UNIVERSITY OF IOANNINA
DEPARTMENT OF ECONOMICS

Addressing Direct Crowding in/out by Deriving and Estimating an Euler Equation for Investment

Doctoral dissertation by

Lamprini Syrogiannouli, MSc

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ABSTRACT

I solve a discrete-time dynamic problem of profit maximization of the representative firm with a power-series adjustment cost function. I focus on the effect of government investment and of several quality-of-institutions variables, such as control of corruption, political stability, and government effectiveness, on private investment. To address this issue, I derive and estimate an Euler equation for investment (EEI) by Dynamic Programming as well as by Calculus-of-Variations. I estimate the EEI using the method of Generalized Methods of Moments (GMM) and annual aggregate data from a panel of 27 OECD countries over the period 1995-2015, as well as from an expanded panel of 32 countries, to check the robustness of the estimates to substantial changes in the sample. My main findings are as follows: First, a crowding-in effect exists, i.e., government investment encourages private investment. Second, the conventional (quadratic) adjustment-cost function is too restrictive, whereas the power-series adjustment-cost function performs better. Third, according to the literature, previous specifications of the EEI fail empirically, whereas the one used here fares better.

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Chapter 1

INTRODUCTION

1.1 Public and private investment: “friends” or “enemies”?

Investment, private and public, has been a central topic in macroeconomics for many decades, as it drives economic growth. In this study, I investigate the direct effect, if any, of public investment on private investment. That is, I address the following question: is public investment a substitute of or a complement to private investment? This direct relationship has been dubbed “direct crowding-out” when public investment is a substitute for private investment and “direct crowding-in” when it is a complement. For example, if the construction of a new road by the government encourages private investment on gas stations, restaurants, etc., along the road, then public and private investment are complements, and there is direct crowding-in. On the other hand, the construction of new public schools and universities might discourage private investment on education, in which case public and private investment are substitutes, and there is direct crowding out.

This definition of direct crowding out clearly differs from the standard one, which is related to deficit financing and works *indirectly* through the interest rate. Similarly, the above definition of direct crowding in differs from the standard one, which is related to the expansionary effect of fiscal policy and works indirectly through the increase in aggregate output.

To my knowledge, the existing literature considers both, direct and indirect, crowding-out/in effects simultaneously. For example, Aschauer (1989b) finds an indirect crowding-in effect that cancels out the direct crowding-out effect in the US. Argimón et al. (1997) present similar conclusions based on a panel of 14 OECD countries.

In this study, I address the above question by deriving and estimating an Euler Equation for private investment (EEI). More specifically, I use dynamic programming and optimal control methods to solve a discrete-time dynamic profit maximization problem under uncertainty, where public investment enters as an exogenous shock to the production function of a representative firm, and several indicators of the quality of institutions (e.g., control of corruption, political stability, and government effectiveness) enter as exogenous shocks to the firm's adjustment-cost function. The latter is modeled as a power-series function, as in Whited (1998), and proves to be empirically superior to the traditional (neoclassical) quadratic adjustment-cost function, thus leading to an empirically successful EEI.

My empirical findings suggest the existence of a direct crowding-in effect, so an increase in public investment is expected to enhance private investment. To my knowledge, there exist no studies that use the above modeling strategy to investigate the direct crowding-out/in effect. The following section provides further details on the crowding-out/in effects, both direct and indirect.

1.2 Definitions of crowding-out and crowding-in effect

Buiter (1977) is one of the first authors who characterized the effects of public capital on private capital. He made an important classification concerning the direct and indirect interaction of public and private capital as well as the definitions of complementarity and substitutability of public and private capital. As was noted earlier, indirect or *ex post* crowding out exists when governmental activity influences private-sector economic activity via changes in the interest rate. This is also called transactional or portfolio crowding out, which is not the topic of this study. Direct or *ex ante* crowding-out/in effect, on the other hand, exists when the activities of the government affect directly the firms' behavior. In other words, public policy influences directly the decisions of the private sector regarding income, wealth, consumption, and investment. In this context, Tatom (1991, p. 3) explains that the public sector provides intermediate services to the private sector. Of course, it is of great interest to estimate the degree of crowding-in/-out effect. At one extreme, Aschauer (1989b) refers to the complete direct crowding out, i.e., the case of a dollar-for-dollar decrease in private capital as a result of an increase in public capital. More generally, however, as Buiter (1977, p. 309, footnote 2) notes:

> Crowding out is not of course an all-or-nothing phenomenon. The degree of crowding out can be defined as the ratio of the induced change in the scale of some private activity to the change in the scale of the public economic activity that brought it about. The crowding-out debate, in other words, is about the signs and magnitudes of public policy multipliers.

Holz-Eakin (1988), Aschauer (1989b) and Munnell (1990a) provide evidence that the impact of aggregate public capital on private sector output and productivity is large. Munnell (1992, p. 191) provides an example from her findings:

> A 1 percent increase in the stock of public capital would increase output by 0.34 percent. Given the size of the public capital stock and output, these figures imply a marginal productivity of public capital of roughly 60 percent; that is, a $1 increase in the public capital stock would raise output by $0.60.

This example indicates that public capital boosts the productivity of private capital, thus encouraging private investment. Aschauer (1990, p.16) confirms this finding: "increases in GNP resulting from increased public infrastructure spending are estimated to exceed those from private investment by a factor of between two and five." On the other hand, public capital may be a substitute for private capital, thus crowding out private investment. The literature confirms that both crowding in and crowding out co-exist.[1]

There exist studies arguing that the crowding-in effect dominates the crowding-out effect, the so called "complementarity hypothesis." The opposite view is the "substitutability

[1] Munnell (1992, p. 192) mentions that she estimated equations that confirm this.

hypothesis." The evidence is not conclusive, however, if the crowding-in effect dominates the crowding-out effect or the other way around, to what degree, and which factors determine these effects (see Chapter 2).

1.3 Factors that influence the crowding-in/out effect

The empirical results of the literature on crowding-in/out are mixed. Factors that may influence these effects include the type of government investment, the country, and the sample period. For a given country, but for different time periods, the results may differ.

One of the main factors is the type of public spending. Ramsey (1928), Cass (1965), and Koopmans (1965) analyze three types of public spending: productive, consumption, and wasteful. Productive government spending spur the crowding-in effect. Generally, financing different categories of government expenditure may produce different effects on private investment. An example is the study of Wang (2005), who uses data from 1961 to 2000 from the Canadian economy and finds that public expenditure on health and education have positive effects on private investment, expenditure on infrastructure has a negative effect, whereas other government expenditure, like social security, has negative but insignificant effects. Another example is Barro's (1990) simple endogenous growth model with government, where government expenditure suggests that public investment on infrastructure (like construction of roads, posts, sanitations, schools, etc.) complements private investment. Aschauer (1989b) underlines the importance of productive government spending on the private sector.

Another important factor, which many studies underline, is the stage of development of the country. An interesting case in the literature is Win Ho's article (2001), which examines crowding-out/in effect in Taiwan. He finds that government expenditure causes crowding in from 1968 to 1980, while from 1980 to 1999 his findings indicate crowding-out effect. He claims that the reason for this finding is the stage of development of Taiwan's economy, supporting his conclusions on the curve of production possibility frontier[2] (PPF), which indicates that in this time span there was a significant change in the stage of development of Taiwan. Another example is the study by Erden and Holcombe (2005), who use a panel of data from developed countries, where they find crowding-out, and another panel of data from developing countries, where they find crowding-in. As well, Gjini and Kukeli (2012) showed that there is a crowd-out effect of public investment on private investment in Western European countries, but it does not in Eastern European countries.

As well, the time that elapses from the time the policy is implemented until its results emerge can characterize the relationship between public and private investment (see section 1.4). de Oliveira Cruz et al. (1999) for Brazil (1947-1990) indicates that private investment is crowded out by public investment in the short run, while for the long run this changes into crowding in.

Finally, the characteristics of each country/economy are also key factors determining crowding-out or -in effect. Some of these characteristics are:

a) The existence of institutions that protect and foster investment. A stable economy attracts investors. Equally important is the effectiveness of the investment (public and private), and this depends partly on the socioeconomic conditions of the economy. As Cavallo and Daude (2011, p. 66) note, "weak institutions distort the effectiveness of public investments, such that in an economy with high levels of corruption and rent-seeking, each dollar invested by the public sector produces less public services compared to an economy with good institutions." Also, using a panel of 63 developing countries from 1970 to 2000,

[2] This is a measure of the stage of development of the countries.

Everhart and Sumlinski (2001) find that better institutions render the correlation between public and private investment positive.

b) Karras (1994) shows that the relationship between government and private spending is also influenced by the size of the government. He argues that, as the size of the government sector increases, it is likely that the relationship between private and public spending turns into substitutability rather than complementarity. Perhaps this change in the relationship is due to the provision of more public services rather than infrastructure as the economy matures and the size of the government sector expands.

c) The geographical allocation of productive public investment also plays a role. Erenburg and Wohar (1995) and Munnell (1992) point out that, due to distance, public spending on infrastructure is not beneficial for all the national firms.

1.4 Short- and long- run crowding-out/in effect

Buiter (1977) categorizes crowding-out/in effects with respect to the time horizon (short- and long-run). The effect of public spending on private investment requires time to be observable and be available to the society and can change over time. This has not always been considered in the macroeconomic literature. It is a growing aspect of the literature, as more and more studies investigate the short- and long-run effects of the complementarity and substitutability hypotheses.

The most important articles that investigate the dynamic aspect of crowding-in/out effects are listed below:

1) Monadjemi and Huh (1998), who did not find evidence for long run crowding-in effect. They develop an error-correction model (ECM) and a vector autoregression (VAR) model for Australian data, which include real private investment, real

corporate profit, interest rate, and real public investment. They examine the long run effects by examining the coefficient of public investment on current private investment and *k* of its lagged values.

2) Voss (2002), who investigates the short-term and long-term interactions between government investment and private investment with reference to Canada and the USA during the last four decades using a VAR model. The study demonstrates that there is no evidence of crowding in; in fact, innovations to government investment tend to crowd out private investment.
3) Kalyvitis (2003), who develops an endogenous growth model and, using Canadian data, finds empirically that government expenditure on infrastructure causes private capital to accumulate in the long-run, since the long run coefficient of interest equals one and is statistically significant.
4) Hatano (2010), who considers public capital as a factor of production along with labor and private capital. He uses an ECM for private investment, where public investment is an explanatory variable, and concludes that the crowding-out effect is a short-run flow and crowding-in is a long-run stock effect. In particular, his data show that the first-year of fiscal policy the crowding-out effect dominates crowding-in, but in the second and the following years, private investment increases, so in the long run the crowding-in effect dominates.
5) Singh (2012), who suggests dominance of long-run crowding-in, based on an ECM and an over-parameterized VAR in levels.
6) Ramajo et. al (2013), who use data from Spain and find that, at the aggregate level, crowding-in dominates in the short-, medium- and long-run, but at the regional level, at least in some regions, crowding-out dominates in the short-, medium-, and long-run. They emphasize that the degree of crowding-in effect is greater in the

long-run than in the medium- or short-run. In their study, they formulate a Multiregional Spatial VAR model for the Spanish regional system.

These articles show that a consensus on the time horizon of the crowding-in/out effects has not been reached.

1.5 Aim and innovation of this dissertation

This dissertation was motivated by the following question, which I consider crucial: does productive public investment encourage or discourage private investment? After decades of research, this question remains unsolved, despite some early warnings, such as that by Eberts and Fogarty (1987, p. 3): "despite the importance of these factors to business and local government officials, very little work has been done to explore the relationship between private and public investment." I aim to investigate this unsolved question by constructing a theoretical model in Chapter 3. To my knowledge, the present study differs from the existing ones in the following two respects:

A. Socioeconomic indices

As I already described earlier (in Section 1.1), I allow several indicators of the quality of institutions to act as exogenous shocks to the firm's adjustment-cost function. Evidently, the representative firm incurs additional costs in the presence of corruption, bureaucracy, political instability, and the like. For example, it is more costly to increase a firm's capital stock in a country with a lot of corruption and bureaucracy, as a quick approval by the authorities may require that the firm go through a lot of red tape, bribery, etc. To my knowledge, this is the first study that models quality of institutions as shocks to the adjustment cost function, whereas previous studies modeled them as shocks to the production function, as in Cavallo and Daude (2011).

B. The use of two panels of annual aggregate data from many countries

The traditional investment model assumes that the adjustment-costs function is quadratic. This assumption has been considered restrictive and potentially a source of misspecification of the neoclassical model of investment; see Whited (1998) and Chatelain and Teurlai (2001). The reaction of these authors was to use an approximation to the adjustment-cost function, namely, to use a power-series function. Based on microeconomic data from 772 manufacturing firms included in the Compustat database, Whited (1998) reports that the model she constructed performs slightly better by employing the power-series function. Chatelain and Teurlai (2001), who also use microeconomic data from 4025 French firms, provide evidence against the quadratic adjustment-cost specification. The present study uses macroeconomic data and provides evidence against the quadratic adjustment-cost specification as well, a finding that is consistent with the criticism of the quadratic adjustment-cost specification included in Cooper and Haltiwanger (2006). To my knowledge, this is the first study that uses this modeling strategy and two panels of macroeconomic data from many countries to estimate successfully an Euler Equation for investment (EEI).

As I mentioned earlier, using the above modeling strategy, I derive an original EEI using dynamic programming and calculus of variations to solve the representative firm's problem. These methods are described in Whited (1998) and Adda and Cooper (2003). To the best of my knowledge such approach, deriving EEI, has not been used in the literature to address the direct crowding-out or –in effect.

In the theoretical model I develop in Chapter 3, I consider public spending shocks to the production function of a representative firm, as in Ratner (1983). As Bean (1989, p. 498) argues, government expenditure is not in vain: "Not all public spending is of the "hole-in-the-ground" variety; spending on services such as health and education and on the police force is a substitute for private expenditure." This statement refers to both public consumption and investment and assumes that they are substitutes for private spending, thus implying direct crowding-out. In the case where public and private capital are direct complements, there emerges a direct crowding-in effect. My empirical findings support the latter.

1.6 Structure of the dissertation

In the next chapter, I provide a brief review of the literature. Chapter 3 presents the theoretical model step by step. Chapter 4 describes the empirical analysis and reports and discusses the results. Finally, Chapter 5 summarizes the main findings of the study.

Chapter 2

REVIEW OF THE LITERATURE

2.1 Introduction

The relationship between public spending in investment and private investment has occupied much of the macroeconomic research. In this chapter, I present the evolution of private investment. Then, I review the theoretical and empirical literature related to the modeling of private investment including public sector.

