OPENING THE BLACK BOX: AGGREGATE IMPLICATIONS OF PUBLIC INVESTMENT HETEROGENEITY

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Abstract

With multiple types of public capital, the aggregate implications of public investment crucially depend on the sum of the output elasticities of public capital across types. Abstracting from this heterogeneity and considering a single homogeneous type underestimates the effects of public investment. This is because the output elasticity of aggregate public capital is biased: it does not coincide with the sum of output elasticities of the different types. A quantitative model with public investment in equipment, structures, and intangibles implies substantial negative bias. Heterogeneity in public investment roughly doubles the long-run fiscal multiplier and optimal scale of public investment.

Keywords: public capital, intellectual property products, equipment, structures, fiscal multiplier.

JEL classification: E22, E62, H54.

Resumen

Las implicaciones agregadas de la inversión pública (con múltiples tipos de capital público), dependen, de forma crucial, de la suma de las elasticidades de producción del capital público entre los distintos tipos. Abstraerse de esta heterogeneidad y considerar un solo tipo homogéneo supone subestimar los efectos de la inversión pública. Ello se debe a que la elasticidad de producción del capital público agregado está sesgada: no coincide con la suma de las elasticidades de producción de los distintos tipos. Un modelo cuantitativo con inversión pública en equipos, estructuras e intangibles implica un sesgo negativo sustancial. La heterogeneidad en la inversión pública, aproximadamente, duplica el multiplicador fiscal a largo plazo y la inversión pública óptima.

Palabras clave: capital público, productos de propiedad intelectual, equipos, estructuras, multiplicador fiscal.

Códigos JEL: E22, E62, H54.

1 Introduction

Public investment is a multifaceted concept that encompasses a broad spectrum of assets consisting of equipment (e.g., military hardware, machineries, and vehicles), structures (e.g., residential housing, highways), and intellectual property products (IPP—e.g., R&D and software). For instance, the Inflation Reduction Act included measures to boost investment in semiconductor equipment, infrastructure for the distribution and storage of clean energy, as well as R&D in high-tech manufacturing. Despite this observation, the macroeconomic literature on public investment predominantly narrows its focus to a single type of public investment and thus on a homogenous stock of public capital. In this paper, show that heterogeneity in public investment is critical for understanding the aggregate effects of public spending.

We start with a simple economy with multiple types of public capital. The production side consists of a firm assembling output using labor. The government uses lump-sum taxes to finance exogenous spending in multiple types of public investment. The stock of public capital of each type raises the productivity of private inputs to an extent that is defined by the output elasticity of public capital. Public capital types differ along two dimensions: the output elasticities and the size of their stocks.

We analytically derive the optimal amount of public investment and the output response to a change in public investment and find that both depend positively on the *sum* of the output elasticities across types. We then ask what is the output elasticity of aggregate public capital that the econometrician recovers from the data when our model with multiple types is the true data generating process. Using the estimation procedure of Bouakez et al. (2017) and Ramey (2021), who regress the logarithm of aggregate productivity on the logarithm of the aggregate stock of public capital, we show that the econometrician estimates an aggregate output elasticity which is a *weighted sum* of the output elasticities across types.

When the stocks of public capital are homogeneous across types, the weights equal to one, so that the aggregate output elasticity coincides with the sum of the output elasticities across types. In this case, even though types may differ in the output elasticities, a model with a single type of public capital yields exactly the same aggregate implications of public investment than a multiple-type economy.

However, this is not the case when public capital stocks are heterogeneous across types. In this instance, the weights differ from one: the aggregate output elasticity is biased as it does not coincide anymore with the sum of types' output elasticities. Consequently, considering a unique type of public capital mismeasures the effects of public investment. The direction and extent of the bias depend on the correlation between output elasticities and public capital stocks across types. If types with high output elasticities have large public capital stocks, the bias is positive: the aggregate output elasticity is higher than the sum of types' output elasticities, and a single-type model overstates the aggregate effects of public investment. On the contrary, in the empirically relevant case, when output elasticity and public capital stocks are not strongly correlated across types, the bias turns into negative: a single-type model underestimates the implications of public investment.

