming the parameters $(\tau_1, \tau_2, \pi_1, \pi_2)$ to parameters that have clearer economic meanings. First, the scale parameter $\bar{\phi}$ is defined as the mean of the two costs: $\bar{\phi} \equiv (\phi_1 + \phi_2)/2$. This parameter measures the scale of the costs (a higher value indicates greater scale). Second, the dispersion parameter d is defined as $d \equiv \phi_2/\phi_1$. This parameter measures the dispersion between the two costs (a higher value indicates more dispersion). Next, define $\pi(t; q)$ as the probability that the cost will be ϕ_q after t periods given that the current cost is ϕ_q. We have $\pi(0; q) = 1$ and $\pi(t+1; q) = \pi_q \pi(t; q) + (1 - \pi_{q'})(1 - \pi(t; q))$ for all $t \geq 0$, where in each equation $q' = 1$ if $q = 2$, and $q' = 2$ if $q = 1$. From these equations, we can derive

$$\pi(t; 1) = a + (1 - a)b^t \quad \text{and} \quad \pi(t; 2) = 1 - a + ab^t \tag{2.6}$$

where $a \equiv (1 - \pi_2)/(2 - \pi_1 - \pi_2)$ and $b \equiv \pi_1 + \pi_2 - 1$. As t increases, $\pi(t; 1)$ converges to a and $\pi(t; 2)$ converges to $1 - a$. Thus, the parameter a is the long-run probability that the cost will be ϕ_1. I will call this parameter the frequency parameter (a higher value indicates greater occurrence of the low cost in the long run). The parameter b determines how quickly $\pi(t; 1)$ and $\pi(t; 2)$ converge to a and $1 - a$, respectively. For instance, if $b = 0.9$, each period $\pi(t; p)$ approaches a by 10 percent of the gap between the two. I will call this parameter the persistence parameter (a higher value indicates greater persistence of the cost).

Now I have defined the four new parameters $(\bar{\phi}, d, a, b)$. A combination of these four parameter values corresponds to a unique combination of the primitive parameter values $(\phi_1, \phi_2, \pi_1, \pi_2)$. Of the four new parameters, the dispersion parameter d, the frequency parameter a, and the persistence parameter b characterize the uncertainty of investment costs, whereas the scale parameter $\bar{\phi}$ determines only the scale of taxes without affecting uncertainty. The scale parameter, nonetheless, does affect capital price. In examining the relationship between the uncertainty parameters (d, a, b) and capital price, we need to make an assumption as to what value of $\bar{\phi}$ accompanies each combination of (d, a, b). One simple assumption is to set $\bar{\phi}$ so that the *time-weighted* average cost, that is, $\phi_1 a + \phi_2(1 - a)$, is fixed for all sets of values of (d, a, b). This is, in fact, the default assumption in most studies of uncertainty. Under this assumption about $\bar{\phi}$, the shares of investment that take place under a low versus high cost vary depending on the uncertainty parameter values (d, a, b) and are not proportional to a. Then, the *investment-weighted* average cost (weighing ϕ_1 and ϕ_2 by the amount of investment carried out under the respective rate) varies. This would be fine if our concern was the effect of uncertainty in the forces of nature (e.g., rainfall). Our concern is, however, the effect of policy-related uncertainty, and this implication does not seem desirable since policy is presumably chosen with consideration of the investors' responses (e.g., collecting taxes and extorting bribery). The notion of average cost seems to correspond more to the investment-weighted than to the time-weighted cost in the context of policy uncertainty. To isolate the effect of policy uncertainty from the effect of the level of policy-related costs, we need to fix the investment-weighted average cost by appropriately changing $\bar{\phi}$ under various (d, a, b).[4]

Therefore, I adopt this alternative assumption about the scale parameter $\bar{\phi}$: The value of $\bar{\phi}$ is chosen so that the investment-weighted average one-period cost is constant for all (d, a, b).[5] To be precise, I will define the investment-weighted average one-period cost, denoted as $\tilde{\phi}$, as follows: First, let a combination of parameter values $\{\bar{\phi}, d, a, b\}$, the corresponding primitive parameter values $\{\phi_1, \phi_2, \pi_1, \pi_2\}$, the corresponding equilibrium capital price P, and the corresponding optimal investment rule (J, N) be given. Given this investment rule and using Equations (2.1)–(2.5), the equilibrium value of an optimal project can be written as

$$v(J, 0, 1) = -\omega + \beta^{J-1}\pi_1^{N-1} Ph(J) \tag{2.7}$$

where the first term ω is the expected discounted sum of investment costs; the second term is the expected discounted return from investment; and

$$\omega = \sum_{n=0}^{N-1} \beta^n \pi_1^n \phi_1 + \sum_{n=N}^{J-1} \beta^n \pi_1^{N-1} \phi(n - N + 1) \tag{2.8}$$

To understand this expression intuitively, observe that the probability that a project will be continued at age n is π^n for $n = 0, 1, \ldots, N-1$, and π_1^{N-1} for

[4] Aside from the conceptual issue, in relating the model to the data, fixing the investment-weighted average cost operationally means fixing whatever factors determine the actual policy-related costs as a share of actual investment.

[5] This assumption is crucial for the result. If we were to fix the time-weighted average cost instead, the investors' behavior (i.e., J and N) would be the same but the effect of policy uncertainty would be to *lower* the capital price. Thus the two alternative assumptions lead to the opposite results.

$n = N, N+1, \ldots, J-1$, and that if the project is continued at age n, the one-period investment cost at that date is ϕ_1 for $t = 0, 1, \ldots, N-1$, and $\phi(n - N + 1)$ for $n = N, N+1, \ldots, J-1$, where $\phi(t)$ is the expected one-period cost conditional on that the cost is ϕ_1 at $t = 0$: $\phi(t) = \phi_1 \pi(t; 1) + \phi_2(1 - \pi(t; 1))$ (see Equation (2.6)).

Now suppose that at any date the one-period investment cost is a constant value ϕ instead of ϕ_1 or ϕ_2, while the other parameter values and the investor's behavior remain the same. Let $\omega(\phi)$ denote the expected discounted sum of investment costs of a new project in this case. We have

$$\tilde{\omega}(\phi) = \sum_{n=0}^{N-1} \beta^n \pi_1^n \phi + \sum_{n=N}^{J-1} \beta^n \pi_1^{N-1} \phi \tag{2.9}$$

Now the average one-period cost $\tilde{\phi}$ is defined as the one-period cost under which the expected discounted sum of investment costs is equal to the expected discounted sum of investment costs under the variable one-period cost:

$$\omega = \tilde{\omega}(\tilde{\phi}) \tag{2.10}$$

To equate the values of $\tilde{\phi}$ for all (d, a, b), we want to make sure that for each (d, a, b), there exists $\bar{\phi}$ under which $\tilde{\phi}$ is equal to a given constant. In Proposition A in the Appendix, I show that changes in $\bar{\phi}$ do not change (J, N) and simply lead to proportional changes in $\tilde{\phi}$. Thus, for any given (d, a, b), we can make $\tilde{\phi}$ to be any value by scaling $\bar{\phi}$ up or down: For each (d, a, b), there indeed exists $\bar{\phi}$ under which $\tilde{\phi}$ is equal to a given constant.

With the assumption on $\bar{\phi}$, now we are ready to assess the effect of policy uncertainty on the investment behavior and the capital price. The following proposition characterizes the effect.

Proposition 2. *In the absence of policy uncertainty* (*i.e.*, $d = 1$, $a = 1$, *or* $b = 1$), *the optimal type of project is unique*; *its duration is at least as long as that of any optimal type of project under policy uncertainty* (*i.e.*, $d > 1$, $a < 1$, *and* $b < 1$); *there is no abandonment of projects*; *and*, *fixing* $\tilde{\phi}$, *the equilibrium capital price is at least as low as any equilibrium capital price under policy uncertainty.*

Proof. See the Appendix.

This proposition can be intuitively explained as follows: There will be no policy uncertainty in future one-period costs if $d = 1$ (i.e., the two one-period costs are the same), if $a = 1$ (i.e., the one-period cost is always a low cost), or if $b = 1$ (i.e., the one-period cost never changes). With no negative shock to the cost, no projects will be abandoned. If there is policy uncertainty (i.e., $d > 1$, $a < 1$, and $b < 1$), the one-period cost, which is equal to the low cost at the beginning of the project, may change to a high cost later. Further into the future, the likelihood that the cost will be high increases: The expected one-period cost increases over the age of the project. Therefore, investors can lower the one-period cost by managing a shorter-term project. Thus policy uncertainty makes investors favor shorter-term projects. Further, if the one-period cost of an ongoing project becomes high and if the project is far enough from completion, investors can lower the one-period cost by abandoning the project and starting a new project with a low initial cost (see Proposition 1). Thus, policy uncertainty also makes investors abandon some ongoing projects.[6] Now recall that the average one-period investment cost is held constant in *equilibrium* by adjusting the scale of the possible values. Thus, although each investor considers the shorter-term bias and project abandonment to be a way of saving on the one-period investment cost, there is no such saving in equilibrium. In fact, holding the average one-period cost, the shorter-term bias, and project abandonment can only lead to a lower rate of return: The shorter-term projects yield lower (expected) production of capital per unit cost, and the abandonment of projects increases the expected cost of producing a unit of capital. Under competitive investment, the capital price will then go up to make up for the lower rate of return. Thus, policy uncertainty increases the capital price.