2.2 Evolution of private investment models

For decades, macroeconomic and microeconomic literature identifies the factors to influence capital accumulation. At the beginning the Accelerator model, Clark (1917); Koyck (1954). Then the flexible accelerator theory, Eisner and Stortz (1963). Later the neoclassical intertemporal optimization model, Jorgenson (1963); Hall and Jorgenson (1967). After the q-models, Brainard and Tobin (1968); Tobin (1969). Then Hayashi's marginal q model formed in the literature. All these models still are present in the modeling of private investment, as benchmark models to explaining private investment behavior. I give briefly their frames below.

The accelerator theory describes the situation where the optimal desired capital stock is proportional only to output, under the assumptions that: the ratio between capital and output remains constant (machines are working at full capacity, so production cannot increase further) and factories work under full employment. The evolution of this theory is the flexible accelerator that includes also lags in the capital stock.

The Neoclassical private investment theory considers that firms are assumed to produce output using two inputs, labor and capital, and sell at a price. Labor services are hired at a level of wage and the capital stock is the sum of the previous gross investments minus depreciations.

Q investment theory incorporates all the assumptions of the neoclassical theory of investment, but puts a restriction on the speed of capital stock adjustment by adding an adjustment-cost function. By that I mean that, like in the neoclassical model, one unit of output can be transformed into one unit of capital, but this capital (which we call "uninstalled capital") is not useful until it is installed. Thus, unlike the neoclassical model in the *q* investment models, firms have to pay some installation or adjustment costs in order to install capital. The Marginal *q* Investment theory describes the adjustment cost to have convex form. In this case, literature splits into *q* models (test on the marginal condition on investment) and Euler equation models (test on marginal condition on the stock of capital). In the first case, the market value of the firms divided by the stock of capital (Tobin's *q* ratio) summarizes all the expected determinants of investment under technology conditions derived by Hayashi (1982). There are several problems with the *q* investment theories, the measurement of Tobin's *q* ratio and *q*-marginal is one and the simplifications that are very far from real life are the main disadvantages that made researchers change strategy in the estimation of private investment.

The Euler equation approach has the virtue over the *q* investment theories that there is no need to measure Tobin's *q* ratio and *q*-marginal. Gilchrist and Himmelberg (1995, p.545) explain that the measurement problems associated with Tobin’s *q* ratio are avoided when researchers estimate the firm's intertemporal first-order condition for investment (the Euler equation for investment). Chapter 3 presents such a model. Quadratic adjustment costs are more frequent in the literature (see section 3.3). The latest theories in the investment modelling include non convexities. In this spirit, this study employs and evaluates an adjustment cost function that adds power series of the rate of investment to capital instead of only the squared rate of investment to capital. The definition and characteristics of the adjustment costs are described in detail in section 3.3.1.

2.3 Modeling private investment including public investment

In terms of modeling public investment, literature presents the following approaches to analyzing the interaction between public investment and private investment.

A. Production Function incorporating public investment

The first approach assumes that public capital influences the private capital stock directly through the production function. Arrow and Kurz (1970) and Ratner (1983) were among the first researchers that explicitly add public capital to the production function to test whether the marginal product of public capital is positive. More specifically, they employ a Cobb-Douglas aggregate production function where public capital is a separate input.

$$Y_t = f(L_t, K_t, GI_t) = AL_t^a K_t^b GI_t^c, \tag{2.1}$$

Where Y_t is the product, A is a parameter that represents the level of technology, L_t is labor, K_t is private capital and GI_t is public spending on investment. [3]

[3] Some researchers, like Aschauer (1989b) add in the production function also government consumption.

B. Private investment models that incorporates public investment

The second approach includes models of private investment (see section 2.2) that incorporate public investment to capture direct effect of public investment on private investment. Erden and Holcombe (2005) use a flexible accelerator investment model and add government investment, their empirical results indicate positive impact (the estimated coefficient is positive and statistically significant) for developing countries and negative impact (the estimated coefficient is negative and statistically significant) for the panel of developed countries.

Literature that indicate positive impact of public investment on private investment:

Blejer and Khan (1984) for the period of 1971-1979 examine the behavior of private investment for 24 developing countries and report that the public investment on infrastructure has a positive effect on private investment, while non-infrastructure investment has negative effects. Greene and Villanueva (1991) for a panel of 23 developing countries for the period 1975-1987 find that gross public capital formation crowds in private investment. Ramirez (1994) for Mexico for the period 1950-1990 finds evidence that public investment crowds in private investment.

Literature that indicate negative impact of public investment on private investment:

Voss (2002) who uses data for the US and Canada and Cavallo and Daude (2001) who analyze data for 116 developing countries, both conclude that the crowding-out effect was predominant based on their estimation of a reduced-form private investment function. More specifically, supposing a function that has private investment as the dependent variable and public investment as one of the independent variables, the coefficient of the public investment variable was estimated to be significantly negative in both studies. This is confirmed by the following result of a regression analysis, which was performed assuming a log-linear function that has real private investment for year t (I_t) as the dependent variable, and real public investment (GI_t), real gross domestic product (Y_t) and private capital at the end of the previous year t-1 (K_{t-1}) as independent variables. Which indicate negative sign for the GI_t.

C. General Equilibrium approach

The combination of the two categories of modelling public investment above may be the way to capture the impact of the two competing forces. In this context, Aschauer (1989b), Tatom (1991), Munnell (1990, 1991, 1992) and more recent Argimon et al. (1997) among others, use a general equilibrium approach model to express and measure the relationship between private investment and public spending. They employ the following two equations:

$$I_t = i\,(\psi_t, GI_t, GC_t), \qquad (2.2)$$

$$\psi_t = f_K(K_t, GK_t) \qquad (2.3)$$

Where I_t is the private investment, ψ_t is the marginal product of private capital, GI_t is the public investment, K_t is the private capital stock, GK_t stands for public capital stock, and GC_t is the public consumption. Aschauer (1989b) in his empirical investigation of Equations (2.2) and (2.3) finds positive association of the marginal product and private investment and negative (with an estimated value close to -1) association of the public investment on the private investment. At the same system, estimates of public capital indicate positive association with the marginal product of private capital. His finding prove the existence of the two forces:

a. direct crowding out, public investment substitutes private investment,[4] and

[4] Aschauer (1989b) explains the reason of this result is that private sector uses public capital and have no motive to proceed with private investment.

b. direct crowding in, public investment complements private investment because private sector is more productive given the input of public capital in the production function.[5] Both forces exist[6]. Thus, the dominant force is an empirical question.

Various empirical studies confirm that the first force operates in the economies. Voss (2002) shows this happening in the US, Sundararajan and Thakur (1980) for India and Korea, Wai and Wong (1982) for five developing countries, Nazmi and Ramirez (1997) for Mexico, Badawi (2003) for Sudan, Narayan (2004) for Fiji and Mithra (2006) for India again.

There is a body of literature that provide evidence that the dominate force is the second, i.e. public investment boosts the national level of investment. Aschauer (1989a, 1989b) and Munnell (1990, 1992) report results that prove the productive role of public capital by looking at U.S. time series data (on productive government capital and private capital) and conclude that public capital is more productive than private capital in the private production technology.

Other studies find no evidence of public capital affecting productivity of the private sector. Tatom (1991) follows the same pattern as Aschauer and Munnell and concludes on p. 13: "An increasing number of people are advocating increased government capital spending to raise private sector output, productivity and private capital formation. The evidence presented here, based on the post-World War II experience, suggests that a rise in public capital spending would have no statistically significant effect on these measures." Also, Holtz-Eakin (1994), Evans and Karas (1994), Strum and Haan (1995), and Pereira (1999) find public investment to have a negligible impact on productivity.

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[5] In this channel there are three scenarios of how public and private investment interact: A) an increase in the public capital increases output directly in the same way that an increase in any other factor of production raises output. B) Government investment increases private investment spending directly and output indirectly by raising the marginal productivity of the private capital stock relative to a given real interest rate. C) Government investment increases output via its positive effect on the marginal productivity of labor, that is, by increasing the amount of both private and public capital per worker.

[6] Munnell (1992) argues, "Everyone agrees that public capital investment can expand the productive capacity of an area, both by increasing resources and by enhancing the productivity of existing resources."

In any case of modelling public investment, one should note that the nature of government spending in investment has some special characteristics. More specific government decisions on investment are expected to be less risk averse than investment decisions from the private sector, especially in high risky projects. de Oliveira Cruz and Teixeira (1999) underline this characteristic on p. 76: "Another argument in favor of public investment is that the State is more willing to make higher-risk investments than the private sector. In the developing economies, sectors which require large volumes of initial capital and long lead times are considered to be of high risk (Dixit and Pindyck, 1994). Also Aschauer (1988, p. 180) describes that in the case of direct crowding out private sector is unable or unwilling to provide the investment so government fills in this gap, so they are not competitors. It would be hard for the private sector to make such investments, not only because of the risk but also because of the limited size of the secondary securities market. It would be difficult for the incipient financial sector of those countries to finance long-term projects that require a large volume of resources." Thus in different economies this characteristic of government expenditure may differ and this is a factor that may fluctuate direct crowding-out or –in effect.

Another set of papers refers to the efficiency of public investment as well as on the role of good governance as a determinant of the productivity of public investment projects. For example, Keefer and Knack (2007) find that public investment (as a fraction of GDP and as the share of total investment) is higher in countries with bad institutions, in their study this reflects the enhanced rent-seeking incentives of governments with low quality of institutions. Cavallo and Daude (2001, p. 67) evaluate the efficiency of the governance by adding a variable about the quality of institutions in the aggregate production function along with public investment and private capital stock. They use a big sample of 116 countries and they explain the mechanism about the interaction of quality of institutions and private investment:

"Thus, it is reasonable to assume that public institutions affect private investment rates primarily through two effects. First, bad institutions reduce private investment directly by decreasing the appropriability of returns to investors. Second, they reduce the effectiveness of public investments, i.e. each dollar invested in the public sector yields less in terms of public services (e.g. infrastructure). In this paper, we provide evidence that good institutions are a key factor mediating the relationship between public and private investment in developing countries." Taking this under consideration, this study focuses on the effect of several quality-of-institutions variables, such as control of corruption, political stability, and government effectiveness, on private investment. For that, these variables are incorporated in the adjustment cost function.

2.4 Empirical investigation of private investment including public investment

Part of the previous section presents the theoretical finding by Aschauer (1989b) and the verification that comes from Munnell (1990, 1992). Although these theoretical findings are consistent, the empirical approach they apply has been criticized. Aschauer (1989b) criticized for using Ordinary Least Squares (OLS) to estimate the coefficients without considering the possible non-stationarity of the time series data for US he uses. Aaron (1990) and Finn (1993) among others identified this issue and used the first difference to resist against possible non-stationarity. Their results indicate the magnitude of crowding in to be lower. Others after this correction, using first differences, found that the effect between output and public investment is no longer significant, for example Hulten and Schwab (1991a, 1991b).

As I mention before, Aschauer (1989a) and Erden and Holcombe (2005) claim that the final answer on the relationship of public and private investment is an empirical question.

Thus, many articles on the topic do not develop a theoretical model. They investigate the topic only empirically. Such studies are Sigh (2012) and Aubyn and Afonso (2008).

Aubyn and Afonso (2008) assess the macroeconomic returns of public and private investment using Vector Autoregressive Analysis (VAR) framework for a sample of 14 European countries, plus Japan, Canada and the United States. Their empirical results showed that both public and private investment positively affect output for most economies of the sample. While the complementarity effect varied across countries.

Some empirical studies consider important to model dynamic perspective of the public investment related to public investment. For that, researchers model the short- and long-run effects of the complementarity and substitutability hypotheses, i.e. in the form of time lags. They use econometric tools such as VAR in order to analyze time lags. In fact, studies using VAR conducted by Erenburg and Wohar (1995) and Pereira (2001), which target the United States, and a study by Otto and Voss (1996), which target Australia, confirm the positive effect of public investment on private investment. However, Voss (2002), who studies the United States and Canada, deny the crowding-in effect. Unfortunately, the results of VAR analysis have remained ambiguous until now. Similar examples of the literature on VAR analysis are presented in Section 1.4.

Other studies examine the effect of public investment on private investment using other types of empirical analysis, like Error Correction Model (ECM) and Autoregressive Distributed Lag (ARDL). For example, Muthu (2017) uses time series data for India over the period 1971-1972 and 2009-2010. He uses ARDL model to examine the long-run relationship between public and private investment. Samuel (2012) for Kenya for the period from 1964 up to 2006, uses ECM to show that investment in agriculture had a significant positive effect. On the other hand, investment in infrastructure had insignificant positive effect. Section 1.4 includes other examples of the literature that use ECM.

The studies summarized above do not provide clear evidence on the relationship between private investment and public investment. None of these studies employs an EEI to investigate the matter. Next chapter develops such theoretical model.

Chapter 3
THEORETICAL MODEL

3.1 Introduction

The concept of the representative firm, introduced by Marshall (1920), describes the behavior of a typical or average firm. The objective of the representative firm is to maximize current and expected future discounted profits by choosing the optimal level of the capital stock. My model explores the interactions between capital stock choices and external factors, such as government investment. A crucial question that I intend to investigate is, how does government spending on infrastructure, institutions, R&D, education, health, etc., influence the firm's investment decisions?

Even though firms choose the level of investment by participating in free markets, they take government expenditure as given. I assume that government investment improves technology and productivity by producing knowledge, by establishing and securing property rights, and by improving public institutions and infrastructure. To explore this possibility, I add a profitability shock, $A(\mathbf{v}_t)$, to the representative firm's production function, thus allowing it to reduce the crowding-out effect of government spending or even cause crowding in. In addition, I consider socio-demographic exogenous variables, such as control of corruption, political stability, and rule of law, assuming that these variables enter the adjustment cost, but not the production function.

My aim is to derive an Euler equation for private investment (EEI) by maximizing expected future discounted profits under uncertainty. The EEI implies that the representative firm's optimal plan has the property that any marginal, temporary and feasible change in the firm's behavior has marginal benefits equal to marginal costs in the present and the future. I derive the EEI by solving the above optimization problem via Dynamic Programming as well as via standard optimal control theory (see, e.g., Whited (1998). To my knowledge, there does not exist in the literature an EEI that addresses direct crowding out or in.