We then extend the simple framework into a fully-fledged model by introducing three different types of public investment and public capital—public equipment, structures, and IPP—into an otherwise standard New Keynesian economy. As in the simple framework, the three types differ in terms of the output elasticities and the stocks of public capital. The latter comes from heterogeneity in public capital depreciation rates and public investment shares (i.e., the share of total public investment into each type). We also consider heterogeneity in time-to-build and time-to-spend delays.

We leverage information on the U.S. economy to discipline the extent of heterogeneity across public investment types. The output elasticity of IPP capital is set to 0.07, in line with recent evidence of Fieldhouse and Mertens (2023) on the effects of public R&D on productivity. The elasticity of structures equals 0.05, as in Ramey (2021), while that of equipment is 0.005, intended as the lowest productive value for this type of public capital.[1] The depreciation rates are set using data from the U.S. Bureau of Economic Analysis (BEA) on the depreciation and the net stock of public capital by type. We find annual depreciation rates of 12.4% for equipment, 1.9% for structures, and 17.0% for IPP. Finally, equipment, structures, and IPP account for 26%, 45%, and 29% of total public investment, respectively.

The data indicate that while IPP has the highest output elasticity, it features the lowest stock of public capital. The latter is due to the combination of a low public investment share and a high depreciation rate. This implies that the correlation between output elasticities and public capital stocks across types is close to zero. Accordingly, our simple theoretical setting predicts that the aggregate output elasticity should feature a negative bias. To verify it, we simulate our three-type model and estimate the aggregate output elasticity using only information on aggregate public capital and observed aggregate productivity. We find a substantial negative bias: the estimate of the aggregate output elasticity is 0.0718, almost half of the sum of the output elasticities across the three types.

The negative bias of the aggregate output elasticity implies that a model with a single type of public capital understates the aggregate effects of public investment. We find this underestimation to be severe. We start by computing the

[1]We also provide empirical evidence supporting our calibration choices, highlighting that, if anything, the calibration of the elasticity of IPP capital is conservative, while that of equipment is overstated.

steady-state optimal public investment: the multiple-type model implies an optimal ratio of public investment over GDP of 10.3%, which is 78% larger than that generated by the single-type economy. We then look at the fiscal multipliers, and find that the long-run multiplier of total public investment in our model is 1.54, which doubles the value of 0.72 associated with the single-type economy.[2]

Interestingly, the long-run multiplier varies substantially across public investment types: it is 0.45 for equipment, 0.58 for structures, and 3.99 for IPP. The rationale of the high multiplier for IPP is twofold: (*i*) it features a high output elasticity, thus yielding the strongest productivity gains for private inputs; and (*ii*) its high depreciation rate implies that any given amount of public investment in IPP changes relatively more its total stock, and, through that, firms' productivity.

Since multipliers vary substantially across types, changes in the composition public investment between equipment, structures, and IPP both across government levels and over time imply stark differences in the multiplier of total public investment. We uncover this fact with a final exercise in which we feed the model with shocks that replicate the public investment composition of the general, federal, and local government in every year between 1950 and 2023. We find substantial variation in the long-run multipliers: they are below one for the local government and range between a minimum of 0.95 in 1952 and a maximum of 2.75 in 2023 for federal spending. These differences are uniquely driven by changes in the composition of public investment shocks: while federal spending is strongly tilted towards IPP—especially in recent years—structures account for the lion's share of the local government's public investment.