3. LONG-RUN AGGREGATE INVESTMENT AND OUTPUT UNDER POLICY UNCERTAINTY

In this section, I embed the investment environment of Section 2 into a neoclassical aggregate model. As mentioned earlier, the results of this modeling choice accord well with the empirical pattern regarding capital price, investment, and output across income levels. I should, however, note the simplicity of this exercise. First, the effect of policy uncertainty on aggregate investment and output operates through investment behavior only and not through, for example, consumption-good production. Since the "time to build" applies more readily to investment than to consumption-good production, it seems justifiable to abstract from policy uncertainty in consumption-good production. Second, in the model, policy-related investment cost is industry-specific. Since there are many industries, there is no uncertainty at the aggregate level. Thus, the model abstracts from policy uncertainty at the macroeconomic or the firm/project levels. In reality, of course, policy uncertainty is present at all levels and, in principle, it can be modeled at all levels as well but the resulting dynamics would be quite complicated. Modeling policy uncertainty at the industry level rather than at the macroeconomic or the firm/project level is justifiable since the data analysis in Section 4 suggests that a large part of uncertainty is at the industry level (see footnote 11 in Section 4) and since the amount of uncertainty at the firm/project level is difficult to assess given the lack of data at that level. To save on notation, I also abstract from market interaction among many (identical) people. There is a

[6] It is not difficult to find anecdotal evidence for this kind of effect of policy uncertainty. For example, in 1986 in the Kenyan town of Nakuru, the government decided to develop a work space that can house 550 local artisans. After allocating a plot of land and constructing sheds initially on half of the plot, "things were not to proceed as anticipated." The problem was that the artisans could not acquire the title deeds for their individual shares of the plot. Eventually, the "disillusioned artisans departed leaving the plot desolate," vandalism followed, and an "unknown developer" claimed that he had been allocated the plot (Agutu, 1998). It seems plausible that given the uncertainty regarding the title deeds, the artisans would not have made long-term investments (e.g., setting up durable work benches and other tools, acquiring appropriate transport equipment to and from the market and suppliers, hiring workers, and forming partnerships with each other) and instead produced goods on a short-term basis.

single person who manages multiple projects across industries. If I were to model market interaction, it would only complicate notations and would not alter the results since there is no externality in the market version of the model that can be internalized by a single person. (The policy variables are exogenous to the person, so that the distortionary effects of policy uncertainty are of course maintained.)

The main result is that through its effect on capital price, sustained policy uncertainty leads to lower long-run aggregate investment and output. In addition, policy uncertainty increases the ‘‘volatility’’ of industry-level investment, and this result is instrumental in the empirical and quantitative exercises in Sections 4 and 5.

3.1. *The Environment of the Model Economy.* There is one person whose one-period utility is $u(c)$, where c is consumption and u is increasing and concave, and who discounts future utility by the one-period discount rate $\beta < 1$. At each date, the person produces output using his capital, invests a part of the output to produce new capital, and consumes the rest of the output. The output production function is

$$y = k^{\alpha} \tag{3.1}$$

where y is output, k is capital, and $0 < \alpha < 1$. The one-period resource constraint is

$$c + x \leq y \tag{3.2}$$

where x is investment (costs). The capital evolves according to the rule

$$k' = k(1-\delta) + \tilde{k} \tag{3.3}$$

where k' is the next period's capital, δ is the depreciation rate, and $\tilde{k}$ is the new capital. Note that the investment x is not equal to the new capital $\tilde{k}$ given the ‘‘time to build’’ in capital production.

Capital is produced in an investment environment that is identical to that described in Section 2, except for the following two differences: First, I assume that there are many identical industries, indexed by $i \in \{1, 2, \ldots, I\}$, where capital is produced and that the one-period investment cost is industry-specific. Second, the person can manage multiple projects across industries at the same time. As in Section 2, a project of type j requires j consecutive periods of investment and yields $h(j)$ units of new capital in the jth period. The one-period investment cost is ϕ units of output, where ϕ is the one-period cost for a project of size 1 in the industry to which the project belongs. The one-period cost ϕ is composed of 1 unit of technical cost and $\phi - 1$ units of policy-related cost. The possible values of ϕ are ϕ_1 and ϕ_2, and ϕ evolves according to a Markov chain, which is common across industries, and whose transition probabilities are π_1 and π_2.

Let $z(j, n, i)$ denote the number of projects of type j, aged n, in industry i. At each date, the person chooses the numbers of new projects $\{z(j, 0, i)\}$. He also decides whether to continue old projects. Let $\{g(j, n, i)\}$ denote these decisions: If $g(\cdot) = 1$, the project is continued and if $g(\cdot) = 0$, the project is abandoned. The numbers of projects then evolve according to the rule

$$z'(j, n+1, i) = g(j, n, i)z(j, n, i) \tag{3.4}$$

for $n = 0, 1, 2, \ldots, j-2$, and the quantity of new capital is determined by the rule

$$\tilde{k} = \sum_{i=1}^{I} \sum_{j=1}^{\infty} g(j, j-1, i) z(j, j-1, i) h(j) \tag{3.5}$$

Let $\phi(i)$ denote the one-period cost of industry i. The quantity of investment is then determined by the rule

$$x = \sum_{i=1}^{I} \sum_{j=1}^{\infty} \phi(i) z(j, 0, i) + \sum_{i=1}^{I} \sum_{j=1}^{\infty} \sum_{n=1}^{j-1} \phi(i) g(j, n, i) z(j, n, i) \tag{3.6}$$

This completes the description of the environment of the model.

3.2. *Capital Price in Steady State.* In this economy, there is uncertainty at two levels: uncertainty in the one-period cost at the industry level and uncertainty in the aggregate variables $\tilde{k}$, k, y, c, and x. The aggregate uncertainty arises because the share of a cohort of investment projects whose one-period cost changes from one date to the next is not certain and so the investment decision is adjusted to the realizations of these shares. Although aggregate uncertainty is an interesting issue in its own right, for reasons mentioned earlier I will concentrate on industry-level uncertainty and eliminate aggregate uncertainty by fixing these shares by approximation under the assumption that there are a large number of industries. The following two paragraphs lay out the details of the approximation.

I will first rewrite the constraints regarding investment (Equations (3.4)–(3.6)) in terms of projects indexed by current one-period cost instead of indexed by industry. Let $\tilde{z}(j, n, q)$ denote the sum of the numbers of projects across industries that are of type j, aged n, and with the current one-period cost equal to ϕ_q:

$$\tilde{z}(j, n, q) = \sum_{i=1}^{I} e(i, q) z(j, n, i) \tag{3.7}$$

where $e(i, q)$ is an indicator function and is equal to 1 if $\phi(i, q) = \phi_q$ and equal to 0 otherwise. Let $\tilde{g}(j, n, q)$ denote the fraction of the sum $\tilde{z}(j, n, q)$ that is continued:

$$\tilde{g}(j, n, q) = \frac{\sum_{i=1}^{I} e(i, q) g(j, n, i) z(j, n, i)}{\sum_{i=1}^{I} e(i, q) z(j, n, i)} \tag{3.8}$$

Let $\tilde{\pi}(j, n, q)$ denote the fraction of the sum of the continued projects $\tilde{g}(j, n, q)\tilde{z}(j, n, q)$ that face the same cost ϕ_q the next period:

$$\tilde{\pi}(j, n, q) = \frac{\sum_{i=1}^{I} e'(i, q) e(i, q) g(j, n, i) z(j, n, i)}{\sum_{i=1}^{I} e(i, q) g(j, n, i) z(j, n, i)} \tag{3.9}$$

where $e'(\cdot)$ is the indicator function for the next period. From Equations (3.4)–(3.9), we can show that the sums $\{\tilde{z}(\cdot)\}$ evolve according to

$$\tilde{z}'(j, n+1, q) = \tilde{\pi}(j, n, q)\tilde{g}(j, n, q)\tilde{z}(j, n, q) + (1 - \tilde{\pi}(j, n, q'))\tilde{g}(j, n, q')\tilde{z}(j, n, q') \tag{3.10}$$

for $n = 0, 1, 2, \ldots, j-2$, where in each equation $q' = 1$ if $q = 2$, and $q' = 2$ if $q = 1$; the quantity of new capital is determined by

$$\tilde{k} = \sum_{q=1}^{2} \sum_{j=1}^{\infty} \tilde{g}(j, j-1, q)\tilde{z}(j, j-1, q)h(j) \tag{3.11}$$

and the quantity of investment is determined by

$$x = \sum_{q=1}^{2} \sum_{j=1}^{\infty} \phi_q \tilde{z}(j, 0, q) + \sum_{q=1}^{2} \sum_{j=1}^{\infty} \sum_{n=1}^{j-1} \phi_q \tilde{g}(j, n, p)\tilde{z}(j, n, p) \tag{3.12}$$

Equations (3.10)–(3.12) correspond to Equations (3.4)–(3.6); the difference is that they are written in terms of projects indexed by current one-period cost instead of indexed by industry.

The values of the fractions $\{\tilde{\pi}(\cdot)\}$ are not certain and depend on the distribution of continued projects across industries $\{g(\cdot)z(\cdot)\}$ and the realizations of next-period costs across industries. The uncertainty in $\{\tilde{\pi}(\cdot)\}$ implies uncertainty in $\{\tilde{z}'(\cdot)\}$ and therefore uncertainty in future values of x and $\tilde{k}$, and this in turn implies uncertainty in future values of k, y, and c. Since the person's utility is concave, he prefers less uncertainty in the aggregate variables, and for this reason, the number of industries I is important to him. First, if I is larger, the fraction of industries whose one-period cost changes, $\sum_{i=1}^{I} e'(i, q)e(i, q)/\sum_{i=1}^{I} e(i, q)$, is more certain. Second, the person can spread his projects more across industries and thereby decrease the investment in one industry relative to the aggregate investment, $z(\cdot)/x$. For these two reasons, a greater number of industries allows the person to reduce uncertainty in $\{\tilde{\pi}(\cdot)\}$ and thereby in aggregate variables. As the number of industries approaches infinity, the aggregate uncertainty disappears altogether: As $I \to \infty$, $\tilde{\pi}(j, n, q) \to \pi_q$. In order to dispense with aggregate uncertainty, I assume that the number of industries is large enough that the person's decision problem can be considered with the approximations

$$\tilde{\pi}(j, n, q) = \pi_q \tag{3.13}$$

and

$$\tilde{z}'(j, n+1, q) = \pi_q \tilde{g}(j, n, q)\tilde{z}(j, n, q) + (1 - \pi_{q'})\tilde{g}(j, n, q')\tilde{z}(j, n, q') \tag{3.14}$$

With no aggregate uncertainty, the person's decision problem simplifies. At each date, the person takes as given the quantity of capital k and the numbers of various ongoing projects $\{\tilde{z}(j, n, q)\}_{n\geq 1}$. Let the state of the economy, denoted by μ, be the set of these variables: $\mu = \{k\} \cup \{\tilde{z}(j, n, q)\}_{n\geq 1}$. The person's decision problem is to maximize his expected discounted utility by choosing the consumption c, the investment x, the new capital $\tilde{k}$, the numbers of new projects $\{\tilde{z}(j, 0, i)\}$, and whether to continue ongoing projects $\{\tilde{g}(j, n, q)\}_{n\geq 1}$, given the state μ and the constraints (3.1)–(3.3), (3.11), (3.12), and (3.14). In general, the state of the economy will change over time. In particular, given the neoclassical utility and production functions, the state will converge to the steady state, that is, the state that, once arrived at, is maintained throughout all subsequent dates. Since the objective of this article is to assess the effect of uncertainty on long-run investment and output, I will focus on the steady state of the economy.