3.2 Specification of the profit function

I adopt the profit function used by Abel and Eberly (1994), Whited (1998), Cooper and Haltiwanger (2005), and others, namely,

$$\Pi(K_t, \mathbf{v}_t) = A(\mathbf{v}_t)K_t, \tag{3.1}$$

where $\mathbf{v}_t$ is a stochastic shock, originating possibly from "randomness in technology, in the prices of costlessly adjustable inputs, or in the price of output" (Abel and Eberly, 1994, p. 1371), as well as from random changes in government investment. Abel and Eberly (1994, p. 1377, see especially footnote 15) derive such a profit function under the assumptions that production is characterized by constant returns to scale and that the firm is a price taker in both input and output markets. Under these assumptions, other factors of production are not present in this profit function, but "have already been 'maximized out' of the problem," as Whited (1998, p. 480) notes. Romer (2006, p. 390) explains in words the form of (3.1):

> The assumption that the firm's profits are proportional to its capital is appropriate if the production function has constant returns to scale, output markets are competitive, and the supply of all factors other than capital is perfectly elastic. Under these assumptions, if one firm has, for example, twice as much capital as another, it employs twice as much of all inputs; as a result, both its revenues and its costs are twice as high as the other's.

Thus, starting from a positive value of profit, if the firm doubles its capital stock (as well as the other inputs), both its revenues and costs double, hence its profits double.

To clarify (3.1), consider the profit function

$$\Pi(K_t, \mathbf{L}_t, \mathbf{v}_t) = \max_{L_t}\left[R(K_t, \mathbf{L}_t, \mathbf{v}_t) - \mathbf{L}_t \boldsymbol{\omega}(\mathbf{v}_t)\right]. \tag{3.2}$$

Here, $R(K_t, \mathbf{L}_t, \mathbf{v}_t) = P(\mathbf{v}_t,\ Q_t)F(K_t, \mathbf{L}_t, \mathbf{v}_t)$ is the firm's revenue function, P_t is the price of output, which the firm takes as given, Q_t is industry output, $F(K_t, \mathbf{L}_t, \mathbf{v}_t)$ is the firm's production function, assumed to be linearly homogeneous in K_t and $\mathbf{L}_t$,[7] and $\omega(\mathbf{v}_t)$ is a vector of input prices, which the firm also takes as given. Let $\mathbf{l}_t = \mathbf{L}_t/K_t$ be the vector of the ratios of the "costlessly adjustable" inputs, $\mathbf{L}_t$, to the capital stock, K_t. The revenue function is also assumed to be linearly homogeneous in K_t and $\mathbf{L}_t$. Substituting the vector $\mathbf{l}_t$ in Equation (3.2), the profit function can be written as

$$\Pi(K_t, \mathbf{v}_t) = \max_{l_t}\left[R(1, \mathbf{l}_t, \mathbf{v}_t) - \mathbf{l}_t \boldsymbol{\omega}(\mathbf{v}_t)\right] K_t, \tag{3.3}$$

where the term in the brackets does not depend on K_t and can be denoted as

$$A(\mathbf{v}_t) = \max_{l_t}\left[R(1, \mathbf{l}_t, \mathbf{v}_t) - \mathbf{l}_t \boldsymbol{\omega}(\mathbf{v}_t)\right], \tag{3.4}$$

where $A(\mathbf{v}_t) > 0$. In accordance with the discussion following Equation (3.1), the ratios in the vector $\mathbf{l}_t$ are constant, so the function $A(\mathbf{v}_t)$, which will be specified in the empirical part, does not depend on K_t. Given the definition (3.4), Equation (3.3) can be written as Equation (3.1).

3.3 Specification of the costs

The purchase of new capital comprises two categories of costs. The first is the direct purchase price of capital, denoted by p_t, multiplied by the amount of purchased capital stock. The second category is adjustment costs, which include installation costs, labor expenses, reconfiguring other aspects of production, et cetera; see, e.g., Eisner and Strotz (1963). The

[7] A function $f(x_1, \ldots, x_n)$ is homogeneous of degree r in $x_1, \ldots, x_n$ if $f(tx_1, \ldots, tx_n) = t^r f(x_1, \ldots, x_n)$, where $t > 0$ and r is a real number. It is linearly homogeneous, or homogeneous of degree 1, if r=1, i.e., $f(tx_1, \ldots, tx_n) = t\, f(x_1, \ldots, x_n)$; see Silberberg (1978, p. 86).

cost-of-adjustment function is typically assumed to be strictly convex and to have a value of zero at zero investment, but this view has been changing, as some researchers argue that this form does not reflect the actual conditions of the economy.

3.3.1 Adjustment costs function

A good description of adjustment costs is given by Cooper and Haltiwanger (2006, p. 611):

> Costs of adjusting the stock of capital reflect a variety of interrelated factors that are difficult to measure directly or precisely so that the study of capital adjustment costs has been largely indirect through studying the dynamics of investment itself. Changing the level of capital services at a business generates disruption costs during installation of any new or replacement capital and costly learning must be incurred as the structure of production may have been changed. Installing new equipment or structures often involves delivery lags and time to install and/or build. The irreversibility of many projects caused by a lack of secondary markets for capital goods acts as another form of adjustment cost.

The choice of the adjustment cost function for econometric work depends on empirical considerations and varies from industry to industry. For the purpose of theoretical analysis, this function should be general enough to approximate the actual function in a fairly wide range of empirical situations and yet be specific enough to derive some behavioral implications from the mathematical analysis.

Most researchers consider the adjustment cost function to be quadratic[8] in the investment rate, i.e.,[9]

$$C(K_{t+1}, K_t, \boldsymbol{\eta}_t) = \frac{\alpha_1}{2}\left(\frac{I_t}{K_t}\right)^2 A_1(\boldsymbol{\eta}_t), \tag{3.5}$$

where $\alpha_1 > 0$ and $\boldsymbol{\eta}_t$ is a vector of variables that influence the adjustment cost. The presence of the term $A_1(\boldsymbol{\eta}_t)$ in (3.5) is an innovation of the present study, to account for some

[8] Hayashi (1982), Gilchrist and Himmelberg (1995), Cooper and Haltiwanger (2005), and many other authors use a quadratic cost function.

[9] Gilchrist and Himmelberg (1995) assume that the cost of installing new capital is increasing and convex.

socioeconomic variables that may influence adjustment costs, e.g., corruption, bureaucracy, etc.; see below. The main reasons why researchers adopt this functional form for adjustment costs are as follows:

1) It is a simple and good approximation of accounting for different costs (hiring, layoff, overtime, inventory, machine setup), and offers the advantage that, after solving the maximization problem, we obtain a linear relationship between I_t/K_t. There is no evidence that quadratic adjustment costs perform best against other functional forms, however.
2) According to Cooper and Haltiwanger (2005), quadratic adjustment costs are often used in the literature. They write (p. 18): "The quadratic adjustment cost parameter has received enormous attention in the literature since a regression of investment rates on the average value of the firm (termed average *q*) will identify this parameter when the profit function is proportional to capital stock and the cost of adjustment function is convex and homogenous of degree one."

My choice of adjustment cost function combines convex and non-convex adjustment costs. In particular, following Newey (1994) and Whited (1998), I use a power series of the ratio I_t/K_t to approximate the adjustment cost function, namely,

$$C(K_{t+1}, K_t, \boldsymbol{\eta}_t) = \left(\alpha_0 + \sum_{m=2}^{M} \frac{1}{m} \alpha_m \left(\frac{I_t}{K_t} \right)^m \right) K_t A_1(\boldsymbol{\eta}_t). \tag{3.6}$$

This adjustment cost function is still linearly homogeneous in investment and capital. *M* is a truncation parameter, which will be determined empirically. This choice of adjustment cost function, allows us to capture nonlinearities (as suggested by the standard RESET),[10] and to

[10] The Ramsey Regression Equation Specification Error Test (RESET) is a general specification test for the linear regression model. More specifically, it tests whether squared, cubed, etc., fitted values help explain the response variable. The intuition behind the test is that if powers of the explanatory variables have any

avoid any misspecification bias that can result from the omission of these nonlinearities. Whited (1998) notes that adding these parameters slightly improved her model, but it was not yet satisfactory, so, I added the power series in the adjustment cost function to improve the flexibility of my model and to better estimate the EEI.

I expect to improve further the model by including additional variables in $A_1(\boldsymbol{\eta}_t)$, which plays the role of an exogenous shock to the cost-of-adjustment function reflecting the quality of institutions, e.g., control of corruption, political stability, etc. A firm that invests in a country with low quality of institutions and low level of infrastructure incurs additional costs. For example, to get quick approval from authorities to expand a factory, the firm may have to go through a lot of red tape, bribe some clerks, et cetera. Finally, I assume that there are no borrowing constraints.

3.4 The profit maximization problem

The firm is assumed to solve a discrete time, intertemporal maximization problem under uncertainty by choosing the amount of capital. In particular, using the methodology of Adda and Cooper (2003, p. 115), I solve a discrete-time dynamic programming problem of profit maximization of the representative firm. First, I construct the Bellman equation. During the current period (t) the firm makes decisions on the current production and the use of the current and next period's capital stock. The firm has information on the current price of capital and the interest rate and needs to make a decision on the capital stock of the next period. Bellman's equation is

explanatory power, the model is misspecified in that the data generating process might be better approximated by a polynomial or another non-linear functional form.

$$V(K_t, p_t, \mathbf{z}_t) =$$
$$\max_{K_{t+1}} \left[\Pi(K_t, \mathbf{v}_t) - C(K_{t+1}, K_t, \boldsymbol{\eta}_t) - p_t(K_{t+1} - (1-\delta)K_t) + \frac{1}{1+r_t} E_t V(K_{t+1}, p_{t+1}, \mathbf{z}_{t+1}) \right], \tag{3.7}$$

where the vector $\mathbf{z}_t$ contains the variables included in the functions $A(\mathbf{v}_t)$ and $A_1(\boldsymbol{\eta}_t)$. The transition equation (capital accumulation equation) is

$$K_{t+1} = (1-\delta)K_t + I_t, \tag{3.8}$$

where the parameter $\delta \in [0,1)$ is the rate of depreciation of the capital stock, assumed to be constant. According to Equation (3.8), current investment equals the future capital stock minus the current depreciated capital stock.

Bellman‘s equation (3.7) says that the firm determines how much capital it has to invest in order to maximize current profits plus discounted expected future returns,

$$\Pi(K_t, \mathbf{v}_t) + \frac{1}{1+r_t} E_t V(K_{t+1}, p_{t+1}, \mathbf{z}_{t+1}), \tag{3.9}$$

minus the cost of purchasing new capital as well as the adjustment cost,

$$p_t(K_{t+1} - (1-\delta)K_t) + C(K_{t+1}, K_t, \boldsymbol{\eta}_t). \tag{3.10}$$

The state variables in this problem are: 1) K_t, the current level of capital stock; 2) p_t, the purchase price of capital;[11] and 3) the vector $\mathbf{z}_t$. These variables include all the current and past information we need to solve the forward-looking optimization problem (Adda and Cooper 2003, p. 200). The control variable, the variable chosen by the agent, is the future capital stock, K_{t+1}. The discount factor, usually denoted as β, is measured by $1/(1 + r_t)$, where r_t is the real rate of interest.[12]

[11] Note that p_t is the price of new capital in terms of goods. In other words, it is a relative price.
[12] This is the rate of interest on one period loans extending between periods t and t+1.

3.4.1 Solution of the maximization problem

Again, following Adda and Cooper (2003, pp. 18, 188-191), I begin by differentiating the Bellman equation, (3.7), with respect to K_t:

$$V_{K_t}(K_t, p_t, \mathbf{z}_t) = \Pi_{K_t}(K_t, \mathbf{v}_t) - C_{K_t}(K_{t+1}, K_t, \boldsymbol{\eta}_t) + (1-\delta)p_t. \tag{3.11}$$

Next, I update Equation (3.11) by one period, after noting that the value function V holds for all (K, p, $\mathbf{z}$); hence it will hold for (K_{t+1}, p_{t+1}, $\mathbf{z}_{t+1}$):

$$V_{K_{t+1}}(K_{t+1}, p_{t+1}, \mathbf{z}_{t+1}) = \Pi_{K_{t+1}}(K_{t+1}, \mathbf{v}_{t+1}) - C_{K_{t+1}}(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1}) + (1-\delta)p_{t+1}. \tag{3.12}$$

To be consistent with the uncertainty of the future values of all the variables, I take expectations in Equation (3.12):

$$E_t V_{K_{t+1}}(K_{t+1}, p_{t+1}, \mathbf{z}_{t+1}) = E_t[\Pi_{K_{t+1}}(K_{t+1}, \mathbf{v}_{t+1}) - C_{K_{t+1}}(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1}) + (1-\delta)p_{t+1}], \tag{3.13}$$

where E_t is the expectations operator conditional on the information set available to the firm at the beginning of period t.

Next, to obtain the first-order condition for optimal investment policy, I differentiate Equation (3.7) with respect to K_{t+1}, which yields

$$C_{K_{t+1}}(K_{t+1}, K_t, \boldsymbol{\eta}_t) + p_t = \frac{1}{1+r_t} E_t\left\{V_{K_{t+1}}(K_{t+1}, p_{t+1}, \mathbf{z}_{t+1})\right\}. \tag{3.14}$$

The left-hand side of this equation measures the marginal cost of purchasing new capital plus the marginal adjustment cost, whereas its right-hand side measures the marginal benefit of capital accumulation. Now put Equation (3.13) into (3.14):

$$\begin{aligned} &C_{K_{t+1}}(K_{t+1}, K_t, \boldsymbol{\eta}_t) + p_t \\ &= \frac{1}{1+r_t} E_t[\Pi_{K_{t+1}}(K_{t+1}, \mathbf{v}_{t+1}) - C_{K_{t+1}}(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1}) + (1-\delta)p_{t+1}]. \end{aligned} \tag{3.15}$$

This is the EEI. Its left-hand side is the representative firm's marginal cost of adding new capital, whereas its right-hand side is the marginal gain from the additional capital, which is expected to materialize in the next period [see Adda and Cooper, p. 191, right below Equation (8.5)]. At the maximum, these two must be equal.