This paper builds on the literature that studies the implications of public investment for the fiscal multiplier, and uncover the optimal amount of public capital (Baxter and King, 1993; Fernald, 1999; Leeper et al., 2010; Leduc and Wilson, 2013; Bouakez et al., 2017, 2020; Boehm, 2020; Ramey, 2021; Roulleau-Pasdeloup, 2022; Malley and Philippopoulos, 2023; Peri et al., 2024). However, this entire strand focuses on a single type of public investment and a homogeneous stock of public capital. We contribute to this literature by showing that (*i*) heterogeneity in public investment may substantially bias the aggregate implications derived with a model with a single type of public capital, and (*ii*) incorporating public investment in equipment, structures, and IPP into an otherwise standard economy doubles the optimal level of public investment and the output multiplier.

We relate to the work that studies the implications of the heterogeneous incidence of public spending across industries (Acemoglu et al., 2016; Bouakez et al., 2023, 2024; Basso and Rachedi, 2024; Cox et al., 2024; Peri et al., 2024). We borrow from this literature the notion that studying public spending at the

[2]Consistently with the evidence of Ilzetzki et al. (2013) and Boehm (2020), the multiplier is close to zero on impact in both the singly-type and multiple-type economies.

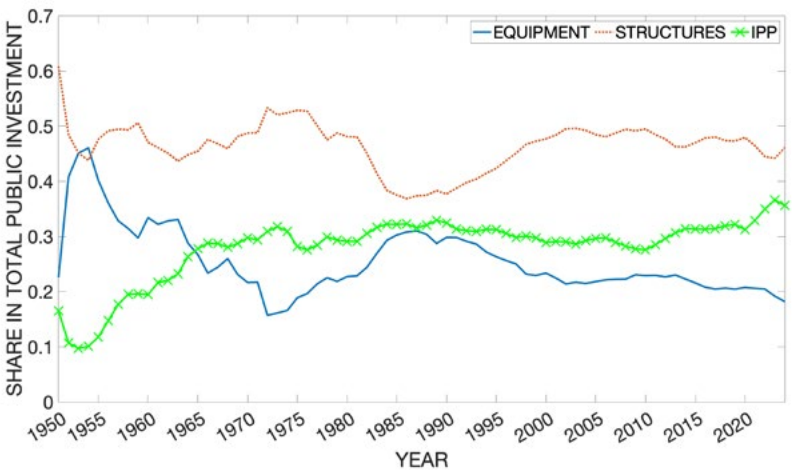
aggregate level conceals a large deal of heterogeneity, which is key for the aggregate implications of government expenditures. Our approach is complementary as instead we focus on one single sector, and open up the heterogeneity across multiple types of public investment.

Finally, the relevance of heterogeneity in private capital was at the core of the Cambridge capital controversy (Solow, 1955; Sraffa, 1960; Fisher, 1965; Jorgenson and Griliches, 1967), and spurred a recent literature that spotlights the key role of private investment and capital heterogeneity for understanding aggregate productivity dynamics, business cycle fluctuations, and secular trends (Gomme and Rupert, 2007; Wilson, 2009; Baqaee and Farhi, 2019; Koh et al., 2020). Although we share a similar spirit, we focus on *public* spending: we emphasize the relevance of explicitly accounting for heterogeneity in public investment and public capital among different types.

2 Heterogeneity in Public Investment

The measure of government spending that contributes to GDP according to the expenditure approach consists of the sum of public consumption and public investment expenditures. Public consumption is the sum of the remuneration of public employees, the purchases of goods and services from the private sector, and the depreciation of government-owned fixed capital (see Moro and Rachedi, 2022). Public investment equals the sum of the value of investment into multiples types, which include machineries, vehicles, furniture, military hardware, barracks, highways, hospitals, housing, schools, software, and R&D, among others. For the sake

Figure 1: Public Investment Composition in the Data.



Note: The figure reports the share of public equipment (continuous blue line), public structures (dotted red line), and public IPP (green crossed line) in total public investment for the general government from 1950 to 2023.

of clarity, we focus on three major categories: equipment, structures, and IPP.

Figure 1 reports the shares of public equipment, public structures, and public IPP in total public investment for the general government from 1950 to 2023.