In the steady state, consumption stays constant so that marginal utility stays constant. Then the person discounts future output by the one-period discount rate β.

The value of a unit of capital is the sum of discounted marginal products that accrue to it. This value is the implicit capital price. In the steady state, capital also stays constant so that marginal product stays constant. We have

$$P=\sum_{t=1}^{\infty}\beta^{t}(1-\delta)^{t-1}\alpha k^{\alpha-1} \tag{3.15}$$

Thus, the capital price stays constant in the steady state. With a constant discount rate and a constant capital price, the investment environment in the steady state is the same as in Section 2, except that here one person manages all projects, whereas in the environment in Section 2 each competitive investor manages one project. Since there are no externality or other distortionary elements in the environment in Section 2 that can be internalized by the person in this section, this difference between the two environments does not affect investment allocation and capital price: Given the model parameter values regarding investment, the projects selected and continued are the same between the two environments, and the implicit capital price here is the same as the equilibrium capital price in Section 2. Thus, the steady-state investment behavior is characterized by an optimal investment rule (J, N)—that is, $\tilde{z}(J,0,1)>0$; $\tilde{z}(j,0,p)=0$ for $j\neq J$ or $q=2$; $\tilde{g}(J,n,1)=1$ for $n=1,2,\ldots,J-1$; $\tilde{g}(J,n,2)=0$ for $n=1,2,\ldots,N-1$—and $\tilde{g}(J,n,2)=1$ for $n=N,N+1,\ldots,J-1$)—and policy uncertainty increases the steady-state capital price.

3.3 *The Effect of Policy Uncertainty on Long-Run Investment and Output.* Now let us consider the effect of policy uncertainty on steady-state investment and output levels. In this economy the effect of policy uncertainty on investment and output operates through the capital price; therefore, it is conveniently described in terms of the effect of policy uncertainty on the capital price. For presentation of the results, it is also convenient to compare two hypothetical countries, denoted by the subscripts s and s'. A caveat should be mentioned here. If the two countries can engage in costless trade, where the country with a higher capital price can buy capital goods and sell consumption goods, a common capital price will prevail and policy uncertainty will have no effect on the investment and output difference between the two countries. Trade of such a type of course takes place in reality but with the costs of shipping goods, tariffs, and other restrictions. Further, there is significant nontradable investment. Aside from the obvious examples such as construction, tradable investment goods usually involve nontradable investment that is less visible: Machinery can be imported but the installation, maintenance, and worker training are local investments. In the following, I roughly assume that there is no cross-country trade.

Let us first see how policy uncertainty affects long-run investment. We can derive from Equations (2.7), (2.8), (3.1), (3.3), (3.11), (3.12), (3.14), and (3.15) that if $P_s<P_{s'}$, $x_s/y_s<x_{s'}/y_{s'}$ in general and for β close to 1,

$$\frac{x_s}{y_s}\cong\frac{x_{s'}}{y_{s'}} \tag{3.16}$$

From this equation, we can see that policy uncertainty has little effect on the investment share of output. However, note that in the model, investment is measured in terms of investment cost. Alternatively, investment can be measured in terms of investment output, that is, capital production.[7] Let us see how policy uncertainty affects long-run investment under this alternative measurement of investment. We can derive from Equations (3.1), (3.3), and (3.15)

$$\frac{P_s \tilde{k}_s}{y_s} = \frac{P_{s'} \tilde{k}_{s'}}{y_{s'}} \tag{3.17}$$

This equation, similar to Equation (3.16), implies that policy uncertainty has no effect on the investment share of output if investment is measured in terms of capital production and if country-specific capital prices are used in the measurement. However, since policy uncertainty increases the capital price, this equation implies that policy uncertainty lowers the real amount of capital production as a share of output. In other words, policy uncertainty lowers the investment share of output if investment is measured in terms of capital production under internationally common prices.

Let us now see how policy uncertainty affects long-run output. We can derive from Equations (3.1) and (3.15)

$$\frac{y_s}{y_{s'}} = \left(\frac{P_{s'}}{P_s}\right)^{\alpha/(1-\alpha)} \tag{3.18}$$

To interpret this equation, policy uncertainty lowers the long-run output level by increasing the capital price and consequently lowering real investment. These effects of policy uncertainty on investment and output levels are consistent with the empirical findings mentioned earlier.

3.4. *Industry Investment Dynamics.* In the steady state, although the aggregate variables stay constant, investment at the industry level fluctuates. When an industry faces a low one-period cost, new projects will be started and the old unfinished projects, if there are any, will be continued in that industry. On the other hand, when an industry faces a high one-period cost, no new projects will be started and some old unfinished projects may be abandoned. To be precise, let $\tilde{x}(i)$ denote the investment in industry i: [8]

[7] These two ways of measuring investment, investment cost versus capital production, are only a conceptual dichotomy, and the investment data would be in practice generated by some intermediate way. For example, Summers and Heston (1993) measure investment using a weighted (across countries) capital price common to all countries. However, some of the capital in their measurement is not final capital: It embodies previous investment but also serves as an input to further investment (e.g., production of machinery is investment, but machinery may be used to construct a production line or a factory). Thus, their way of measurement falls in between the two conceptual extremes.

[8] The industry investment here is defined to be exclusive of policy-related costs unlike the aggregate investment in Equation (3.6). Thus, the aggregate investment, as defined in Equation (3.6), is the sum of industry investments, as defined here, plus the aggregate policy-related costs. (I could also define the aggregate investment to be exclusive of policy-related costs but only at the expense of introducing the aggregate policy-related costs as a separate variable, which would not change the results of the model.) I have defined the industry investment this way because the simulation exercise in Section 5 is much easier to carry out with this definition. Since the simulated investment is matched with the data, it would be conceptually better to use whichever of the two definitions, inclusive versus exclusive of policy-related costs, that is closer to what the data measure, but it is not clear which one is closer: Some regulatory costs would be measured as part of investment, but investment taxes or bribery would not.

$$\tilde{x}(i) = z(J, 0, i) + \sum_{n=1}^{J-1} g(J, n, i) z(J, n, i) \tag{3.19}$$

Recall that the person diversifies investment across industries to minimize aggregate uncertainty. Thus, the number of new projects is the same for all industries. Further, in the steady state the aggregate number of new projects stays constant, and the number of industries with a low one-period cost is constant (under the assumption of many industries). Thus, the number of new projects started in a low-cost industry stays constant over time. Let $\bar{z}$ denote the number of new projects started in a low-cost industry in the steady state, and $\{\hat{\phi}(i,t)\}_{0 \leq t \leq J-1}$ the history of one-period costs, where $\phi(i,t)$ is the cost at t periods ago in industry i. The industry investment $\tilde{x}(i)$ is determined by the numbers of projects $\{z(J,n,i)\}_{0 \geq n \geq J-1}$ and the continuation decisions $\{g(J,n,i)\}_{1 \geq n \geq J-1}$, which are in turn determined by the number of new projects $\bar{z}$, the optimal investment rule (J, N), and the history $\{\hat{\phi}(i,t)\}_{0 \leq t \leq J-1}$ in the following way: For $1 \leq n \leq J-1$, $z(J,n,i) = 0$ if $\hat{\phi}(i,s) = \phi_2$ for any $s \in \{\max(1, n-N+1), \max(1, n-N+1)+1, \ldots, n\}$, and $z(J,n,i) = \bar{z}$ otherwise; $z(J,0,i) = 0$ if $\hat{\phi}(i,0) = \phi_2$ and $z(J,0,i) = \bar{z}$ if $\hat{\phi}(i,0) = \phi_1$; $g(J,n,i) = 0$ if $\hat{\phi}(i,0) = \phi_2$ or if $n < N$, and $g(J,n,i) = 1$ otherwise. In this way, as history $\{\hat{\phi}(i,t)\}_{0 \leq t \leq J-1}$ evolves over time, so does the corresponding industry investment $\tilde{x}(i)$.

Since the evolution of the history $\{\hat{\phi}(i,t)\}_{0 \leq t \leq J-1}$ is governed by the parameters a and b, the industry investment dynamics (i.e., statistics on investment sequence at the industry level) are determined by (J, N, a, b), excluding $\bar{z}$, which determines nothing more than the scale of the investment sequence. Since J and N are in turn determined by the uncertainty parameters (d, a, b), policy uncertainty affects not only the capital price and output, but also the industry investment dynamics. In particular, if there is no uncertainty (i.e., $d = 1$, $a = 1$, or $b = 1$), the industry investment $\tilde{x}(\cdot)$ will be constant over time and equal to $J\bar{z}$. Under uncertainty (i.e., $d > 1$, $a < 1$, and $b < 1$), on the other hand, the industry investment $\tilde{x}(\cdot)$ will fluctuate over time. Thus policy uncertainty makes industry investment "volatile" (the meaning of which will be made precise in Section 4).