For the purpose of estimating the EEI, I eliminate E_t from Equation (3.15) and add a rational expectations error, ε_{t+1}, to the other side of the equation, i.e.,

$$\begin{aligned} &C_{K_{t+1}}(K_{t+1}, K_t, \boldsymbol{\eta}_t) + p_t + \varepsilon_{t+1} \\ &= \frac{1}{1+r_t}\left[\Pi_{K_{t+1}}(K_{t+1}, \mathbf{v}_{t+1}) + p_{t+1}(1-\delta) - C_{K_{t+1}}(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1}) \right], \end{aligned} \tag{3.16}$$

or

$$\frac{1}{1+r_t}[\Pi_{K_{t+1}}(K_{t+1}, \mathbf{v}_{t+1}) + p_{t+1}(1-\delta) - C_{K_{t+1}}(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1})] - C_{K_{t+1}}(K_{t+1}, K_t, \boldsymbol{\eta}_t) - p_t = \varepsilon_{t+1}. \tag{3.17}$$

To calculate the two marginal adjustment-cost terms that appear in (3.17), I write Equation (3.6) as

$$C(K_{t+1}, K_t, \boldsymbol{\eta}_t) = \alpha_0 K_t A_1(\boldsymbol{\eta}_t) + \frac{1}{2}\alpha_2 I_t^2 K_t^{-1} A_1(\boldsymbol{\eta}_t) + \frac{1}{3}\alpha_3 I_t^3 K_t^{-2} A_1(\boldsymbol{\eta}_t) + \ldots \tag{3.18}$$

Differentiating Equation (3.18) with respect to K_{t+1} and recalling from (3.8) that $I_t = K_{t+1} - (1-\delta)K_t$ yields

$$\frac{\partial C(K_{t+1}, K_t, \boldsymbol{\eta}_t)}{\partial K_{t+1}} = 0 + \alpha_2 I_t K_t^{-1} A_1(\boldsymbol{\eta}_t) + \alpha_3 I_t^2 K_t^{-2} A_1(\boldsymbol{\eta}_t) + \ldots \tag{3.19}$$

or

$$C_{K_{t+1}}(K_{t+1}, K_t, \boldsymbol{\eta}_t) = \frac{\partial C(K_{t+1}, K_t, \boldsymbol{\eta}_t)}{\partial K_{t+1}} = \sum_{m=2}^{M} \alpha_m \left(\frac{I_t}{K_t}\right)^{m-1} A_1(\boldsymbol{\eta}_t), \tag{3.20}$$

since

$$\frac{\partial I_t}{\partial K_{t+1}} = \frac{\partial (K_{t+1} - (1-\delta)K_t)}{\partial K_{t+1}} = 1. \tag{3.21}$$

Leading Equation (3.6) by one period yields

$$C(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1})$$
$$= \alpha_0 K_{t+1} A_1(\boldsymbol{\eta}_{t+1}) + \frac{1}{2}\alpha_2 I_{t+1}^2 K_{t+1}^{-1} A_1(\boldsymbol{\eta}_{t+1}) + \frac{1}{3}\alpha_3 I_{t+1}^3 K_{t+1}^{-2} A_1(\boldsymbol{\eta}_{t+1}) + \ldots \tag{3.22}$$

Differentiating (3.22) with respect to K_{t+1} yields

$$\frac{\partial C(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1})}{\partial K_{t+1}}$$
$$= \alpha_0 A_1(\boldsymbol{\eta}_{t+1}) + \frac{1}{2}\alpha_2 I_{t+1}^2 \left(-1\right) K_{t+1}^{-2} A_1(\boldsymbol{\eta}_{t+1}) + \alpha_2 I_{t+1}(-(1-\delta)) K_{t+1}^{-1} A_1(\boldsymbol{\eta}_{t+1}) \tag{3.23}$$
$$+ \frac{1}{3}\alpha_3 I_{t+1}^3 \left(-2\right) K_{t+1}^{-3} A_1(\boldsymbol{\eta}_{t+1}) + \alpha_3 I_{t+1}^2 \left(-\left(1-\delta\right)\right) K_{t+1}^{-2} A_1(\boldsymbol{\eta}_{t+1}) + \ldots,$$

since

$$\frac{\partial I_{t+1}}{\partial K_{t+1}} = \frac{\partial (K_{t+2} - (1-\delta)K_{t+1})}{\partial K_{t+1}} = -(1-\delta), \tag{3.24}$$

so Equation (3.23) takes the following form:

$$C_{K_{t+1}}(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1}) = \frac{\partial C(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1})}{\partial K_{t+1}}$$
$$= \alpha_0 A_1(\boldsymbol{\eta}_{t+1}) - \sum_{m=2}^{M} \frac{m-1}{m} \alpha_m (\frac{I_{t+1}}{K_{t+1}})^m A_1(\boldsymbol{\eta}_{t+1}) - \left(1-\delta\right) \sum_{m=2}^{M} \alpha_m (\frac{I_{t+1}}{K_{t+1}})^{m-1} A_1(\boldsymbol{\eta}_{t+1}). \tag{3.25}$$

Finally, using (3.1) and substituting (3.20) and (3.25) into (3.17) yields the following empirical form of the EEI:

$$\frac{1}{1+r_t}\{A(\mathbf{v}_{t+1}) - \alpha_0 A_1(\boldsymbol{\eta}_{t+1}) + \sum_{m=2}^{M} \frac{m-1}{m} \alpha_m \, (\frac{I_{t+1}}{K_{t+1}})^m A_1(\boldsymbol{\eta}_{t+1})$$
$$+(1-\delta)[\sum_{m=2}^{M} \alpha_m (\frac{I_{t+1}}{K_{t+1}})^{m-1} A_1(\boldsymbol{\eta}_{t+1}) + p_{t+1}]\} - \sum_{m=2}^{M} \alpha_m (\frac{I_t}{K_t})^{m-1} A_1(\boldsymbol{\eta}_t) - p_t = \varepsilon_{t+1}. \tag{3.26}$$

The same equation emerges using standard optimal control theory, as, for example, in Whited (1998).

Appendix 3.A: Special case - Quadratic Costs

In our case, after setting $A_1(\boldsymbol{\eta}_t) \equiv 1$, Bellman's Equation [Eq. (8.6) in Adda and Cooper (p. 192)] is

$$V[K_t, A(\mathbf{v}_t)] = \max_{K_{t+1}} A(\mathbf{v}_t)K_t - \frac{\alpha_1}{2}[\frac{K_{t+1} - (1-\delta)K_t}{K_t}]^2 K_t - p[K_{t+1} - (1-\delta)K_t] \quad \text{(A.1)}$$

$$+\frac{1}{1+r_t}E_t V[K_{t+1}, A(\mathbf{v}_{t+1})]$$

Differentiate this function with respect to K_{t+1} and set the derivative equal to zero:

$$-\alpha_1 \frac{[K_{t+1} - (1-\delta)K_t]}{K_t} - p + \frac{1}{1+r_t}E_t V_K[K_{t+1}, A(\mathbf{v}_{t+1})] = 0. \quad \text{(A.2)}$$

Since, by definition, we have that $I_t = K_{t+1} - (1\text{-}\delta)K_t$. It follows that, given K_t, changes in I_t can occur only through changes in K_{t+1}, and this relation is 1-1.

Now define $i_t = I_t/K_t$, so Equation (A2) can be written as

$$-\alpha_1 i_t - p + \frac{1}{1+r_t}E_t V_K[K_{t+1}, A(\mathbf{v}_{t+1})] = 0. \quad \text{(A.3)}$$

Solving (A3) for it, we obtain

$$i_t = \frac{1}{\alpha_1}\{\frac{1}{1+r_t}E_t V_K[K_{t+1}, A(\mathbf{v}_{t+1})] - p\}, \quad \text{(A.4)}$$

which is our version of Adda and Cooper's Equation (8.7).

Next, guess at a solution and verify that it works. Following Adda and Cooper (p. 192), we assume that

$$V[K_t, A(\mathbf{v}_t)] = \varphi[A(\mathbf{v}_t)]K_t, \quad \text{(A.5)}$$

where $\varphi(.)$ is an unknown function, assumed to be continuous and increasing, i.e., $\varphi'(.) > 0$. Hence, $V_{Kt}[K_t, A(\mathbf{v}_t)]=\varphi[A(\mathbf{v}_t)]$, and

$$E_t V_{K_t}[K_{t+1}, A(\mathbf{v}_{t+1})] = E_t \varphi[A(\mathbf{v}_{t+1})]. \quad \text{(A.6)}$$

Following Adda and Cooper (p. 192), we assume that

$$A(\mathbf{v}_t) \equiv A_t = \lambda_0 + \lambda_1 G_t, \tag{A.7}$$

and

$$A_{t+1} = \rho A_t + \varepsilon_{t+1},\ 0 < \rho < 1. \tag{A.8}$$

Thus, by invoking Jensen's inequality, the expectation $E_t\varphi(A_{t+1})$ in Equation (A6) can be written as

$$E_t\varphi\left(\mathrm{A}_{t+1}\right) \equiv \tilde{\varphi}(A_t)\ . \tag{A.9}$$

From Equations (A8) and (A9), we see that, since $\varphi'(.) > 0$ and $0 < \rho < 1$, it must also be the case that $\tilde{\varphi}'(A_t) > 0.$ Equation (A6) can now be written as

$$E_t V_{K_t}[K_{t+1}, A(\mathbf{v}_{t+1})] = \tilde{\varphi}(A_t). \tag{A.10}$$

Inserting (A10) into (A4) yields

$$i_t = \frac{1}{\alpha_1}[\frac{1}{1+r_t}\tilde{\varphi}(A_t) - p] \equiv z(A_t). \tag{A.11}$$

To verify that our guess, Equation (A5), works, substitute (A11) into the original functional equation on which Equation (A1) is based. Before doing so, however, note that, because of (A5), the last expectation in the term of Equation (A1) can be written as

$$E_t V(K_{t+1}, A_{t+1}) = E_t\{\varphi(A_{t+1})K_{t+1}\}. \tag{A.12}$$

But from the definition: $I_t = K_{t+1}$ - $(1 - \delta)K_t$. We obtain $K_{t+1} = I_t + (1 - \delta)K_t$. And since from Eq. (A11) we get $I_t = K_t\, \mathrm{z}(A_t)$, the last equation becomes

$$K_{t+1} = K_t \mathrm{z}(A_t) + (1 - \delta)K_t = K_t[\mathrm{z}(A_t) + (1 - \delta)]. \tag{A.13}$$

Inserting this into Eq. (A12), the latter can be written as

$$E_t V(K_{t+1}, A_{t+1}) = E_t\{\varphi(A_{t+1})K_t[z(A_t) + (1 - \delta)]\} = K_t[z(A_t) + (1 - \delta)]E_t\varphi(A_{t+1}), \tag{A.14}$$

or, using (A9),

$$E_t V(K_{t+1}, A_{t+1}) = K_t[z(A_t) + (1 - \delta)]\tilde{\varphi}(A_t). \tag{A.15}$$

Therefore, the original functional equation can be written as

$$\varphi(A_t)K_t = A_t K_t - \frac{\alpha_1}{2}[z(A_t)]^2 K_t - pK_t z(A_t) + \frac{1}{1+r_t} K_t \tilde{\varphi}(A_t)[z(A_t) + (1 - \delta)], \qquad \text{(A.16)}$$

which must hold for all (A, K), a property of the original functional equation. Notice that every term in (A16) involves K_t multiplicatively, so it cancels out. In other words, both the left-hand and the right-hand sides of (A16) are proportional to K_t. Thus, our guess, Equation (A5), leads to an investment function, Equation (A11), which confirms the guessed proportionality, which proves that it works.

From Equations (A7) and (A11), since $\tilde{\varphi}'(A_t) > 0,$ it follows that $\lambda_1 > 0$ (< 0) implies direct crowding in (out).

Appendix 3.B: Euler Equation for investment on the special case - Quadratic Costs

To derive EEI, I begin with Equation (3.14), which is repeated here for convenience as Equation (B.1):

$$C_{K_{t+1}}(K_{t+1}, K_t, \boldsymbol{\eta}_t) + p_t = \frac{1}{1+r_t} E_t \left\{ V_{K_{t+1}}(K_{t+1}, p_{t+1}, \mathbf{z}_{t+1}) \right\}, \tag{B.1}$$

where

$$V_{K_{t+1}}(K_{t+1}, p_{t+1}, \mathbf{z}_{t+1}) = \Pi_{K_{t+1}}(K_{t+1}, \mathbf{v}_{t+1}) - C_{K_{t+1}}(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1}) + (1-\delta) p_{t+1}.$$

Assuming there is an optimal solution; Equation (B.1) is a necessary condition. On the left side of Equation (B.1) are measured the costs of the investment. On the right side are measured the expected marginal gains that the new invested capital with return to the company in the next period. Maximization equation or Bellman equation must be true for all (K_t, $\boldsymbol{\eta}_t$). In this section, I employ quadratic adjustment costs defined as follows

$$C(K_{t+1}, K_t, \boldsymbol{\eta}_t) = \frac{\alpha_1}{2}\left(\frac{I_t}{K_t}\right)^2 K_t A_1(\boldsymbol{\eta}_t) = \frac{\alpha_1}{2}\left(\frac{K_{t+1} - (1-\delta)K_t}{K_t}\right)^2 K_t A_1(\boldsymbol{\eta}_t). \tag{B.2}$$

The derivative of (B.2) with respect to K_{t+1} is

$$C_{K_{t+1}}(K_{t+1}, K_t, \boldsymbol{\eta}_t) = \alpha_1 \frac{I_t}{K_t} A_1(\boldsymbol{\eta}_t). \tag{B.3}$$

Leading Equation (B.2) by one period and then differentiating with respect to K_{t+1} yields

$$C_{K_{t+1}}(K_{t+2}, K_{t+1}, \boldsymbol{\eta}_{t+1}) = -\alpha_1(1-\delta)\frac{I_{t+1}}{K_{t+1}} A_1(\boldsymbol{\eta}_{t+1}) - \frac{\alpha_1}{2}\left(\frac{I_{t+1}}{K_{t+1}}\right)^2 A_1(\boldsymbol{\eta}_{t+1}). \tag{B.4}$$

In addition, updating Equation (3.1) by one period, i.e.,

$$\Pi(K_{t+1}, \mathbf{v}_{t+1}) = A(\mathbf{v}_{t+1}) K_{t+1}, \tag{B.5}$$

and differentiating (B.5) with respect to K_{t+1} yields

$$\Pi_{K_{t+1}}(K_{t+1}, \mathbf{v}_{t+1}) = A(\mathbf{v}_{t+1}). \tag{B.6}$$

Substituting (B.3), (B.4) and (B.6) into (B.1) yields

$$\alpha_1 \frac{I_t}{K_t} A_1(\boldsymbol{\eta}_t) + p_t = \frac{1}{1+r_t} E_t \{A(\mathbf{v}_{t+1}) + \frac{\alpha_1}{2} (\frac{I_{t+1}}{K_{t+1}})^2 A_1(\boldsymbol{\eta}_{t+1}) + (1-\delta)[\alpha_1 \frac{I_{t+1}}{K_{t+1}} A_1(\boldsymbol{\eta}_{t+1}) + p_{t+1}]\} \tag{B.7}$$

or

$$\alpha_1 i_t A_1(\boldsymbol{\eta}_t) + p_t = \frac{1}{1+r_t} E_t \{A(\mathbf{v}_{t+1}) + \frac{\alpha_1}{2} (i_{t+1})^2 A_1(\boldsymbol{\eta}_{t+1}) + (1-\delta)[\alpha_1 i_{t+1} A_1(\boldsymbol{\eta}_{t+1}) + p_{t+1}]\}. \tag{B.8}$$

which is the EEI using quadratic adjustment costs.