This graph indicates that no single type accounts for the lion's share of total public investment. In other words, aggregate public investment is indeed a bundle of different types. In addition, there have been swings in the relevance of each type over time. On the one hand, the shares of public structures and equipment have been declining: from 23% in 1950 to 18% in 2023 for equipment and from 61% in 1950 to 46% in 2023 for structures. On the other hand, IPP has more than doubled its share, going from 17% in 1950 up to 36% in 2023.[3]

Why is it important to account for the composition of public investment across types? This is because public investment markedly differ from each other. Throughout the paper, we focus on five dimensions of heterogeneity.

1. *Elasticity of private output to public capital.* This dimension determines to what extent changes in the stock of public capital alter private output. Intuitively, the stock of public capital raises the productivity of private inputs. While this effect can be large for structures, such as hospitals, schools, and highways, and—even to a larger extent—for IPP investment such as R&D, investment in equipment is likely to have a much more limited impact on firms' productivity, if any.

2. *Depreciation rate.* This dimension captures the extent to which different types of public capital deteriorate over time at different rates. Structures tend to have a very long service life: according to the BEA, the service life of hospitals and schools is 50 years. Instead, the service life of equipment is much more limited, with, for example, 20 years for F-16 planes and 9 years for medical hardware. IPP has the shortest service life, with a duration of 3 years for software and 8 years for R&D.

3. *Investment shares.* This dimension refers to the differences in the shares of public investment by type over total public investment: half of total public investment goes into structures, and the other half is almost equally split between equipment and IPP.

4. *Time-to-spend delay.* This dimension describes the delays between the moment when the government allocates funds for new investment projects and the moment when these funds are actually being disbursed. This captures any delay in the legislative, administrative, and bureaucratic procedures, as well as any other logistical challenges. While time-to-spend delays may be negligible for equipment, the funds provided for new highway construction by the ARRA in February 2009 were entirely spent only in 2013.

5. *Time-to-build delay.* This dimension describes the delays between the disbursement of the funds to finance new investment and the moment when

[3] The standard deviations of both raw and HP-filtered shares of equipment, structures, and IPP in public investment is 1.5/2 times larger than those associated with private investment.

this new investment becomes a productive part of the stock of public capital. This captures the required duration for completing new investment projects. While installing new equipment and making it fully functional requires little time, the opposite applies to structures: constructing a new highway or complex facilities, such as hospitals, may take few years.

3 Simple Conceptual Framework

This section studies an economy with multiple types of productive government spending, which may differ along two dimensions: the output elasticity (i.e., the extent to which the stock of public capital of a given type raises the productivity of private inputs) and the size of the stock.

We characterize analytically the aggregate implications of public investment—in terms of optimal public investment and the output response to public investment—and show that they are pinned down by the sum of the output elasticities across types. We then study what happens if one abstracts from the existence of multiple types and considers homogeneous productive public spending types. Since the sum of the output elasticities across types is the sufficient statistic for the aggregate effects of public investment, it all boils down to whether one can recover an aggregate output elasticity which equals the sum of the output elasticities across types.

We then provide conditions under which: (i) the aggregate elasticity equals the sum of the output elasticities across types, so that an economy with either a single or multiple public capital types yields exactly the same aggregate implications of public investment; (ii) the aggregate elasticity is lower than the sum of the output elasticities across types, so that a single-type economy understates the aggregate implications of public investment; and (iii) the aggregate elasticity is greater than the sum of the output elasticities across types, so that a single-type economy overestimates the aggregate implications of public investment. In doing so, we emphasize the relevance of heterogeneity in public capital stocks and the correlation between public capital stocks and output elasticities across types.