4. ANALYSIS OF INDUSTRY INVESTMENT DATA ACROSS COUNTRIES

In the model of Sections 2 and 3, we saw that policy uncertainty decreases the long-run aggregate investment and output, and it also makes the industry-level investment volatile. Then the model implies a negative relationship between the output level and the industry investment volatility across countries, and this can be examined in a set of cross-country investment data. To this end, in this section I investigate the industry-level investment sequences across countries of diverse output levels and find that the investment in lower-income countries is indeed more volatile. Given the scarcity of data for low-income countries and the justifiable doubts on their quality, the quantitative aspect of the finding should be considered with caution. At any rate, the exercise in this section is not meant to be a hard test for the model, but it still provides indirect support for the model.

4.1. *The Data.* The data come from the various issues of the *Industrial Statistics Yearbook* published by the United Nations Industrial Development Organization (UNIDO). The data comprise the annual gross investment for 27 three-digit ISIC manufacturing industries and cover the period from 1967 to 1988 for 16 countries. I chose this period because the data before 1967 are organized by a different industrial classification system and the data after 1988 were not available for most countries. For many developing countries, especially those in sub-Saharan Africa, the data are incomplete, missing for many years and industries. This incompleteness of data limits the number of countries whose data can be used. I selected 16 countries that have reasonably extensive data in terms of both years and industries and that represent various output levels.[9] Table 1 reports the list of 16 countries and the coverage of years and industries for each country. The first column of Table 2 reports the per capita output in 1985 U.S. dollars averaged over the data period from the data set of Summers and Heston (1993).

4.2. *Industry Investment Dynamics in the Data.* The raw investment data are not comparable across years and countries and require some adjustments. First, the measures of investment are in units of the current currencies of the respective countries. To compare investment across years, I converted each measure of investment into U.S. dollars of the respective year using the purchasing power parities of composite capital[10] from Summers and Heston (1993), and then converted the value into 1985 U.S. dollars using the U.S. GDP deflator. Second, the level of investment is different across industries and countries. Also, the investment sequences for some industries in some countries would exhibit long-run growth or contraction. Since the theoretical analysis in this article abstracts from these differences across industries and countries, I eliminated these features of the data in the following way: Let z_{sit} denote the investment of country s, industry i, and year t in the data. Let $\bar{z}_{sit}$ be the trend investment and λ_{sit} the percentage deviation from the trend:

$$z_{sit} = \bar{z}_{sit}(1 + \lambda_{sit}) = \rho_{si}\, \bar{e}^{\sigma_{si}}(1 + \lambda_{sit}) \tag{4.1}$$

The parameters ρ_{si} and σ_{si} are the level and the growth rate of investment for the industry i in country s and are chosen by minimizing the sum of squared deviations over t.

I consider the investment dynamics to be three country-specific statistics defined as follows: Let $\{\lambda_{sit}\}$ be the investment sequence with respect to t holding s and i. For country s, the dispersion statistic $disp_s$ is the average of the standard deviations of the sequences $\{\lambda_{sit}\}$ over i; the persistence statistic $pers_s$ is the average of standard deviations of the first-order differences of the sequences $\{\lambda_{sit}\}$ over i; and the

[9] In Section 3, results were derived for the steady state. By assuming exogenous productivity growth, I can modify the model and derive the same results for balanced growth (i.e., there are no changes in the effect of policy uncertainty on capital price and the levels of investment and output). Thus, the results are of countries in balanced growth whose relative output levels remain constant over time. For this reason, I selected countries whose per capita output growth rates over the period are not exceptionally high or low. The exceptions are Brazil and Korea.

[10] Purchasing power parities of capital for individual industries are not available.

TABLE 1
YEARS AND INDUSTRIES OF AVAILABLE DATA

Country	Years	Industries
Brazil	67–69, 71–74, 76–78, 80	1–6, 8–11, 16–17, 24–26
Canada	67–88	1–17, 19–27
Colombia	67–70, 72–88	1–12, 14, 16, 18–20, 22–27
Denmark	67–88	1–6, 8–13, 17, 20, 23–27
Ecuador	67–88	1–6, 8–14, 16, 20, 23, 25–26
Ethiopia	67, 70–86	1–4, 11, 12
India	77–87	1–17, 19–26
Korea	67–88	1–17, 19–26
Malawi	69–75, 80–86	1–4, 8–10, 12, 20, 23
Philippines	68–75, 77, 79–88	1, 3–6, 8–12, 14, 16–26
Spain	67–76, 79–88	1–2, 4–7, 10–13, 16–20, 22
Sri Lanka	79, 81–86, 88	1–5, 7–10, 12–13, 16–18, 20, 23–26
Tanzania	67–74, 81–85	1–13, 16, 23–24, 26
United Kingdom	70–88	1–27
United States	67–88	1–27
Zimbabwe	73–88	1–5, 7–13, 16–17, 25–26

INDEX OF INDUSTRIES: 1, food products; 2, beverages; 3, tobacco; 4, textiles; 5, wearing apparel; 6, leather and products; 7, footwear; 8, wood products; 9, furniture, fixtures; 10, paper and products; 11, printing, publishing; 12, industrial chemicals; 13, other chemical products; 14, petroleum refineries; 15, petroleum, coal products; 16, rubber products; 17, plastic products; 18, pottery, china, etc.; 19, glass and products; 20, nonmetal products; 21, iron and steel; 22, nonferrous metals; 23, metal products; 24, machinery; 25, electrical machinery; 26, transport equipment; 27, professional goods.

frequency statistic $freq_s$ is the average of the percentages of positive elements in the sequences $\{\lambda_{sit}\}$ over i. Columns 2–4 of Table 2 report these statistics. Figures 1–3 plot $\{disp_s\}$, $\{pers_s\}$, and $\{freq_s\}$ against output level.

We can see the pattern that the investment sequences in low-income countries exhibit greater volatility: greater deviation, less persistence, and lower frequency of above-the-trend investment.[11]

5. QUANTITATIVE ADAPTATION OF THE MODEL ECONOMY

In this section, I assess the extent to which policy uncertainty can account for the observed differences in the long-run capital price, investment, and output across countries. I calibrate the model (i.e., assign uncertainty parameter values to countries of various output levels as well as parameter values that are common across countries) and then derive from these calibrated parameters the cross-country differences in the capital price, investment, and output, which can be accounted for

[11] I also examined the investment dynamics at more aggregate levels, namely at the levels of manufacturing investment as a whole and economy-wide investment. The same patterns of investment dynamics with respect to the output level are observed. Across countries, however, investment at more aggregate levels is much less volatile than at the industry level, indicating that much of the industry-level volatility and the underlying causes are idiosyncratic: At the individual-industry level, the standard deviation (*disp*) averaged across countries is 0.3636, compared to 0.2176 at the manufacturing-industry level and to 0.1453 at the economy-wide level.

TABLE 2
COUNTRY STATISTICS

Country	*pout*	*disp*	*pers*	*freq*	*dist*
Brazil	3093	0.3175	0.3160	0.3394	0.0174
Canada	13,164	0.2730	0.2814	0.3741	0.0085
Colombia	2600	0.4214	0.5415	0.2671	0.0102
Denmark	11,073	0.2620	0.2978	0.3684	0.0235
Ecuador	2573	0.4405	0.5368	0.2096	0.0451
Ethiopia	296	0.4680	0.6323	0.1944	0.0244
India	827	0.3158	0.4444	0.3434	0.0379
Korea	2968	0.4117	0.4858	0.2545	0.0273
Malawi	483	0.4585	0.6291	0.2714	0.0448
Philippines	1604	0.4574	0.5262	0.2656	0.0415
Spain	7085	0.2986	0.3260	0.3063	0.0494
Sri Lanka	2025	0.4274	0.6349	0.3224	0.0841
Tanzania	444	0.4498	0.5520	0.2579	0.0264
United Kingdom	10,029	0.2301	0.2325	0.3782	0.0348
United States	14,681	0.1782	0.1744	0.4175	0.0439
Zimbabwe	1211	0.4076	0.4919	0.3086	0.0343

by differences in policy uncertainty. Since in the model the policy-related cost is meant to capture a broad spectrum of costs, there is no obvious set of data that can be directly mapped to the uncertainty parameter values. As an alternative, I calibrate the model by a simulation method, using the results from the industry data analysis in Section 4: I simulate the industry investment sequences for various model parameter values and select the ones that generate the actual investment dynamics.

As mentioned earlier, this calibration procedure is crude since it implicitly assumes that all industry investment dynamics are due to policy uncertainty of the type modeled here, and ignores the other sources of investment volatility. Presumably, some of the investment volatility would be driven by non-policy-related shocks such as terms-of-trade shocks, technological innovation shocks, and shocks from nature, yet some other by macroeconomic policy uncertainty from which the model in this article abstracts.[12] The procedure adopted here would then lead to mismeasurement of the cross-country differences in policy uncertainty and its effect on investment and output insofar as there is a systematic difference across income levels in the part of investment volatility attributable to these other factors. Thus, the quantitative results of the exercise should be considered as tentative. With this qualification, the exercise suggests that policy uncertainty can account for a large

[12] Note that in the model, policy uncertainty at the industry level can be interpreted to include macroeconomic policy uncertainty insofar as macroeconomic policy uncertainty affects investment and output by making investment cost uncertain. If we were to modify the model to allow residual uncertainty after aggregation (by having a small number of industries) and to fix the interest rate (by having international lending/borrowing), we would have modeled macroeconomic uncertainty and the resulting model-generated investment dynamics would be the same as that of the current model. In this sense, the procedure adopted here measures the effect of policy uncertainty that includes macroeconomic policy uncertainty.