Chapter 4
ECONOMETRIC ANALYSIS

4.1 Introduction

This chapter investigates econometrically the theoretical conclusions derived in Chapter 3. I begin by describing the data and testing the stationarity properties of the variables based on several panel unit-root tests. I then estimate the Euler equation for investment by the Generalized Method of Moments (GMM). In the last section, I interpret the results.

4.2 Data description

The econometric analysis is based on two unbalanced panels of annual aggregate data for the period 1996-2015. The first consists of 32 countries, namely, Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, United Kingdom, and the United States. The second consists of 27 OECD counties, which are included in the first panel, and is constructed from it by deleting five countries that are not members of OECD, namely, Bulgaria, Croatia, Cyprus, Malta, and Romania. The inclusion of a country in the sample depends on data availability. The sources of the data are: (1) AMECO, the annual macroeconomic database of the European Commission's directorate for economic and financial affairs, (2) the World Development Indicators (WDI), and (3) the Worldwide Governance Indicators (WGI), a research dataset on six indicators summarizing the views on the quality of governance provided by a large number of enterprises, citizens, and expert survey respondents in industrial and developing countries. These indicators are gathered from a number of survey institutes, non-governmental organizations, international organizations, and private-sector firms. The six indicators are based on 31 underlying data sources reporting the perceptions of governance of a large number of survey respondents and expert assessments worldwide; their values range from -2.5 to 2.5, where higher values indicate better quality of institutions. Details on the underlying data sources, the aggregation method, and the interpretation of the indicators, can be found in the WGI methodology paper.[13]

Tables 4.1 and 4.2 describe the definitions and descriptive statistics of the variables. Appendix Table 1 shows the original panel data I downloaded, their definitions, their units and specific source.

Table 4.1: Descriptive statistics of all variables for the panel of 32 countries, 1996-2015

Variables	Definition	Mean	Standard deviation	Minimum	Maximum	N
Private investment	I_{it}/GDP_{it}	18.89	4.28	4.73	38.93	635
Public investment	GI_{it}/GDP_{it}	3.73	1.16	0.65	12.53	635
Relative price of capital	$PI_{it}/PGDP_{it}$	103.85	8.14	91.55	155.46	640
Interest rate	$(real\ interest\ rate_{it}/100) + 1$	1.02	0.03	0.88	1.24	567
Indices on quality of institutions						
Control of Corruption	Index	1.05	0.85	-0.82	2.59	465
Rule of Law	Index	1.10	0.63	-0.61	2.12	465
Regulatory Quality	Index	1.17	0.43	-0.16	2.08	465

[13] Kaufmann D., Kraay A. and Mastruzzi M. (2010). The Worldwide Governance Indicators : A Summary of Methodology, Data and Analytical Issues. World Bank Policy Research Working Paper No. 5430

Government Effectiveness	Index	1.17	0.64	-0.62	2.36	465
Political Stability and Absence of Violence/Terrorism	Index	0.83	0.42	-0.48	1.67	450
Voice and Accountability	Index	1.12	0.36	-0.34	1.83	450

Abbreviation: GDP, Gross Domestic Product.

Table 4.2: Descriptive statistics for the panel of OECD countries, 1996-2015

Variables	**Definition**	**Mean**	**Standard deviation**	**Minimum**	**Maximum**	**N**
Private investment	I_{it}/GDP_{it}	19.08	4.31	6.99	38.93	540
Public investment	GI_{it}/GDP_{it}	3.69	1.14	1.47	12.53	540
Relative price of capital	$PI_{it}/PGDP_{it}$	103.61	8.20	91.55	155.46	540
Interest rate	$(real\ interest\ rate_{it}/100) + 1$	1.02	0.03	0.88	1.24	492
Indices on quality of institutions						
Control of Corruption	Index	1.18	0.82	-0.82	2.59	394
Rule of Law	Index	1.23	0.57	-0.27	2.12	394
Regulatory Quality	Index	1.24	0.40	-0.12	2.08	394
Government Effectiveness	Index	1.26	0.62	-0.62	2.36	394
Political Stability and Absence of Violence/Terrorism	Index	0.88	0.42	-0.48	1.67	379
Voice and Accountability	Index	1.19	0.32	0.24	1.83	379

Abbreviation: GDP, Gross Domestic Product; PGDP, Deflator of Gross Domestic Product.

Definitions of the quality-of-institutions indicators (as reported in the source):

1) Control of Corruption (*CC*) – capturing perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests.

2) Rule of Law (*RL*) – capturing perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence.

3) Regulatory Quality (*LQ*) – capturing perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.

4) Government Effectiveness (*GE*) – capturing perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.

5) Political Stability and Absence of Violence/Terrorism (*PV*) – capturing perceptions of the likelihood of political instability and/or politically - motivated violence, including terrorism.

6) Voice and Accountability (VA) – capturing perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media.

In addition, I use the following three dummy variables to take into account events that might have affected private investment: (1) D97, which represents the euphoria of investment during 1997. Hervey and Merkel (2001, pp. 2-3) talk about the technological change hypothesis, for the investment boom in 1998 and 1999. Hollman (2001, pp. 7-8) notes: "In 1999, manufacturing productivity increased an astonishing 6.4 percent.... The surge in U.S. productivity has led to an investment boom. Since 1991, U.S. gross private domestic investment as a share of GDP has risen steadily, reaching 17.7 percent in 1999 and a postwar high of 18.3 percent in the first half of 2000." Thus, I define D97 to take on the value of 1 for the years 1997-2000. (2) D2001, to take into account the pause of financial activity for some time after the 9/11 attack on the Twin Towers in 2001. Roberts (2009) describes the duration of this effect on p. 14 as follows: "Unlike many other disasters, the 9/11 attack had significant negative macroeconomic impacts in the very short run, and it may well have had significant negative consequences in 2002 in the absence of mitigating actions taken by the private and public sectors." Thus, I define D2001 to take on the value of 1 for the years 2001-2002. (3) D2008, to take into account the collapse of Lehman Brothers, which, like a domino, influenced business worldwide. I define D2008 to take on the value of 1 for the years 2008-2015.

4.3 Econometric methodology and results

4.3.1 Panel unit-root tests

Before proceeding to estimation, it is crucial to investigate if the two panels are nonstationary, i.e., if the variables contain unit roots, in which case the regressions would be spurious. I use the following six panel unit-root tests: (1) the Fisher – type Augmented Dickey-Fuller (ADF) test (Choi (2001)), where H_0: unit root; (2) the Fisher-PP tests (Maddala and Wu (1999)), where H_0: unit root; (3) the Im, Pesaran, Shin (2003) (IPS) test, where H_0: unit root; (4) the Levin, Lin, Chu (2002) (LLC) test, where H_0: unit root; (5) the Hadri (2000) test, where H_0: no unit root; and (6) the Breitung (2000) test, where H_0: unit root.

Table 4.3 reports a summary of the results from the unit-root tests for all the variables of interest for the 32-country panel, produced by the econometric program EViews10. The testing equations include individual constants or both individual constants and a time trend. For example, the Breitung test includes both individual constants and time trends. I consider the panel data to be stationary, I(0), when at least one unit-root test supports this hypothesis. I also applied the same unit-root tests for the 27-country panel; the results are similar to those for the 32-country panel, i.e., they suggest stationarity of the variables in the above sense.

Table 4.3: Panel unit-root tests

Test	Fisher –ADF		Fisher-PP		IPS		LLC		Hadri		Breitung	Decision
Variable	χ^2_μ	χ^2_τ	χ^2_μ	χ^2_τ	W_μ	W_τ	t^*_μ	t^*_τ	$Z_{2\mu}$	$Z_{2\tau}$	t	
CC_{it}	80.8*	95.2**	98.7**	103.9**	-1.1	-1.9**	-3.3***	-6.2***	11.1***	9.4***	2.1	I(0)
RL_{it}	75.9	85.6**	88.9**	94.1**	-0.2	1.2	-2.8	-5.6***	14.3***	10.9***	2.4	I(0)
RQ_{it}	85.6**	145.4***	82.3*	264.9***	-0.9	-6.3***	-4.1***	-12.9***	9.6***	10.0***	-4.34***	I(0)
GE_{it}	116.6***	102.2**	107.7***	151.1***	-3.6***	-2.6**	-5.9***	-5.6***	12.2***	7.5***	0.3	I(0)
PV_{it}	142.1***	129.3***	145.9***	188.4***	-5.9***	-4.9***	-8.1***	-10.6***	8.4***	8.1***	-1.2	I(0)
VA_{it}	75.3	69.5	76.1	88.9**	-0.8	-1.1	-2.7**	-6.5***	10.3***	9.0***	-1.3	I(0)
i_{it}	354.0***	114.9***	330.3***	101.7**	-4.6***	-5.0***	-11.0***	-11.2**	7.4***	9.0***	-0.9	I(0)
gi_{it}	93.4**	113.5***	344.5***	89.6**	-2.6**	-5.5***	-0.03	-11.4***	6.9***	11.4***	-0.6	I(0)
R_{it}	90.5**	105.7***	86.5**	104.2***	-2.5**	-2.9**	-3.8***	-4.5***	4.8***	5.7***	3.5***	I(0)
p_{it}	73.2	96.3**	106.4***	66.3	0.1	-2.4**	-3.5***	-2.7**	14.6***	10.8***	0.3	I(0)

Notes: (1) the subscript μ indicates that the testing equation includes only an intercept, whereas the subscript τ indicates that it includes an intercept and a trend; (2) in the Fisher-ADF, IPS, LLC, and Breitung tests, the lag length in each cross-section ADF regression is chosen by the Schwartz criterion; (3) in the Fisher-PP, LLC, and Hadri tests a kernel-based consistent estimator of the residual covariance is obtained using the lag truncation parameter selection method of Newey and West (1994); (4) in the Hadri test, H_0: no unit root, whereas in all the other tests, H_0: unit root; (5) ***, **, and * indicate statistical significance at the 1-percent, 5-percent, and 10-percent level, respectively.

4.4 Empirical specification of the Euler equation

The results of the previous section allows me to proceed with the empirical analysis since the stationarity hypothesis is supported by at least one unit-root test for all the variables of interest. In order to derive an empirical Euler equation for investment explicitly, it is necessary to specify the adjustment-cost function. As I explain in Chapter 3, I use a power-series adjustment-cost function, as in Whited (1998), the general form of which is given in Equation (3.6), which I repeat here as Equation (4.1) for convenience:

$$C(K_{t+1}, K_t, \boldsymbol{\eta}_t) = \left(\alpha_0 + \sum_{m=2}^{M} \frac{1}{m} \alpha_m \left(\frac{I_t}{K_t} \right)^m \right) K_t A_1(\boldsymbol{\eta}_t). \tag{4.1}$$

I begin estimation by assuming $M = 2$ and keep increasing the value of this truncation parameter until the coefficients of the newly inserted variables associated with the higher values of M become statistically insignificant. It turns out that the "stop value" is $M = 5$, as in Chatelain and Teurlai (2001), so I report the results for the case $M = 4$.

The Euler Equation for investment (EEI) has the form of Equation (3.26), which I repeat here as Equation (4.2) for convenience:

$$\begin{aligned} &\frac{1}{1+r_{it}} \{ A(\mathbf{v}_{it+1}) - \alpha_0 A_1(\boldsymbol{\eta}_{it+1}) + \sum_{m=2}^{M} \frac{m-1}{m} \alpha_m \left(\frac{I_{it+1}}{K_{it+1}}\right)^m A_1(\boldsymbol{\eta}_{it+1}) \\ &+ (1-\delta)[\sum_{m=2}^{M} \alpha_m \left(\frac{I_{it+1}}{K_{it+1}}\right)^{m-1} A_1(\boldsymbol{\eta}_{it+1}) + p_{it+1}]\} - \sum_{m=2}^{M} \alpha_m \left(\frac{I_{it}}{K_{it}}\right)^{m-1} A_1(\boldsymbol{\eta}_{it}) - p_{it} = \varepsilon_{it+1}. \end{aligned} \tag{4.2}$$

By expanding the polynomial in Equation (4.2) and setting $i_{it} = I_{it}/K_{it}$, $R_{it} = 1 + r_{it}$, $M = 5$, and $\delta = 0$ (to avoid over-parameterization), Equation (4.2) can be written as follows:

$$\begin{aligned} &\frac{1}{R_{it}} \{ A(\mathbf{v}_{it+1}) - \alpha_0 A_1(\boldsymbol{\eta}_{it+1}) + (\tfrac{1}{2}\alpha_2 i_{it+1}^2 + \tfrac{2}{3}\alpha_3 i_{it+1}^3 + \tfrac{3}{4}\alpha_4 i_{it+1}^4 + \tfrac{4}{5}\alpha_5 i_{it+1}^5) A_1(\boldsymbol{\eta}_{it+1}) \\ &\quad + [(\alpha_2 i_{it+1} + \alpha_3 i_{it+1}^2 + \alpha_4 i_{it+1}^3 + \alpha_5 i_{it+1}^4) A_1(\boldsymbol{\eta}_{it+1}) + p_{it+1}]\} \\ &\quad - (\alpha_2 i_{it} + \alpha_3 i_{it}^2 + \alpha_4 i_{it}^3 + \alpha_5 i_{it}^4) A_1(\boldsymbol{\eta}_{it}) - p_{it} = \varepsilon_{it+1}, \end{aligned} \tag{4.3}$$

where i = 1, 2, …, N (N = number of countries in the panel) and t = 1, 2, …, T (T = number of years for each country). For example, for M=2, Equation (4.3) becomes

$$\frac{1}{R_{\mathrm{it}}}\{A(\mathbf{v}_{\mathrm{i}t+1})-\alpha_0A_1(\boldsymbol{\eta}_{\mathrm{i}t+1})+\tfrac{1}{2}\alpha_2 i_{\mathrm{it+1}}^2A_1(\boldsymbol{\eta}_{\mathrm{i}t+1})+\alpha_2 i_{\mathrm{it+1}}A_1(\boldsymbol{\eta}_{\mathrm{i}t+1})+p_{\mathrm{it+1}}\}-\alpha_2 i_{\mathrm{it}}A_1(\boldsymbol{\eta}_{\mathrm{i}t})-p_{\mathrm{i}t}=\varepsilon_{\mathrm{i}t+1}. \quad (4.4)$$