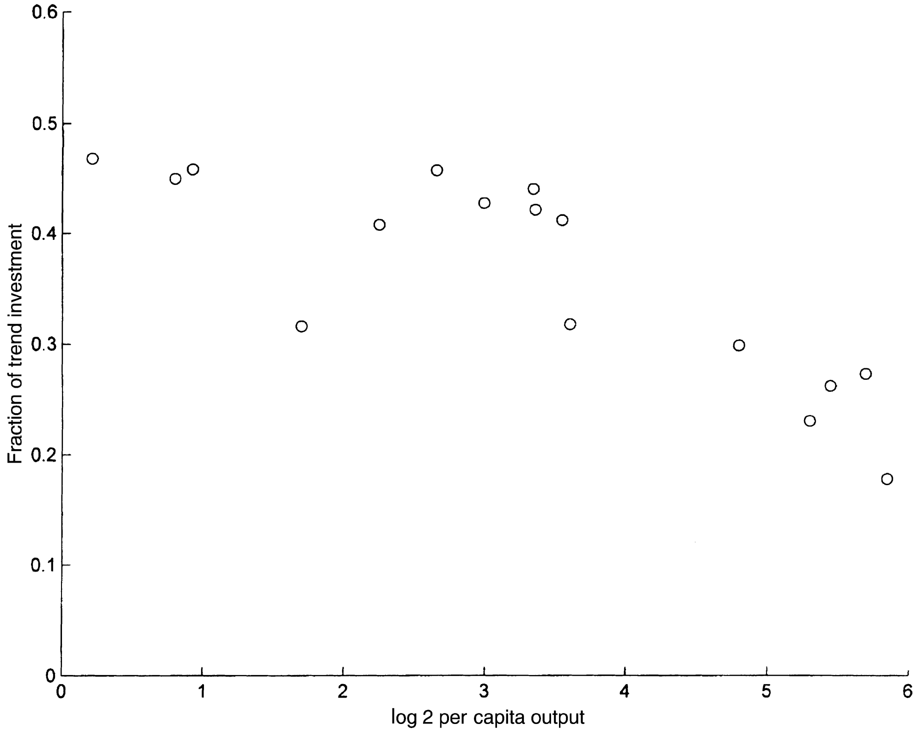

FIGURE 1

DISPERSION OF INVESTMENT (*disp*)

portion of the observed cross-country differences in long-run capital price, investment, and output.

In calibrating the model parameters, the discount parameter β, the capital share parameter α, the depreciation parameter δ, and the capital return function h are assumed to be common to all countries. I consider the length of a period to be a quarter and set $\beta = 0.99$. This implies an annual real interest rate of about 4 percent in the steady state. The parameter α is important in determining the extent to which uncertainty can account for investment and output differences and will be discussed later. The value of parameter δ is inconsequential in terms of the effect of uncertainty on the capital price, investment, and output, and so I do not assign any particular value to it. The uncertainty parameters d, a, and b are country-specific. In the following three subsections I will explain the procedure that I used to derive these parameter values across countries as well as the capital return function h.

5.1. *Summarizing the Patterns of Investment Dynamics.* I first summarized the patterns of investment dynamics with respect to the output level in the data by a line $\bar{l}$ in the space of *disp*, *pers*, and *freq*. Let s denote the country, and $\{\eta_s\} = \{(disp_s, pers_s, freq_s)\}$, $s = 1, 2, \ldots, 16$, the investment dynamics found in the data. We

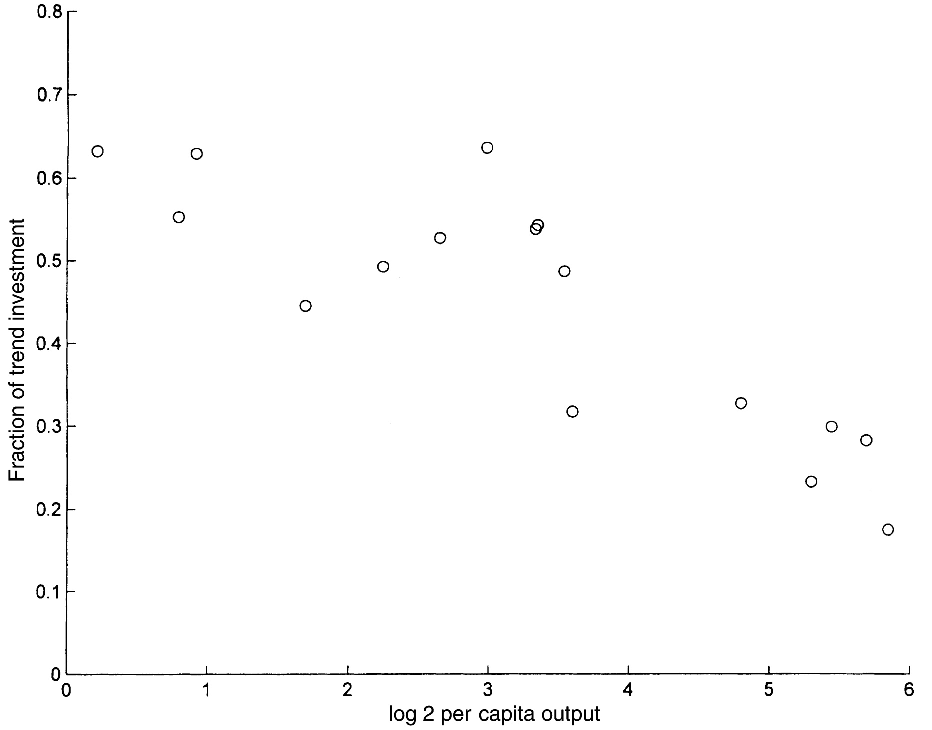

FIGURE 2

PERSISTENCE OF INVESTMENT (*pers*)

can think of each η_s as a point in the space where the axes are *disp*, *pers*, and *freq*. Let $l = l(\gamma_1, \gamma_2, \gamma_3, \gamma_4)$ denote a line in that space:

$$pers = \gamma_1 + \gamma_2 \times disp \quad \text{and} \quad freq = \gamma_3 + \gamma_4 \times disp \tag{5.1}$$

Given a line l, the distance between two points $\eta = (disp, pers, freq)$ and $\eta' = (disp', pers', freq')$ in the space is defined as

$$\Delta(\eta, \eta'; l) = \left[(disp - disp')^2 + \left(\frac{pers - pers'}{\gamma_2} \right)^2 + \left(\frac{freq - freq'}{\gamma_4} \right)^2 \right]^{1/2} \tag{5.2}$$

The distance between a point $\eta = (disp, pers, freq)$ and a line $l = (\gamma_1, \gamma_2, \gamma_3, \gamma_4)$ is defined as

$$\Delta(\eta, l) = \min\{\Delta(\eta, \eta'; l) : \eta' \in l\} \tag{5.3}$$

The line that represents the relationships among the three variables in the data is defined as

$$\bar{l} = \arg\min \left\{ \sum_{s=1}^{16} \Delta(\eta_s, l)^2 \right\} \tag{5.4}$$

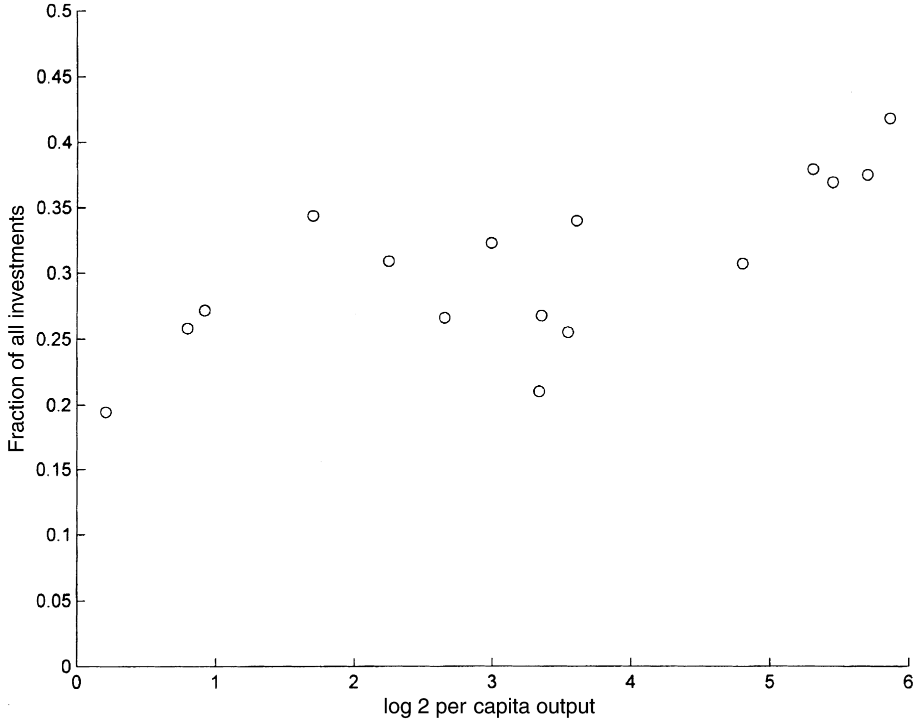

FIGURE 3

FREQUENCY OF HIGH INVESTMENT (*freq*)

In this way I derived $\bar{l}=(-0.2882, 2.0135, 0.6204, -0.8677)$. Column 5 of Table 2 reports the distances between the line and each of the country points $\{\eta_s\}$. The distances are relatively small, indicating that the line $\bar{l}$ is a good summary of the patterns of investment dynamics in the data.

5.2. *Selecting* $\{(J_s, N_s, a_s, b_s)\}$. Next, I simulated investment sequences for various values of the optimal investment rule (J, N) and transition probabilities, a and b, and selected ones that are "close" to $\bar{l}$. The segment of the line $\bar{l}$ that is relevant to the data is from about the point where $disp=0.2$ to the point where $disp=0.5$. The first point roughly corresponds to the United States, and the latter to Ethiopia. To simplify the analysis, I selected seven points on this segment as the "target" points to be simulated. They are the points where $disp=0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.50$. Let these points be denoted by $\{\bar{\eta}_s\}$, $s=1,2,\ldots,7$. What we need to find is the set of uncertainty parameter values $\{(d_s, a_s, b_s)\}$, $s=1,2,\ldots,7$, and the function h that generate investment dynamics "close" to $\{\bar{\eta}_s\}$. There is no guarantee that there are such parameter values and such a function. On the other hand, there may be many sets of such parameter values and functions.