4.4.1 Nonlinear model

In Equation (4.4), after some empirical "trial and error", I set $A(\mathbf{v}_{it}) = \gamma_0 + \gamma_1 GI_{it}$ and $A_1(\boldsymbol{\eta}_{it}) = \eta_0 + \eta_1 X_{it}$, where GI_{it} is government investment, and X_{it} is a quality-of-institutions index. Thus, Equation (4.4), where M = 2, becomes

$$\begin{aligned}&\gamma_0\frac{1}{R_{\mathrm{it}}}+\gamma_1\frac{GI_{\mathrm{i}t+1}}{R_{\mathrm{it}}}-\alpha_0\eta_0\frac{1}{R_{\mathrm{it}}}-\alpha_0\eta_1\frac{X_{\mathrm{i}t+1}}{R_{\mathrm{it}}}+\alpha_2\eta_0\frac{i_{\mathrm{it+1}}^2}{2R_{\mathrm{it}}}+\alpha_2\eta_1\frac{X_{\mathrm{i}t+1}i_{\mathrm{it+1}}^2}{2R_{\mathrm{it}}}\\&+\alpha_2\eta_0\frac{i_{\mathrm{it+1}}}{R_{\mathrm{it}}}+\alpha_2\eta_1\frac{X_{\mathrm{i}t+1}i_{\mathrm{it+1}}}{R_{\mathrm{it}}}+\frac{p_{\mathrm{it+1}}}{R_{\mathrm{it}}}-\alpha_2\eta_0 i_{\mathrm{it}}-\alpha_2\eta_1 i_{\mathrm{it}}X_{\mathrm{i}t}-p_{\mathrm{i}t}=\varepsilon_{\mathrm{i}t+1},\end{aligned} \quad (4.5)$$

or

$$\begin{aligned}&(\gamma_0-\alpha_0\eta_0)\frac{1}{R_{\mathrm{it}}}+\gamma_1\frac{GI_{\mathrm{i}t+1}}{R_{\mathrm{it}}}-\alpha_0\eta_1\frac{X_{\mathrm{i}t+1}}{R_{\mathrm{it}}}+\alpha_2\eta_0\left(\frac{i_{\mathrm{it+1}}^2}{2R_{\mathrm{it}}}+\frac{i_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i_{\mathrm{it}}\right)\\&+\alpha_2\eta_1\left(\frac{X_{\mathrm{i}t+1}i_{\mathrm{it+1}}^2}{2R_{\mathrm{it}}}+\frac{X_{\mathrm{i}t+1}i_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i_{\mathrm{it}}X_{\mathrm{i}t}\right)+\frac{p_{\mathrm{it+1}}}{R_{\mathrm{it}}}-p_{\mathrm{i}t}=\varepsilon_{\mathrm{i}t+1}.\end{aligned} \quad (4.6)$$

Similarly, for M = 3, I have that

$$\begin{aligned}&(\gamma_0-\alpha_0\eta_0)\frac{1}{R_{\mathrm{it}}}+\gamma_1\frac{GI_{\mathrm{i}t+1}}{R_{\mathrm{it}}}-\alpha_0\eta_1\frac{X_{\mathrm{i}t+1}}{R_{\mathrm{it}}}+\alpha_2\eta_0\left(\frac{i_{\mathrm{it+1}}^2}{2R_{\mathrm{it}}}+\frac{i_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i_{\mathrm{it}}\right)\\&+\alpha_2\eta_1\left(\frac{X_{\mathrm{i}t+1}i_{\mathrm{it+1}}^2}{2R_{\mathrm{it}}}+\frac{X_{\mathrm{i}t+1}i_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i_{\mathrm{it}}X_{\mathrm{i}t}\right)+\alpha_3\eta_0\left(\frac{2i_{\mathrm{it+1}}^3}{3R_{\mathrm{it}}}+\frac{i_{\mathrm{it+1}}^2}{R_{\mathrm{it}}}-i_{\mathrm{it}}^2\right)\\&+\alpha_3\eta_1\left(\frac{2X_{\mathrm{i}t+1}i_{\mathrm{it+1}}^3}{3R_{\mathrm{it}}}+\frac{X_{\mathrm{i}t+1}i_{\mathrm{it+1}}^2}{R_{\mathrm{it}}}-i_{\mathrm{it}}^2X_{\mathrm{i}t}\right)+\frac{p_{\mathrm{it+1}}}{R_{\mathrm{it}}}-p_{\mathrm{i}t}=\varepsilon_{\mathrm{i}t+1}.\end{aligned} \quad (4.7)$$

In the same way, for $M = 4$, I obtain

$$\begin{aligned}
&(\gamma_0-\alpha_0\eta_0)\frac{1}{R_{\mathrm{it}}}+\gamma_1\frac{GI_{\mathrm{i}t+1}}{R_{\mathrm{it}}}-\alpha_0\eta_1\frac{X_{\mathrm{i}t+1}}{R_{\mathrm{it}}}+\alpha_2\eta_0(\frac{i^2_{\mathrm{it+1}}}{2R_{\mathrm{it}}}+\frac{i_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i_{\mathrm{it}})\\
&+\alpha_2\eta_1(\frac{X_{it+1}i^2_{\mathrm{it+1}}}{2R_{\mathrm{it}}}+\frac{X_{it+1}i_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i_{\mathrm{it}}X_{it})+\alpha_3\eta_0(\frac{2i^3_{\mathrm{it+1}}}{3R_{\mathrm{it}}}+\frac{i^2_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^2_{\mathrm{it}})\\
&+\alpha_3\eta_1(\frac{2X_{it+1}i^3_{\mathrm{it+1}}}{3R_{\mathrm{it}}}+\frac{X_{it+1}i^2_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^2_{\mathrm{it}}X_{it})+\alpha_4\eta_0(\frac{3i^4_{\mathrm{it+1}}}{4R_{\mathrm{it}}}+\frac{i^3_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^3_{\mathrm{it}})\\
&+\alpha_4\eta_1(\frac{3X_{it+1}i^4_{\mathrm{it+1}}}{4R_{\mathrm{it}}}+\frac{X_{it+1}i^3_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^3_{\mathrm{it}}X_{it})+\frac{p_{\mathrm{it+1}}}{R_{\mathrm{it}}}-p_{it}=\varepsilon_{it+1}.
\end{aligned} \tag{4.8}$$

Finally, for $M = 5$, I obtain

$$\begin{aligned}
&(\gamma_0-\alpha_0\eta_0)\frac{1}{R_{\mathrm{it}}}+\gamma_1\frac{GI_{\mathrm{i}t+1}}{R_{\mathrm{it}}}-\alpha_0\eta_1\frac{X_{it+1}}{R_{\mathrm{it}}}\\
&+\alpha_2\eta_0(\frac{i^2_{\mathrm{it+1}}}{2R_{\mathrm{it}}}+\frac{i_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i_{\mathrm{it}})+\alpha_2\eta_1(\frac{X_{it+1}i^2_{\mathrm{it+1}}}{2R_{\mathrm{it}}}+\frac{X_{it+1}i_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i_{\mathrm{it}}X_{it})\\
&+\alpha_3\eta_0(\frac{2i^3_{\mathrm{it+1}}}{3R_{\mathrm{it}}}+\frac{i^2_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^2_{\mathrm{it}})+\alpha_3\eta_1(\frac{2X_{it+1}i^3_{\mathrm{it+1}}}{3R_{\mathrm{it}}}+\frac{X_{it+1}i^2_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^2_{\mathrm{it}}X_{it})\\
&+\alpha_4\eta_0(\frac{3i^4_{\mathrm{it+1}}}{4R_{\mathrm{it}}}+\frac{i^3_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^3_{\mathrm{it}})+\alpha_4\eta_1(\frac{3X_{it+1}i^4_{\mathrm{it+1}}}{4R_{\mathrm{it}}}+\frac{X_{it+1}i^3_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^3_{\mathrm{it}}X_{it})\\
&+\alpha_5\eta_0(\frac{4i^5_{\mathrm{it+1}}}{5R_{\mathrm{it}}}+\frac{i^4_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^4_{\mathrm{it}})+\alpha_5\eta_1(\frac{4X_{it+1}i^5_{\mathrm{it+1}}}{5R_{\mathrm{it}}}+\frac{X_{it+1}i^4_{\mathrm{it+1}}}{R_{\mathrm{it}}}-i^4_{\mathrm{it}}X_{it})\\
&+\frac{p_{\mathrm{it+1}}}{R_{\mathrm{it}}}-p_{it}=\varepsilon_{it+1}.
\end{aligned} \tag{4.9}$$

The EEI with quadratic adjustment-costs is given by Equation (B.8) of Chapter 3 and is repeated here for convenience:

$$\alpha_1 i_t A_1(\boldsymbol{\eta}_t)+p_t=\frac{1}{1+r_t}E_t\{A(\mathbf{v}_{\mathrm{t+1}})+\frac{\alpha_1}{2}(i_{t+1})^2A_1(\boldsymbol{\eta}_{t+1})+(1-\delta)[\alpha_1 i_{t+1}A_1(\boldsymbol{\eta}_{t+1})+p_{t+1}]\}.$$

The empirical form of this equation is obtained by first eliminating the expectations operator and introducing a rational expectations error (ε_{it+1}), and writing it in implicit form, as follows:

$$\frac{1}{1+r_{it}}\{A(\mathbf{v}_{\mathrm{it+1}})+\frac{\alpha_1}{2}(i_{it+1})^2A_1(\boldsymbol{\eta}_{it+1})+(1-\delta)[\alpha_1 i_{it+1}A_1(\boldsymbol{\eta}_{it+1})+p_{it+1}]\}-\alpha_1 i_{it}A_1(\boldsymbol{\eta}_{it})-p_{it}=\varepsilon_{it+1}. \tag{4.10}$$

For this special case, I set in Equation (4.10) $A_1(\boldsymbol{\eta}_{it}) = 1$ and, as before, $A(\mathbf{v}_{it}) = \gamma_0 + \gamma_1 GI_{it}$ also $\delta = 0$. Thus, the EEI for quadratic adjustment-costs is

$$\gamma_0 \frac{1}{R_{\text{it}}} + \gamma_1 \frac{GI_{\text{i}t+1}}{R_{\text{it}}} + \alpha_1 \left(\frac{i^2_{\text{it+1}}}{2R_{\text{it}}} + \frac{i_{\text{it+1}}}{R_{\text{it}}} - i_{\text{it}} \right) + \frac{p_{\text{it+1}}}{R_{\text{it}}} - p_{\text{i}t} = \varepsilon_{\text{i}t+1}. \tag{4.11}$$

4.4.1.1 Generalized Method of Moments (GMM) estimation

To estimate Equations (4.6) - (4.9) and (4.11) consistently, I apply Hansen's (1982) generalized method of moments (GMM), which is an instrumental variables estimator that addresses the issue of correlation between the variables involved in these equations and the error term. A useful and easy to understand account of the GMM is given in Adda and Cooper (2003, pp. 80-83).

I use the options of clustered standard errors that are robust to serial correlation. I adopt the fixed-effects model of panel data and assume only country-specific effects, but no time effects, so the unobserved country characteristics, assumed to be constant over time, are taken into account by country dummies, F_i. I used the empirical definition of the public investment rate, $gi_{it} = GI_{it}/GDP_{it}$. Thus, the estimating equations for $M = 2, 3, 4$, and 5, as well as the special case for quadratic adjustment-costs, are as follows:

$M = 2$:

$$\begin{aligned}
&(\gamma_0 - \alpha_0 \eta_0) \frac{1}{R_{\text{it}}} + \gamma_1 \frac{gi_{\text{i}t+1}}{R_{\text{it}}} - \alpha_0 \eta_1 \frac{X_{\text{i}t+1}}{R_{\text{it}}} + \alpha_2 \eta_0 \left(\frac{i^2_{\text{it+1}}}{2R_{\text{it}}} + \frac{i_{\text{it+1}}}{R_{\text{it}}} - i_{\text{it}} \right) \\
&+ \alpha_2 \eta_1 \left(\frac{X_{\text{it+1}} i^2_{\text{it+1}}}{2R_{\text{it}}} + \frac{X_{\text{it+1}} i_{\text{it+1}}}{R_{\text{it}}} - i_{\text{it}} X_{\text{i}t} \right) + \frac{p_{\text{it+1}}}{R_{\text{it}}} - p_{\text{i}t} \\
&+ \sum_{i=1}^{N} \beta_i F_i + \theta_1 D97 + \theta_2 D2001 + \theta_3 D2008 = \varepsilon_{\text{i}t+1}.
\end{aligned} \tag{4.12}$$

$M = 3$:

$$(\gamma_0 - \alpha_0\eta_0)\frac{1}{R_{\mathrm{it}}} + \gamma_1 \frac{gi_{\mathrm{i}t+1}}{R_{\mathrm{it}}} - \alpha_0\eta_1 \frac{X_{\mathrm{i}t+1}}{R_{\mathrm{it}}} + \alpha_2\eta_0(\frac{i^2_{\mathrm{it+1}}}{2R_{\mathrm{it}}} + \frac{i_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i_{\mathrm{it}})$$
$$+\alpha_2\eta_1(\frac{X_{\mathrm{i}t+1}i^2_{\mathrm{it+1}}}{2R_{\mathrm{it}}} + \frac{X_{\mathrm{i}t+1}i_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i_{\mathrm{it}}X_{\mathrm{i}t}) + \alpha_3\eta_0(\frac{2i^3_{\mathrm{it+1}}}{3R_{\mathrm{it}}} + \frac{i^2_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i^2_{\mathrm{it}})$$
$$+\alpha_3\eta_1(\frac{2X_{\mathrm{i}t+1}i^3_{\mathrm{it+1}}}{3R_{\mathrm{it}}} + \frac{X_{\mathrm{i}t+1}i^2_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i^2_{\mathrm{it}}X_{\mathrm{i}t}) + \frac{p_{\mathrm{it+1}}}{R_{\mathrm{it}}} - p_{\mathrm{i}t}$$
$$+\sum_{i=1}^{N}\beta_i F_i + \theta_1 D97 + \theta_2 D2001 + \theta_3 D2008 = \varepsilon_{\mathrm{i}t+1}. \tag{4.13}$$