The details of the simulation method that I used are as follows: Recall from Section 3.3 that the variables of direct importance for simulation are (J, N, a, b): Although the values of the parameter d and the function h affect J and N, we do not need to know them for the purpose of simulation. I selected some candidate values of J, N, a and b. They are $J, N = 1, 2, \ldots, 28$, $a = 0.1, 0.2, 0.3, \ldots, 0.9$, and $b = 0, 0.1, 0.2, \ldots, 0.9$. For each combination of (J, N, a, b), I set the initial investment at zero and simulated 2876 periods of investment sequence. Then I discarded the first 500 elements of the sequence, leaving 2376 periods of the investment sequence. Since we consider the length of a period for the model to be a quarter and the data are annual, I annualized the simulated sequence by summing up each of four consecutive periods' investments, resulting in 594 years of the investment sequence. Then I divided the sequence into 27 22-year sequences, in accordance with the number of industries and the length of the sequences in the data. I calculated the investment dynamics for the simulated sequences the same way as I did for the data: I calculated $(disp, pers, freq)$ for each of the 27 sequences and then averaged them over the sequences. This average is an estimate of the expected point in the space of *disp*, *pers*, and *freq* for the relevant combination of (J, N, a, b).

For each combination of (J, N, a, b), I calculated the distance between the point derived by simulation and each of the seven target points $\{\bar{\eta}_s\}$ on line $\bar{l}$. Now the question is how small should the distance be in order to decide that a combination simulates a target point. One reasonable standard is that the distance should not be much larger than the average distance between the line $\bar{l}$ and the country points $\{\eta_s\}$, which is 0.0346. For each target point, I found many combinations that simulate it by this standard. Due to the computational burden, however, I did not carry all successful combinations to the next step of analysis: For each target point, I ranked the combinations in the order of increasing distance and selected about the first ten. By permutating these selected combinations across target points, I derived multiple sets of combinations $\{(J_s, N_s, a_s, b_s)\}$, $s = 1, 2, \ldots, 7$, that simulate the target points.

5.3. *Deriving* $\{d_s\}$ *and* h. Finally, I derived $\{d_s\}$, $s = 1, 2, \ldots, 7$, and function h that are consistent with each selected set of combinations $\{(J_s, N_s, a_s, b_s)\}$: I derived $\{d_s\}$ and h so that for each s, (J_s, N_s) is the optimal investment rule given (d_s, a_s, b_s) and h. We can show that given a and b, if J and N are the optimal investment rules, there is a range where d must belong, and that this range is independent of h. I discretized d by setting its values to be $1.1, 1.2, 1.3, \ldots$. For each selected combination (J_s, N_s, a_s, b_s), I numerically derived the range of d and took the lowest value of the range to be d_s that is consistent with the combination. Now we have sets of combinations $\{(J_s, N_s, d_s, a_s, b_s)\}$, $s = 1, 2, \ldots, 7$, where the elements of each combination are consistent with each other.

Now we need to derive for each set of combinations $\{(J_s, N_s, d_s, a_s, b_s)\}$ a function h that is consistent with the set. Given d_s, a_s, b_s, and some function h, for J_s to be optimal, it must be that $v(J_s, 0, 1) = 0$ and $v(j, 0, 1) \leq 0$ for all j (see Equations (2.4) and (2.5)). Using Equations (2.1)–(2.5), we can rewrite the first condition as

$$P_s h(J_s) = \psi_s(J_s) \tag{5.5}$$

and the second condition as

$$P_s h(j) \leq \psi_s(j) \tag{5.6}$$

for all j where P_s is the capital price for country s and $\psi_s(\cdot)$ is an expression implicitly defined by these conditions. The capital price P_s is absent in the expression $\psi_s(\cdot)$. From conditions (5.5) and (5.6), we have

$$\frac{h(J_s)}{h(j)} \geq \frac{\psi_s(j)}{\psi_s(J_s)} \tag{5.7}$$

If the function h satisfies this condition, conditions (5.5) and (5.6) will be satisfied under the capital price P_s that solves condition (5.5), and therefore J_s will be optimal. Now for a function h to be consistent with the set $\{(J_s, N_s, d_s, a_s, b_s)\}$, condition (5.7) should be satisfied for all $s = 1, 2, \ldots, 7$. In particular, we have

$$\frac{\psi_s(J_u)}{\psi_s(J_s)} \leq \frac{h(J_s)}{h(J_u)} \leq \frac{\psi_u(J_u)}{\psi_u(J_s)} \tag{5.8}$$

for any $s, u = 1, 2, \ldots, 7$. This condition is sufficient, as well as necessary, for function h to be consistent with the set in the sense that we can simply assume that $h(j)$ is small enough to satisfy condition (5.7) for all $j \notin \{J_s\}$.

There is no guarantee that there is a function h that satisfies condition (5.8) but, if there is such a function, there will be in general many of them. For our purposes, we do not need to characterize these functions completely. Using condition (5.8), we can derive the ranges of factor differences among $\{h(J_s)\}$ and from these differences and using condition (5.5) and Equation (3.16), we can derive the ranges of factor differences in the capital price and output across countries that are consistent with the set $\{(J_s, N_s, d_s, a_s, b_s)\}$. A majority of the selected sets $\{(J_s, N_s, d_s, a_s, b_s)\}$ had no function h satisfying condition (5.8) and therefore were discarded. For each of the selected sets that had such function h, I derived the ranges of factor differences in the capital price and output across countries.

5.4. *Findings and Interpretations.* The exercise in Sections 5.1–5.3 suggests that differences in policy uncertainty across countries can substantially account for capital price differences. Between the lowest-income and the highest-income countries, the difference in policy uncertainty can account for a capital price difference by a factor of about 3, which is comparable to the reported price difference in Summers and Heston (1993). This result, however, is a somewhat rough generalization: There are many sets of parameter values $\{(J_s, N_s, d_s, a_s, b_s)\}$ and many capital return functions h that are consistent with the model and the data and that lead to different estimates of the effect of uncertainty on capital price. At one end, there are parameter values and functions that lead to the capital price difference between the lowest-income and the highest-income countries by a factor of less than 2. The top half of Table 3 illustrates one such case: Normalizing the capital price for a country with its *disp* equal to 0.2 (roughly equivalent to the United States) to be 1, the capital price is 1.06 for a country with its *disp* equal to 0.3 (roughly equivalent to Spain), 1.19 for a country with its *disp* equal to 0.4 (roughly equivalent to Colombia), and 1.72 for a country with its *disp* equal to 0.5 (roughly equivalent to Ethiopia). At the other end, there are

Table 3

illustrations of cross-country differences

disp	*d*	*a*	*b*	*J*	*N*	*dist*	*P*
Illustration 1							
0.20	1.9	0.8	0.3	20	2	0.0084	1.00
0.25	2.3	0.7	0.1	14	2	0.0087	1.03
0.30	1.9	0.7	0.3	10	2	0.0212	1.06
0.35	2.7	0.6	0.1	7	2	0.0421	1.12
0.40	2.7	0.6	0.0	5	2	0.0412	1.19
0.45	2.5	0.5	0.2	3	2	0.0376	1.41
0.50	3.0	0.3	0.3	2	2	0.0045	1.72
Illustration 2							
0.20	1.1	0.7	0.6	20	1	0.0093	1.00
0.25	2.3	0.7	0.1	14	2	0.0087	1.10
0.30	1.9	0.7	0.3	10	2	0.0212	1.14
0.35	2.2	0.6	0.2	9	2	0.0428	1.16
0.40	4.6	0.7	0.0	7	3	0.0429	1.82
0.45	5.6	0.6	0.0	6	3	0.0361	2.00
0.50	8.1	0.4	0.1	3	3	0.0060	4.17

parameter values and functions that lead to the capital price difference between the lowest-income and the highest-income countries by a factor of more than 4. The bottom half of Table 3 illustrates one such case: They imply the corresponding numbers to be 1.16, 2.00, and 4.17, respectively. These are, however, extreme cases, and most of the cases lead to a capital price difference between the lowest-income and the highest-income countries that is of a factor between 2 and 4, the average being about 3.

With respect to the cross-country investment differences, the above result on the capital price implies that between the lowest-income and the highest-income countries, policy uncertainty can account for their difference in the investment share of output, when investment is measured in units of investment output (i.e., capital production), by a factor of about 3 as well (see Equation (3.17)). With respect to the cross-country output differences, the result depends not only on the capital price differences due to policy uncertainty, but also on the capital share parameter α in the production function (see Equation (3.18)). A value used widely in the literature is 1/3, based on the share of physical capital income in national accounts. Assuming this value, the capital price difference of a factor of 3 between the lowest-income and the highest-income countries translates to an output difference of a factor of 1.7. However, if we include in capital not only physical capital but also other types such as human, organizational, and technological capital, the capital share is about 2/3 (see Mankiew et al., 1992; Parente and Prescott, 1994; Chari et al., 1997). If we make a rough assumption that in each country the investment environment for these other types of capital is the same as that for physical capital, policy uncertainty can account for output difference of a factor of 9 between the lowest-income and the highest-income countries. Thus, the result is sensitive to the assumed value of the capital share parameter α.

Nonetheless, these calculations suggest that policy uncertainty in the investment environment is an important factor in accounting for the observed output differences across countries, and it seems reasonable to say that policy uncertainty can account for output difference by a factor of about 2 between the lowest-income and the highest-income countries.

6. CONCLUSION

In this article, I explored one reason why policy uncertainty may negatively affect long-run investment and output. I presented a model economy where policy uncertainty causes investors to favor shorter-term projects and abandon some unfinished projects under negative shocks. Holding the investment-weighted average one-period investment cost, this leads to a higher capital price and consequently to lower levels of long-run aggregate investment and output. The implication of the model in terms of the relations among long-run capital price, investment, and output is consistent with the empirical pattern. In the model, policy uncertainty also makes industry-level investment more volatile. I investigated the industry-level investment in a sample of countries with diverse output levels and found that, consistent with the model, the investment in the lower-income countries is more volatile.