$M = 4$:

$$(\gamma_0 - \alpha_0\eta_0)\frac{1}{R_{\mathrm{it}}} + \gamma_1 \frac{gi_{\mathrm{i}t+1}}{R_{\mathrm{it}}} - \alpha_0\eta_1 \frac{X_{\mathrm{i}t+1}}{R_{\mathrm{it}}} + \alpha_2\eta_0(\frac{i^2_{\mathrm{it+1}}}{2R_{\mathrm{it}}} + \frac{i_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i_{\mathrm{it}})$$
$$+\alpha_2\eta_1(\frac{X_{\mathrm{i}t+1}i^2_{\mathrm{it+1}}}{2R_{\mathrm{it}}} + \frac{X_{\mathrm{i}t+1}i_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i_{\mathrm{it}}X_{\mathrm{i}t}) + \alpha_3\eta_0(\frac{2i^3_{\mathrm{it+1}}}{3R_{\mathrm{it}}} + \frac{i^2_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i^2_{\mathrm{it}})$$
$$+\alpha_3\eta_1(\frac{2X_{\mathrm{i}t+1}i^3_{\mathrm{it+1}}}{3R_{\mathrm{it}}} + \frac{X_{\mathrm{i}t+1}i^2_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i^2_{\mathrm{it}}X_{\mathrm{i}t}) + \alpha_4\eta_0(\frac{3i^4_{\mathrm{it+1}}}{4R_{\mathrm{it}}} + \frac{i^3_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i^3_{\mathrm{it}})$$
$$+\alpha_4\eta_1(\frac{3X_{\mathrm{i}t+1}i^4_{\mathrm{it+1}}}{4R_{\mathrm{it}}} + \frac{X_{\mathrm{i}t+1}i^3_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i^3_{\mathrm{it}}X_{\mathrm{i}t}) + \frac{p_{\mathrm{it+1}}}{R_{\mathrm{it}}} - p_{\mathrm{i}t}$$
$$+\sum_{i=1}^{N}\beta_i F_i + \theta_1 D97 + \theta_2 D2001 + \theta_3 D2008 = \varepsilon_{\mathrm{i}t+1}. \tag{4.14}$$

$M = 5$:

$$
\begin{aligned}
&(\gamma_0 - \alpha_0\eta_0)\frac{1}{R_{\mathrm{it}}} + \gamma_1 \frac{gi_{it+1}}{R_{\mathrm{it}}} - \alpha_0\eta_1 \frac{X_{it+1}}{R_{\mathrm{it}}} \\
&+\alpha_2\eta_0\left(\frac{i_{\mathrm{it+1}}^2}{2R_{\mathrm{it}}} + \frac{i_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i_{\mathrm{it}}\right) + \alpha_2\eta_1\left(\frac{X_{it+1}i_{\mathrm{it+1}}^2}{2R_{\mathrm{it}}} + \frac{X_{it+1}i_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i_{\mathrm{it}}X_{it}\right) \\
&+\alpha_3\eta_0\left(\frac{2i_{\mathrm{it+1}}^3}{3R_{\mathrm{it}}} + \frac{i_{\mathrm{it+1}}^2}{R_{\mathrm{it}}} - i_{\mathrm{it}}^2\right) + \alpha_3\eta_1\left(\frac{2X_{it+1}i_{\mathrm{it+1}}^3}{3R_{\mathrm{it}}} + \frac{X_{it+1}i_{\mathrm{it+1}}^2}{R_{\mathrm{it}}} - i_{\mathrm{it}}^2X_{it}\right) \\
&+\alpha_4\eta_0\left(\frac{3i_{\mathrm{it+1}}^4}{4R_{\mathrm{it}}} + \frac{i_{\mathrm{it+1}}^3}{R_{\mathrm{it}}} - i_{\mathrm{it}}^3\right) + \alpha_4\eta_1\left(\frac{3X_{it+1}i_{\mathrm{it+1}}^4}{4R_{\mathrm{it}}} + \frac{X_{it+1}i_{\mathrm{it+1}}^3}{R_{\mathrm{it}}} - i_{\mathrm{it}}^3X_{it}\right) \\
&+\alpha_5\eta_0\left(\frac{4i_{\mathrm{it+1}}^5}{5R_{\mathrm{it}}} + \frac{i_{\mathrm{it+1}}^4}{R_{\mathrm{it}}} - i_{\mathrm{it}}^4\right) + \alpha_5\eta_1\left(\frac{4X_{it+1}i_{\mathrm{it+1}}^5}{5R_{\mathrm{it}}} + \frac{X_{it+1}i_{\mathrm{it+1}}^4}{R_{\mathrm{it}}} - i_{\mathrm{it}}^4X_{it}\right) \\
&+\frac{p_{\mathrm{it+1}}}{R_{\mathrm{it}}} - p_{\mathrm{it}} + \sum_{i=1}^{N}\beta_iF_i + \theta_1 D97 + \theta_2 D2001 + \theta_3 D2008 = \varepsilon_{it+1}.
\end{aligned}
\tag{4.15}
$$

Quadratic adjustment costs:

$$
\begin{aligned}
&\gamma_0\frac{1}{R_{\mathrm{it}}} + \gamma_1\frac{gi_{it+1}}{R_{\mathrm{it}}} + \alpha_1\left(\frac{i_{\mathrm{it+1}}^2}{2R_{\mathrm{it}}} + \frac{i_{\mathrm{it+1}}}{R_{\mathrm{it}}} - i_{\mathrm{it}}\right) + \frac{p_{\mathrm{it+1}}}{R_{\mathrm{it}}} - p_{it} \\
&+\sum_{i=1}^{N}\beta_iF_i + \theta_1 D97 + \theta_2 D2001 + \theta_3 D2008 = \varepsilon_{it+1}.
\end{aligned}
\tag{4.16}
$$

Note that the estimating Equations (4.12) – (4.16) do not contain a constant term, so I use as many country dummies as the number of countries in the panel (*N*). Note also that the empirical definition of the private investment rate (i_{it}) used in the estimation of these equations is $i_{it} = I_{it}/GDP_{it}$, instead of the theoretical investment rate, $i_{it} = I_{it}/K_{it}$, because the former definition produced better results.

Another issue in the estimating Equations (4.12) - (4.15) is that they are nonlinear in parameters, which appear as products, except for γ_1, which appears linearly. In this case, nonlinear GMM fails to produce estimates of the original parameters (γ_0, γ_1, η_0, η_1, α_0, α_2, α_3), so I introduce the new parameters D_0, D_1, D_2, D_3, D_4, D_5, in order to make the estimating equations linear in these new parameters, which are defined as follows:

$D_0 = \gamma_0 - \alpha_0\eta_0$

$D_1 = -\alpha_0\eta_1$

$D_2 = \alpha_2\eta_0$

$D_3 = \alpha_2\eta_1$

$D_4 = \alpha_3\eta_0$

$D_5 = \alpha_3\eta_1$

Note, however, that an identification problem arises. For example, in the case $M = 2$, Equation (4.12), there are four estimable parameters (D_0, D_1, D_2, D_3) from which *five* original parameters are to be recovered (γ_0, η_0, η_1, α_0, α_2). Therefore, an identifying restriction must be imposed. Somewhat intuitively, I choose to impose the restriction $\eta_1 = -1$, as better quality of institutions is expected to reduce adjustment costs. By embodying this restriction in the corresponding variables, the latter are redefined, and so are the new parameters (the D's), e.g., by setting in Equation (4.12)

$$W_{it} = \frac{1}{R_{\text{it}}},$$

$$Y_{0,\, it+1} = \frac{gi_{it+1}}{R_{\text{it}}}$$

$$Y_{1,\, it+1} = -\frac{X_{it+1}}{R_{\text{it}}},$$

$$Y_{2,\, it+1} = \frac{i_{\text{it+1}}^2}{2R_{\text{it}}} + \frac{i_{\text{it+1}}}{R_{\text{it}}} - i_{\text{it}},$$

$$Y_{3,\, it+1} = -\left(\frac{X_{it+1} i_{\text{it+1}}^2}{2R_{\text{it}}} + \frac{X_{it+1} i_{\text{it+1}}}{R_{\text{it}}} - i_{\text{it}} X_{it}\right),$$

and

$$Y_{4,\, it+1} = \frac{p_{it+1}}{R_{\text{it}}}$$

that equation can be written as

$$D_0 W_{it} + \gamma_1 Y_{0,\, it+1} + D_1 Y_{1,\, it+1} + D_2 Y_{2,\, it+1} + D_3 Y_{3,\, it+1} + Y_{4,\, it+1} - p_{it} + \sum_{i=1}^{N} \beta_i F_i + \theta_1 D97 + \theta_2 D2001 + \theta_3 D2008 = \varepsilon_{it+1}, \qquad (4.12)'$$

where the new parameters are related to the original ones as follows:

$D_0 = \gamma_0 - \alpha_0\eta_0$

$D_1 = -\alpha_0$

$D_2 = \alpha_2\eta_0$

$D_3 = \alpha_2$.

From these definitions, I obtain

$\eta_0 = D_2/D_3$

$\alpha_0 = -D_1$

$\alpha_2 = D_3$

$\gamma_0 = D_0 - D_1D_2/D_3$.

Thus, by imposing the identifying restriction $\eta_1 = -1$ on Equation (4.12), all of its parameters (γ_0, γ_1, η_0, α_0, α_2, α_3) are now identifiable, and hence estimable. Approximate standard errors for the estimated coefficients η_0 and γ_0 are calculated in Appendix 4A.

4.4.1.2 Choice of instruments

A critical issue in the application of GMM is the choice of instrumental variables (IVs), which should be correlated with the variables in the equation, but uncorrelated with the error term. It is common to test the validity of the instruments using Hansen's (1982) *J*-statistic, a specification test known as the test of over-identifying restrictions. The statistic *J* is asymptotically distributed as χ^2 with degrees of freedom equal to the number of instruments minus the number of estimated parameters. The instrument sets I used for each case are as follows:

A. For the OECD panel:

a. IV set for $M = 2$

($1/R_{it\text{-}1}$, $gi_{it\text{-}1}$, $p_{it\text{-}1}$, $i_{it\text{-}1}$, $i^2_{\text{it-1}}$, *D97*, *D2001*, *D2008*, F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, F_{13}, F_{14}, F_{15}, F_{16}, F_{17}, F_{18}, F_{19}, F_{20}, F_{21}, F_{22}, F_{23}, F_{24}, F_{25}, F_{26}, F_{27}, constant), which contains 36 IVs;

b. IV set for $M = 3$

($1/R_{it\text{-}1}$, $gi_{it\text{-}1}$, $p_{it\text{-}1}$, $i_{it\text{-}1}$, $i^2_{\text{it-1}}$, $i^3_{\text{it-1}}$, *D97*, *D2001*, *D2008,* F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, F_{13}, F_{14}, F_{15}, F_{16}, F_{17}, F_{18}, F_{19}, F_{20}, F_{21}, F_{22}, F_{23}, F_{24}, F_{25}, F_{26}, F_{27}, constant), which contains 37 IVs;

c. IV set for $M = 4$

($1/R_{it\text{-}1}$, $gi_{it\text{-}1}$, $p_{it\text{-}1}$, $i_{it\text{-}1}$, *D97*, *D2001*, *D2008*, F_1, F_2, F_3, F_4, F_5, F_6, F_7, F_8, F_9, F_{10}, F_{11}, F_{12}, F_{13}, F_{14}, F_{15}, F_{16}, F_{17}, F_{18}, F_{19}, F_{20}, F_{21}, F_{22}, F_{23}, F_{24}, F_{25}, F_{26}, F_{27}, constant), which contains 35 IVs;

d. IV set for the special case of quadratic adjustment costs

($1/R_{it\text{-}1}$, $gi_{it\text{-}1}$, $p_{it\text{-}1}$, $i_{it\text{-}1}$, F_5, F_9, F_{10}, F_{11}, F_{21}, F_{26}, constant), which contains 11 IVs.

B. For the 32-country panel, the IV set used for the case $M = 4$ is as follows:

($1/R_{it\text{-}1}$, $gi_{it\text{-}1}$, $p_{it\text{-}1}$, F_6, F_9, F_{10}, F_{13}, F_{15}, F_{17}, F_{18}, F_{19}, F_{20}, F_{21}, F_{22}, F_{23}, F_{24}, F_{25}, F_{27}, F_{29}, F_{30}, constant), which contains 21 IVs.

4.4.1.3 Choice of the value of the truncation parameter

The procedure I follow to determine empirically the value of the truncation parameter M is to estimate first Equation (4.12), the case of $M = 2$. Since all of its coefficients are statistically significant, I go on by estimating Equation (4.13) (where $M = 3$), which involves two additional terms and which are also statistically significant. Thus, I proceed with Equation (4.14) ($M = 4$), where one of the two additional terms is insignificant. Finally, I estimate Equation (4.15) ($M = 5$), where both of the additional terms are statistically insignificant. This suggests that, empirically, the "optimal" value of M is 4.

4.4.1.4 Results

The results, produced by using the econometric software STATA 15, are reported in Table 4.4 for each of the six quality-of-institutions indices for the OECD panel, and in Table 4.5 for the 32-country panel. The estimates of the parameter of interest (γ_1) are fairly robust to the substantial change in the sample from a 27-country panel to a 32-country panel. These estimates suggest that there is direct crowding-in effect, i.e., public investment is a complement to private investment, that is, it encourages it. The estimates of the parameters of the adjustment-cost function (α_0, α_2, α_3, α_4) relate to its curvature and imply that adjustment costs are positive for every country and every year in the sample. This claim has been confirmed by substituting the estimates of α_0, α_2, α_3, and α_4 from the first row of Table 4.4 into the adjustment-cost function, Equation (4.1), where the function $A_1(\eta_t)$ was ignored, as its attachment to it serves the purpose of allowing the estimation of the effects of the quality-of-institutions variables on the adjustment costs, but are not part of the latter. Note also that in Equation (4.1), the variables are measured as ratios, not as percentages. Finally, note that the dummies $D97$, $D2001$, and $D2008$ were insignificant and were dropped, one at a time.

As an additional robustness check, I also tried the alternative value of the identifying restriction η_1 = -0.5 in the case of the 32-country panel, M = 4, and X = Control of Corruption index, while leaving other things equal. This did not change the estimates of the parameter of interest ($\hat{\gamma}_1$); the estimates $\hat{\alpha}_0$, $\hat{\alpha}_2$, $\hat{\alpha}_3$, and $\hat{\alpha}_4$ doubled in size; $\hat{\gamma}_0$ did not change; $\hat{\eta}_0$ was halved; and all of these coefficients remained statistically significant.