I also assessed the quantitative importance of policy uncertainty in accounting for cross-country differences in capital price and long-run investment and output. I calibrated the model by a simulation method and found that policy uncertainty can account for large differences in the long-run capital price, investment, and output across countries. Between the lowest-income and the highest-income countries, policy uncertainty can account for the difference in capital price and the investment share of output (under common international prices) by a factor of about 3, and the output level difference by a factor of about 2. The quantitative results, however, should be considered as suggestive since the exercise crudely assumes that all investment dynamics in the data are due to policy uncertainty of the type modeled in the article.

APPENDIX

PROOF OF PROPOSITION 1. The proof is based on the following two Lemmas.

LEMMA 1. *The investor prefers to manage a project with the low cost: For all* $j \in \{1, 2, \ldots\}$ *and all* $n \in \{0, 1, \ldots, j-1\}$, $v(j, n, 1) > v(j, n, 2)$.

PROOF OF LEMMA 1. For any given j, Equation (2.2) implies that $v(j, j-1, 1) > v(j, j-1, 2)$. This condition and Equation (2.3) imply that $\tilde{v}(j, j-1, 1) \geq \tilde{v}(j, j-1, 2)$. This condition and Equation (2.1) imply that $v(j, j-2, 1) > v(j, j-2, 2)$ since $\pi_1 > 1 - \pi_2$ by assumption. This condition and Equation (2.3) imply that $\tilde{v}(j, j-2, 1) > \tilde{v}(j, j-2, 2)$. By repeating these steps (i.e., using the established condition and Equations (2.1) and (2.3) in turns), we have $v(j, n, 1) > v(j, n, 2)$ for all $n \in \{0, 1, \ldots, j-1\}$. ■

LEMMA 2. *The investor prefers to manage an older project: For all* $j \in \{1, 2, \ldots\}$, *all* $n \in \{0, 1, \ldots, j-2\}$, *and* $q = 1, 2$, $v(j, n, q) \leq v(j, n+1, q)$, *and if* $v(j, n, q) \geq \xi$ *in addition*, $v(j, n, q) < v(j, n+1, q)$.

PROOF OF LEMMA 2. For any given j and $q = 1, 2$, Equations (2.2)–(2.4) imply that $\tilde{v}(j, j-1, q) = \max\{Ph(j) - \phi_q - \xi, 0\} < Ph(j)$. This condition and Equations (2.1) and (2.2) imply that $v(j, j-2, q) < -\phi_q + \beta Ph(j) < v(j, j-1, q)$. This condition and Equation (2.3) imply that $\tilde{v}(j, j-2, q) \leq \tilde{v}(j, j-1, q)$. This condition and Equation (2.1) imply that $v(j, j-3, q) \leq v(j, j-2, , q)$. This condition and Equation (2.3) imply that $\tilde{v}(j, j-3, q) \leq \tilde{v}(j, j-2, q)$. By repeating these steps (i.e., using the established inequality and Equations (2.1) and (2.3) in turns), we have $v(j, n, q) \leq v(j, n+1, q)$ and $\tilde{v}(j, n, q) \leq \tilde{v}(j, n+1, q)$ for all $n \in \{0, 1, \ldots, j-2\}$. Now suppose $v(j, n, q) \geq \xi$ for some $n \in \{0, 1, \ldots, j-3\}$ and some $q \in \{1, 2\}$. Then for all $m \in \{n, n+1, \ldots, j-1\}$, we have $v(j, m, q) \geq \xi$ and thus $\tilde{v}(j, m, q) = v(j, m, q) - \xi$. Then for all $m \in \{n, , n+1, \ldots, j-3\}$, we have $v(j, m, q) - v(j, m+1, q) = \pi_q \beta(\tilde{v}(j, m+1, q) - \tilde{v}(j, m+2, q)) + (1 - \pi_q)\beta(\tilde{v}(j, m+1, q') - \tilde{v}(j, m+2, q')) \leq \pi_q \beta(\tilde{v}(j, m+1, q) - \tilde{v}(j, m+2, q)) = \pi_q \beta(v(j, m+1, q) - v(j, m+2, q))$, where $q' = 1$ if $q = 2$, and $q' = 2$ if $q = 1$. Then we have $v(j, n, q) - v(j, n+1, q) \leq \pi_q \beta(v(j, n+1, q) - v(j, n+2, q)) \leq (\pi_q \beta)^2 (v(j, n+2, q) - v(j, n+3, q)) \leq \cdots \leq (\pi_q \beta)^{j-n-2} (v(j, j-2, q) - v(j, j-1, q))$. Since $v(j, j-2, q) < v(j, j-1, q)$, we have $v(j, n, q) < v(j, n+1, q)$. ■

PROOF OF PROPOSITION 1 (CONTINUED). Now from Lemma 1, we have $v(j, 0, 1) > v(j, 0, 2)$, and thus it is not optimal to start any project with the high cost: A project, if started, must have the low cost. Let $J = \arg\max_j\{v(j, 0, 1)\}$. There is such finite J given the assumption about h in Section 2 (see Proposition 2). However, J may not be unique. Fix J for the following: Since $\max_{j,q}\{v(j, 0, q)\} \geq 0$ by assumption, we have $v(J, 0, 1) = \max_{j,q}\{v(j, 0, q)\} \geq 0$ and, from Equation (2.4), $\xi = v(J, 0, 1)$. Thus, it is optimal to start a project of type J and with the low cost. Also, from Lemma 2, we have $v(J, n, 1) > 0$ for all $n \geq 1$, and thus the unique optimal rule on continuing/abandoning the project under the low cost is to continue the project at all ages. It also follows from Lemma 2 that there is a unique M such that $v(J, n, 2) < \xi$ for $n < M$, $v(J, n, 2) \geq \xi$ for $n = M$, and $v(J, n, 2) > \xi$ for $n \geq M$. Then, if $v(J, M, 2) > \xi$, the unique optimal rule on continuing/abandoning the project under the high cost is to abandon the project if it is younger than M, and to continue the project if it is older than or as old as M. If $v(J, M, 2) = \xi$, there are only two optimal rules on continuing/abandoning the project under the high cost: One is the same as if $v(J, M, 2) > \xi$, and the other is the same as if $v(J, M, 2) > \xi$ except that the cutoff age is $M + 1$. Thus any optimal rule on continuing/abandoning the project under the high cost is characterized by a cutoff age N, where $N = M$ or $N = M + 1$. ■

PROPOSITION A. *For any given* (d, a, b), $\bar{\phi}$, *and* $\bar{\phi}'$, *let* P *and* (J, N) *be any equilibrium associated with* $\bar{\phi}$, *and* $\tilde{\phi}$ *the corresponding average one-period cost. Let* $P' \equiv (\bar{\phi}'/\bar{\phi})P$ *and* $\tilde{\phi}' \equiv (\bar{\phi}'/\bar{\phi})\tilde{\phi}$. *Then* P' *and* $\tilde{\phi}'$ *are an equilibrium associated with* $\bar{\phi}'$, *and* $\tilde{\phi}'$ *is the corresponding average one-period cost.*

Proof of Proposition A. Let variables and functions without prime be associated with $\bar{\phi}$, and those with prime associated with $\bar{\phi}'$. That P and (J, N) are an equilibrium under $\bar{\phi}$ means that under P, $v(J, 0, 1) \geq v(j, 0, 1)$ for all j; $v(J, n, 2) \geq \xi$ for all $n \geq N$; $v(J, n, 2) < \xi$ for all $n < N$; and $v(J, 0, 1) = \xi = 0$. Let $\theta \equiv \bar{\phi}'/\bar{\phi}$. Consider the investor's problem under $\bar{\phi}'$ and P'. From the definitions of $\bar{\phi}$ and d (Section 2.2), we have $\phi_1' = \theta\phi_1$ and $\phi_2' = \theta\phi_2$. Then, for any given j and $q = 1, 2$, we have $v'(j, j-1, q) = \theta v(j, j-1, q)$ from Equation (2.2). Then, assuming $\xi' = 0$ for the moment, we have $\tilde{v}'(j, j-1, q) = \theta\tilde{v}(j, j-1, q)$ from Equation (2.3). Then, we have $v'(j, j-2, q) = \theta v(j, j-2, q)$ from Equation (2.1), and thus $\tilde{v}'(j, j-2, q) = \theta\tilde{v}(j, j-2, q)$ from Equation (2.3). By repeating these steps (using the established condition and Equations (2.1) and (2.3) in turns), we have $v'(j, n, q) = \theta v(j, n, q)$ for all j, n, and q. Then, we have $v'(J, 0, 1) \geq v'(j, 0, 1)$ for all j; $v'(J, n, 2) \geq \xi'$ for all $n \geq N$; $v'(J, n, 2) < \xi'$ for all $n < N$; and $v'(J, 0, 1) = \xi' = 0$. Thus, P' and (J, N) are an equilibrium under $\bar{\phi}'$. Now, since $\phi_1' = \theta\phi_1$ and $\phi_2' = \theta\phi_2$, we have $\phi'(t) = \theta\phi(t)$ from the definition of $\phi(t)$ (Section 2.3). Then it is straightforward from Equations (2.8)–(2.10) that $\tilde{\phi}'$ is the average one-period cost under $\bar{\phi}'$. ∎

Proof of Proposition 2. Consider the investment environment under $d = 1$. We have $\phi_1 = \phi_2$ from the definitions of d (Section 2.2). Then, it is straightforward from Equations (2.1)–(2.3) that $v(j, n, 1) = v(j, n, 2)$ for all j and n. Since $v(J, n, 1) \geq \xi$ for all n (see Proposition 1), we then have $v(J, n, 2) \geq \xi$. Then, we have $N = 1$: There is no abandonment of projects. Then, we have, from Equations (2.5) and (2.7),

$$v(J, 0, 1) = -\sum_{n=0}^{J-1} \beta^n \phi_1 + \beta^{J-1} Ph(J) = 0 \tag{A.1}$$

in equilibrium. To see that the equilibrium optimal type J is unique, we can rewrite this equation as $v(J, 0, 1) = \sum_{n=0}^{J-1}\beta^n((\beta^{J-1}h(J)/\sum_{n=0}^{J-1}\beta^n) - \phi_1/P) = 0$. The optimal type J must solve $\max_j\{\beta^{J-1}h(J)/\sum_{n=0}^{J-1}\beta^n\}$: If not, there is j such that $v(j, 0, 1) > v(J, 0, 1)$. Since there is a unique solution to this maximization problem by assumption (Section 2), the equilibrium optimal type J is unique. Now, consider the investment environment under $a = 1$ or $b = 1$. We have, from the definitions of a, b, and $\phi(t)$ (Sections 2.2 and 2.3), $\pi_1 = \phi(t) = 1$ for all t. Then, the one-period cost never changes from ϕ_1 to ϕ_2, and thus there is no abandonment of projects. We also have, from Equations (2.5) and (2.7), $v(J, 0, 1) = \sum_{n=0}^{J-1}\beta^n\phi_1 + \beta^{J-1}Ph(J) = 0$ in equilibrium. This equation is identical to Equation (A.1). Then, following the same reasoning, we can see that the equilibrium optimal type J is unique and identical to that under $d = 1$.

Now, let variables or functions without prime be associated with no uncertainty ((d, a, b) where $d = 1$, $a = 1$, or $b = 1$), and those with prime be associated with uncertainty (any given (d, a, b) where $d \neq 1$, $a \neq 1$, and $b \neq 1$). To show that $J \geq J'$, suppose $J < J'$ to the contrary. We have seen above that $v(J, 0, 1) = -\sum_{n=0}^{J-1}\beta^n\phi_1 + \beta^{J-1}Ph(J) = 0$ in equilibrium. Since J is unique, we have $v(J, 0, 1) > v(J', 0, 1) \geq -\sum_{n=0}^{J'-1}\beta^n\phi_1 + \beta^{J'-1}Ph(J')$. From these two conditions, we have

$$(\text{A.2}) \qquad (\beta^{J-1}h(J))/(\beta^{J'-1}h(J')) > \left(\sum_{n=0}^{J-1}\beta^n\right)\bigg/\left(\sum_{n=0}^{J'-1}\beta^n\right)$$

We also have in equilibrium $v'(J',0,1) = -\sum_{n=0}^{N'-1}\beta^n\pi_1'^n\phi_1' - \sum_{n=N'}^{J'-1}\beta^n\pi_1'^{N'-1}\ \phi'(n-N'+1) + \beta^{J'-1}\pi_1'^{N'-1}P'h(J') = 0$ and, for any $m \in \{1, 2, \ldots, J\}$, $0 \geq v'(J,0,1) \geq -\sum_{n=0}^{m-1}\beta^n\pi_1'^n\phi_1' - \sum_{n=m}^{J-1}\beta^n\pi_1'^{m-1}\phi'(n-m+1) + \beta^{J-1}\pi_1'^{m-1}P'h(J)$. From these two conditions, we have, for any $m \in \{1, 2, \ldots, J\}$,

$$(\text{A.3}) \qquad (\beta^{J-1}h(J))/(\beta^{J'-1}h(J')) < \left(\sum_{n=0}^{m-1}\beta^n\pi_1'^{n-m+1}\phi_1' + \sum_{n=m}^{J-1}\beta^n\phi'(n-m+1)\right)\bigg/\left(\sum_{n=0}^{N'-1}\beta^n\pi_1'^{n-N'+1}\phi_1' + \sum_{n=N'}^{J'-1}\beta^n\phi'(n-N'+1)\right)$$

From conditions (A.2) and (A.3), we can derive

$$(\text{A.4}) \qquad \left(\sum_{n=0}^{N'-1}\beta^n\pi_1'^{n+1-N'}\phi_1' + \sum_{n=N'}^{J'-1}\beta^n\phi'(n-N'+1)\right)\bigg/\sum_{n=0}^{J'-1}\beta^n < \left(\sum_{n=0}^{m-1}\beta^n\pi_1'^{n-m+1}\phi_1' + \sum_{n=m}^{J-1}\beta^n\phi'(n-m+1)\right)\bigg/\sum_{n=0}^{J-1}\beta^n$$

The left-hand side of condition (A.4) is the average of the elements of the sequence $(\pi_1'^{1-N'}, \pi_1'^{2-N'}, \ldots, \pi_1', 1, \phi'(1), \phi'(2), \ldots, \phi'(J'-N'))$ weighted by the weights $(1/\sum_{n=0}^{J'-1}\beta^n, \beta/\sum_{n=0}^{J'-1}\beta^n, \beta^2/\sum_{n=0}^{J'-1}\beta^n, \ldots, \beta^{J'-1}/\sum_{n=0}^{J'-1}\beta^n)$, and the right-hand side of condition (A.4) is the average of the elements of the sequence $(\pi_1'^{1-m}, \pi_1'^{2-m}, \ldots, \pi_1', 1, \phi'(1), \phi('2), \ldots, \phi'(J-m))$ weighted by the weights $(1/\sum_{n=0}^{J-1}\beta^n, \beta/\sum_{n=0}^{J-1}\beta^n, \beta^2/\sum_{n=0}^{J-1}\beta^n, \ldots, \beta^{J-1}/\sum_{n=0}^{J-1}\beta^n)$. Comparison of the two sequences, for the two sides of condition (A.4), shows that the two sequences are an identical expansion from element 1 although possibly with different lengths in either directions, and that for the both sequences the elements are ordered in decreasing order up to element 1 and then in the increasing order thereafter. Since $J < J'$, these characteristics of the two sequences imply that by choosing an appropriate m we can choose the sequence for the right-hand side to be equivalent to a (middle) chunk of the sequence for the left-hand side with the property that any element of the sequence for the right-hand side is smaller than or equal to any element of the sequence for the left-hand side not belonging to that chunk. Let M be such an appropriately chosen m, and let us consider condition (A.4) given M. The sequence for the left-hand side can then be broken into (up to) three subsequences. The first subsequence is $(\pi_1'^{1-N'}, \pi_1'^{2-N'}, \ldots, \pi_1'^{N'-M})$; the middle sequence is $(\pi_1'^{1-M}, \pi_1'^{2-M}, \ldots, \pi_1', 1, \phi'(1), \phi'(2), \ldots, \phi'(J-M))$, which is equivalent to the sequence for the right-hand side; and the last sequence is $(\phi'(J+1-M), \phi'(J+2-M), \ldots, \phi'(J'-N'))$. Let Γ_1 denote the average of the elements for the first subsequence weighted by the weights $(1/\sum_{n=0}^{N'-M-1}\beta^n, \beta/\sum_{n=0}^{N'-M-1}\beta^n, \beta^2/\sum_{n=0}^{N'-M-1}\beta^n, \ldots, \beta^{N'-M-1}/$

$\sum_{n=0}^{N'-M-1}\beta^n$); Γ_2 the average of the elements for the middle subsequence weighted by the same weights as for the sequence for the right-hand side, which makes Γ_2 equivalent to the right-hand side; and Γ_3 the average of the elements for the last subsequence weighted by the weights $(1/\sum_{n=0}^{J'-J-N'+M-1}\beta^n, \beta/\sum_{n=0}^{J'-J-N'+M-1}\beta^n, \beta^2/\sum_{n=0}^{J'-J-N'+M-1}\beta^n, \ldots, \beta^{J'-J-N'+M-1}/\sum_{n=0}^{J'-J-N'+M-1}\beta^n)$. Since any element of the middle subsequence is smaller than or equal to any element for the first or the last subsequences, we have $\Gamma_2 \leq \Gamma_1$ and $\Gamma_2 \leq \Gamma_3$. Further, we can show that the left-hand side is equivalent to the average of $(\Gamma_1, \Gamma_2, \Gamma_3)$ weighted by the weights $(\sum_{n=0}^{N'-M-1}\beta^n/\sum_{n=0}^{J'-1}\beta^n, \sum_{n=N'-M}^{J+N'-M-1}\beta^n/\sum_{n=0}^{J'-1}\beta^n, \sum_{n=J+N'-M}^{J'-1}\beta^n/\sum_{n=0}^{J'-1}\beta^n)$. Then, the left-hand side is greater than or equal to Γ_2, which is equivalent to the right-hand side. Therefore, we have shown that for some m, condition (A.4) is violated. From this contradiction, we conclude that $J \geq J'$.

Now let the average one-period cost $\tilde{\phi}$ be given. Under no uncertainty, $\phi_1 = \tilde{\phi}$ from Equations (2.7)–(2.10) and condition (A.1). Then, we have $0 \geq v(J', 0, 1) \geq -\sum_{n=0}^{J'-1}\beta^n\phi_1 + \beta^{J'-1}Ph(J') = -\sum_{n=0}^{J'-1}\beta^n\tilde{\phi} + \beta^{J'-1}Ph(J)$ in equilibrium, which implies

$$P \leq \sum_{n=0}^{J'-1}\beta^n\tilde{\phi}/(\beta^{J'-1}h(J')) \tag{A.5}$$

From Equations (2.7)–(2.10), we also have $v'(J', 0, 1) = -\sum_{n=0}^{N'-1}\beta^n\pi'^n_1\phi'_1 - \sum_{n=N'}^{J'-1}\beta^n\pi'^{N'-1}_1\phi'(n - N'+1) + \beta^{J'-1}\pi'^{N'-1}_1P'h(J') = -\sum_{n=0}^{N'-1}\beta^n\pi'^n_1\tilde{\phi} - \sum_{n=N'}^{J'-1}\beta^n\pi'^{N'-1}_1\tilde{\phi} + \beta^{J'-1}\pi'^{N'-1}_1P'h(J') = 0$ in equilibrium, which implies

$$P' = \left(\sum_{n=0}^{N'-1}\beta^n\pi'^{n-N'+1}_1\tilde{\phi} - \sum_{n=N'}^{J'-1}\beta^n\tilde{\phi}\right)\bigg/(\beta^{J'-1}h(J')) \tag{A.6}$$

The right-hand side of (A.5) is smaller than or equal to the right-hand side of (A.6), and thus we have $P \leq P'$. ∎

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