Table 4.4: Estimation of Equation (4.14), *M*=4, by GMM, with clustered standard errors, using the panel of 27 OECD countries

	$\hat{\gamma}_0$	$\hat{\gamma}_1$	$\hat{\eta}_0$	$\hat{\alpha}_0$	$\hat{\alpha}_2$	$\hat{\alpha}_3$	$\hat{\alpha}_4$	*J*-statistic	*n*
Control of Corruption									
	3.27	0.40***	-3.81*	5.50*	0.10***	-0.008***	0.0002***	18.86	245
	(0.43)	(2.6)	(-1.3)	(1.7)	(3.5)	(-3.8)	(4.1)	(0.53)	
Political Stability									
	14.65***	0.42**	-0.94***	8.32**	0.41***	-0.02***	0.0005***	10.58	219
	(3.9)	(2.9)	(-3.9)	(2.4)	(6.04)	(-10.4)	(14.7)	(0.97)	
Rule of law									
	25.81***	0.37**	-3.20***	-	0.13***	-0.01***	0.0002***	17.52	245
	(13.6)	(2.2)	(-5.7)		(4.8)	(-5.2)	(5.6)	(0.68)	
Government Efficiency									
	25.81***	0.46**	-3.09***	-	0.14***	-0.01***	0.0002***	14.63	245
	(12.3)	(3.1)	(-6.7)		(4.8)	(-5.2)	(5.6)	(0.84)	
Regulatory Quality									
	26.96***	0.37**	-2.53***	-	0.17***	-0.01***	0.0003***	23.9	245
	(14.8)	(2.3)	(-6.1)		(5.01)	(-5.34)	(5.7)	(0.30)	
Voice of Accountability									
	28.33***	0.45***	-2.58***	-	0.18***	-0.01***	0.0003***	13.65	219
	(12.1)	(3.5)	(-4.2)		(4.1)	(-4.9)	(5.9)	(0.88)	

Notes: (1) ***, **, and * indicate statistical significance at the 1-percent, 5-percent, and 10-percent level, respectively; (2) the values in parentheses below coefficient estimates are z-statistics; (3) those for $\hat{\gamma}_0$ and $\hat{\eta}_0$ are based on approximate standard errors (see Appendix 4A); (4) the values in parentheses below the *J*-statistic are *p*-values; (5) *n* = number of observations actually used in estimation.

Table 4.5: Estimation of Equation (4.14), *M*=4, by GMM, with clustered standard errors, using the panel of 32 countries

	$\hat{\gamma}_0$	$\hat{\gamma}_1$	$\hat{\eta}_0$	$\hat{\alpha}_0$	$\hat{\alpha}_2$	$\hat{\alpha}_3$	$\hat{\alpha}_4$	*J*-statistic	*n*
Control of Corruption									
	1.70***	0.55**	-0.44***	16.11**	0.47***	-0.02***	0.0003***	16.90	283
	(4.18)	(2.2)	(-3.8)	(4.1)	(3.7)	(-3.5)	(3.4)	(0.03)	
Political Stability									
	-4.35**	0.48*	-0.30***	27.80***	0.67***	-0.02***	0.0004***	14.50	257
	(-2.3)	(1.8)	(-2.8)	(4.6)	(3.9)	(-3.6)	(3.7)	(0.07)	
Rule of law									
	1.24**	0.59**	-0.38**	17.83***	0.51**	-0.02**	0.0003**	17.05	283
	(3.02)	(2.2)	(-3.2)	(3.8)	(3.4)	(-3.3)	(3.2)	(0.03)	
Government Efficiency									
	1.68***	0.60**	-0.43***	16.80***	0.49***	-0.02***	0.0003***	18.80	283
	(6.1)	(2.2)	(-3.8)	(4.1)	(3.7)	(-3.6)	(3.6)	(0.02)	
Regulatory Quality									
	-3.60**	0.60**	-0.24**	21.45***	0.51***	-0.02***	0.0003***	11.10	283
	(-2.5)	(2.7)	(-2.7)	(5.1)	(4.7)	(-4.4)	(4.1)	(0.20)	
Voice of Accountability									
	16.10***	0.32	10.4	-	0.12*	-0.005*	-	1.17	257
	(4.8)	(1.0)	(1.3)		(1.7)	(-1.8)		(0.56)	

Notes: (1) ***, **, and * indicate statistical significance at the 1-percent, 5-percent, and 10-percent level, respectively; (2) the values in parentheses below coefficient estimates are *z*-statistics; (3) those for $\hat{\gamma}_0$ and $\hat{\eta}_0$ are based on approximate standard errors (see Appendix 4A); (4) the values in parentheses below the *J*-statistic are *p*-values; (5) *n* = number of observations actually used in estimation.

Note that I included only one index of the quality of institutions at a time in the $A_1(\boldsymbol{\eta}_{it})$ function, as these indices are highly positively correlated, as shown in the correlation matrix below. For example, the correlation coefficient between Control of Corruption and Rule of Law is 0.94. Thus, the simultaneous inclusion of several of these indices would only cause over-parameterization and, as usual, it would cause multicollinearity and large standard errors.

Table 4.6: Correlation matrix amongst the six indices of the quality of institutions

	Control of corruption	**Rule of Law**	**Regulatory Quality**	**Government effectiveness**	**Political Stability**	**Voice of accountability**
Control of corruption	1					
Rule of Law	0.9448	1				
Regulatory Quality	0.8247	0.8440	1			
Government effectiveness	0.9349	0.9362	0.8323	1		
Political Stability	0.6274	0.6524	0.5821	0.6192	1	
Voice of account-ability	0.9135	0.9171	0.8441	0.9038	0.6513	1

In the special case of quadratic adjustment costs, I use the result proved in Appendix 3.A, the investment function that has public investment as an explanatory variable. I derive the EEI for this special case in Appendix 3.B, and the estimating equation is Equation (4.16), which gives a negative, but insignificant, estimate of γ_1, namely, $\hat{\gamma}_1$ = -0.04 (z = -0.10, p-value = 0.92, n = 209). In addition, the value of the J statistic is 100.7 with a p-value = 0.0000, which strongly rejects the model with quadratic adjustment costs as misspecified. Evidently, the power-series adjustment-cost function improves the model's performance substantially.

Generally, the results reported in Tables 4.4 and 4.5 can be considered reliable, as the specification test (the *J*-statistic) does not reject the model, even at levels of significance as high as 97%. An important conclusion is that the coefficients of the higher powers of the power-series adjustment-cost function are statistically significant, which is evidence that the EEI based on the quadratic adjustment-cost function is misspecified.

4.5 Summary

In this chapter, I have used two panel data sets to investigate empirically the direct crowding-in/out effect of public investment on private investment. Estimation of the Euler equations for investment (4.12) - (4.16) by GMM generated reliable evidence in favor of the direct crowding-in effect as well as in favor of the power-series adjustment-cost function, and against the quadratic adjustment-cost function.

Appendix 4.A: Approximate standard errors of the estimated coefficients

Given the definitions of the new parameters (the *D*'s) in section 4.4.1.1, I explain here how I calculate approximate standard errors for the estimated parameters of interest. Let

$$\gamma_0 = D_0 - D_1 D_2 / D_3 = f\left(D_0, D_1, D_2, D_3\right)$$

Apply the formula:

$$Var(\hat{\gamma}_0) \approx \sum_{i=0}^{3} \left(\frac{\partial f}{\partial D_i}\right)^2 Var(\hat{D}_i) \; + \; 2\sum_{i<j} \left(\frac{\partial f}{\partial D_i}\right)\left(\frac{\partial f}{\partial D_j}\right) Cov(\hat{D}_i, \hat{D}_j). \qquad \text{(C.1)}$$

Or

$$\begin{aligned} Var(\hat{\gamma}_0) \approx & \left(\frac{\partial f}{\partial D_0}\right)^2 Var(\hat{D}_0) + \left(\frac{\partial f}{\partial D_1}\right)^2 Var(\hat{D}_1) + \left(\frac{\partial f}{\partial D_2}\right)^2 Var(\hat{D}_2) + \left(\frac{\partial f}{\partial D_3}\right)^2 Var(\hat{D}_3) \\ & + 2\left(\frac{\partial f}{\partial D_0}\right)\left(\frac{\partial f}{\partial D_1}\right) Cov(\hat{D}_0, \hat{D}_1) + 2\left(\frac{\partial f}{\partial D_0}\right)\left(\frac{\partial f}{\partial D_2}\right) Cov(\hat{D}_0, \hat{D}_2) \\ & + 2\left(\frac{\partial f}{\partial D_0}\right)\left(\frac{\partial f}{\partial D_3}\right) Cov(\hat{D}_0, \hat{D}_3) + 2\left(\frac{\partial f}{\partial D_1}\right)\left(\frac{\partial f}{\partial D_2}\right) Cov(\hat{D}_1, \hat{D}_2) \\ & + 2\left(\frac{\partial f}{\partial D_1}\right)\left(\frac{\partial f}{\partial D_3}\right) Cov(\hat{D}_1, \hat{D}_3) + 2\left(\frac{\partial f}{\partial D_2}\right)\left(\frac{\partial f}{\partial D_3}\right) Cov(\hat{D}_2, \hat{D}_3), \end{aligned} \qquad \text{(C.2)}$$

where

$$\frac{\partial f}{\partial D_0} = 1.$$

$$\frac{\partial f}{\partial D_1} = -\frac{\hat{D}_2}{\hat{D}_3}.$$

$$\frac{\partial f}{\partial D_2} = -\frac{\hat{D}_1}{\hat{D}_3}.$$

$$\frac{\partial f}{\partial D_3} = \frac{\hat{D}_1 \hat{D}_2}{\hat{D}_3^{\,2}}.$$

Then the approximate standard error of $\hat{\gamma}_0$ is $\sqrt{Var(\hat{\gamma}_0)}$, where

$$Var(\hat{\gamma}_0) \approx Var(\hat{D}_0) + (-\frac{\hat{D}_2}{\hat{D}_3})^2 Var(\hat{D}_1) + (-\frac{\hat{D}_1}{\hat{D}_3})^2 Var(\hat{D}_2) + (\frac{\hat{D}_1\hat{D}_2}{\hat{D}_3^{\,2}})^2 Var(\hat{D}_3)$$
$$+ 2(-\frac{\hat{D}_2}{\hat{D}_3})Cov(\hat{D}_0, \hat{D}_1) + 2(-\frac{\hat{D}_1}{\hat{D}_3})Cov(\hat{D}_0, \hat{D}_2) + 2(\frac{\hat{D}_1\hat{D}_2}{\hat{D}_3^{\,2}})Cov(\hat{D}_0, \hat{D}_3)$$
$$+ 2(-\frac{\hat{D}_2}{\hat{D}_3})(-\frac{\hat{D}_1}{\hat{D}_3})Cov(\hat{D}_1, \hat{D}_2) + 2(-\frac{\hat{D}_2}{\hat{D}_3})(\frac{\hat{D}_1\hat{D}_2}{\hat{D}_3^{\,2}})Cov(\hat{D}_1, \hat{D}_3) \quad \text{(C.3)}$$
$$+ 2(-\frac{\hat{D}_1}{\hat{D}_3})(\frac{\hat{D}_1\hat{D}_2}{\hat{D}_3^{\,2}})Cov(\hat{D}_2, \hat{D}_3),$$

To calculate the approximate variance of $\hat{\eta}_0$, let[14]

$$\eta_0 = D_2/D_3 = f(D_2, D_3),$$

so

$$Var(\hat{\eta}_0) \approx \left(\frac{\partial f}{\partial D_2}\right)^2 Var(\hat{D}_2) + \left(\frac{\partial f}{\partial D_3}\right)^2 Var(\hat{D}_3) + 2\left(\frac{\partial f}{\partial D_2}\right)\left(\frac{\partial f}{\partial D_3}\right)Cov(\hat{D}_2, \hat{D}_3), \quad \text{(C.4)}$$

where

$$\frac{\partial f}{\partial D_2} = \frac{1}{\hat{D}_3}$$

and

$$\frac{\partial f}{\partial D_3} = -\frac{D_2}{D_3^{\,2}}.$$

Thus,

$$Var(\hat{\eta}_0) \approx (\frac{1}{\hat{D}_3})^2 Var(\hat{D}_2) + (-\frac{\hat{D}_2}{\hat{D}_3^{\,2}})^2 Var(\hat{D}_3) + 2(\frac{1}{\hat{D}_3})(-\frac{\hat{D}_2}{\hat{D}_3^{\,2}})Cov(\hat{D}_2, \hat{D}_3). \quad \text{(C.5)}$$

Since $\alpha_0 = -D_1$, it follows that $Var(\hat{a}_0) = Var(\hat{D}_1)$. Similarly, in the case of M=2, $\alpha_2 = D_3$, so $Var(\hat{a}_2) = Var(\hat{D}_3)$. In the case of M=3, $\alpha_3 = D_5$, so $Var(\hat{a}_3) = Var(\hat{D}_5)$, and in the case of M=4, $\alpha_4 = D_7$, so $Var(\hat{a}_4) = Var(\hat{D}_7)$.

[14] Note that η_0 is over-identified: $\eta_0 = D_2/D_3$ or $\eta_0 = D_2/D_4$.

Chapter 5

CONCLUSIONS

The main purpose of this study has been to investigate the direct effect, if any, of public investment on private investment. To this end, I derive an Euler Equation for private investment using dynamic programming and optimal control methods and estimate it by applying GMM to two panel data sets. The innovation of the study is that it models some socioeconomic indices as exogenous shocks to the adjustment costs. Following Whited (1998), I model adjustment costs as a power series function of the private investment rate, where the cut-off point of the power series is determined empirically.

Using two panel data sets of annual aggregate data, 1996-2015, one from 27 OECD countries and another from 32 countries, which consists of the 27 OECD countries included in the first panel and five additional non-OECD countries, I estimate the Euler Equation for private investment by GMM. The results support the idea of direct crowding-in. They also support the specification of the adjustment-cost function as a power series and strongly reject its specification as a quadratic function, which confirms the relevant empirical literature.

As a policy conclusion, the governments of the countries included in the two panels should consider increasing public investment in sectors where it can be most productive, e.g., in infrastructure. They should also consider improving the quality of their institutions, thus reducing adjustment costs and enhancing further private investment, which drives economic growth.

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APPENDIX

Appendix Table 1: Data sources

Variables	Original series	Units	Source
Private Investment	Private gross fixed capital formation	EURO	AMECO (UIGP)
Public/Government Investment	Public gross fixed capital formation	EURO	AMECO (UIGG)
Relative price of capital	Price deflator gross fixed capital formation (total economy) / Price deflator gross domestic product		AMECO (PIGT)/(PVGD)
Real interest rate	Real long-term interest rates, deflator GDP	%	AMECO (ILRV)
Control of Corruption	Capturing perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests.	Index with range -2.5 up to 2.5	World Bank
Voice and Accountability	Capturing perceptions of the extent to which a country's citizens are able to participate in selecting their government, as well as freedom of expression, freedom of association, and a free media.	Index with range -2.5 up to 2.5	World Bank
Political Stability and Absence of Violence	Capturing perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism.	Index with range -2.5 up to 2.5	World Bank

Government Effectiveness	Capturing perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies.	Index with range -2.5 up to 2.5	World Bank
Regulatory Quality	Capturing perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development.	Index with range -2.5 up to 2.5	World Bank
Rule of Law	Capturing perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood crime & violence.	Index with range -2.5 up to 2.5	World Bank

Abbreviations: GDP, Gross Domestic Product.