3.1 Model Economy

We consider a static economy with multiple types of public capital $K_{G,x}$ with $x \in \{1, \ldots, \mathcal{X}\}$. A risk-neutral representative household—endowed with one unit of time—chooses consumption, C, to solve the problem:

$$\max_{C} \; C \quad \text{s.t. } C + T = WN, \tag{1}$$

where N is labor, T denotes lump-sum taxes, and W is the wage. The budget constraint posits that consumption and taxes are financed with labor income.

A perfectly competitive representative firm hires labor to produce output Y with the technology

$$Y = N \prod_{x=1}^{\mathcal{X}} K_{G_x}^{\gamma_x}. \tag{2}$$

While the technology features constant returns to scale in private inputs, private output is influenced by the multiple stocks of public capital. The parameter γ_x denotes the elasticity of private output with respect to the stock of public capital of type x. Thus, as in Baxter and King (1993), Leeper et al. (2010), Bouakez et al. (2017), and Ramey (2021), public capital raises the productivity of private inputs. The only difference is that here this effect varies across public capital types. Importantly, since the household provides one unit of working time, we can interpret the stocks of public capital in per-capita terms.

The government owns all the stocks of public capital. We consider a unit depreciation rate for all types so that public capital equals public investment, I_{G_x}:

$$K_{G_x} = I_{G_x}, \qquad \forall x \in \{1, \dots, \mathcal{X}\}. \tag{3}$$

We consider each type of public investment as purely exogenous. Insofar as the amounts of public investment vary across types, the stocks of public capital would also differ. In this setting, heterogeneity in the stocks of public capital then derives from heterogeneity in the public investment shares, that is, the share of public investment into each type. In the fully-fledged model in which there is no full depreciation, heterogeneity in the stocks of public capital across types depends also on heterogeneity in depreciation rates.

The resource constraint of the economy implies that output equals the sum of private consumption and public investment:

$$Y = C + \sum_{x=1}^{\mathcal{X}} I_{G_x}. \tag{4}$$

The government finances public investment expenditures with lump-sum taxes, so that its budget constraint reads

$$\sum_{x=1}^{\mathcal{X}} I_{G_x} = T. \tag{5}$$

3.2 Aggregate Implications of Public Investment

We study two aggregate implications of public investment: the optimal amount of public investment and the response of output to a change in public investment.

We start by following Ramey (2021) and deriving the optimal level of public investment as the level of public investment that maximizes households' utility. In the multiple-type economy, the social planner chooses optimally each type of public investment yielding to the following first-order conditions:

$$\frac{I_{G_x}}{Y} = \gamma_x, \qquad \forall x \in \{1, \dots, \mathcal{X}\}. \tag{6}$$

The optimal level of total public investment—defined as the sum of the optimal levels across all types—in terms of GDP for the multiple-type economy is

$$\sum_{x=1}^{\mathcal{X}} \frac{I_{G_x}}{Y} = \sum_{x=1}^{\mathcal{X}} \gamma_x. \tag{7}$$

Thus, the sum of the output elasticities of public capital across types pins down the optimal total level of public investment.

We then move onto the response of output to a change in public investment. To do so, let us define total public investment as $\sum_{x=1}^{\mathcal{X}} I_{G_x}$. Then, the public investment shares, ω_x, equal

$$\omega_x = \frac{I_{G_x}}{\sum_{x=1}^{\mathcal{X}} I_{G_x}}, \qquad \forall x \in \{1, \ldots, \mathcal{X}\}. \tag{8}$$

We can use these shares to rewrite firm's technology in Equation (2) as

$$Y = N \prod_{x=1}^{\mathcal{X}} \omega_x^{\gamma_x} \left[\sum_{x=1}^{\mathcal{X}} I_{G_x}\right]^{\sum_{x=1}^{\mathcal{X}} \gamma_x}. \tag{9}$$

We can now define the change in output relative to its initial level due to a change in total public investment, which is

$$\frac{\partial Y}{Y} \frac{\sum_{x=1}^{\mathcal{X}} I_{G_x}}{\partial \sum_{x=1}^{\mathcal{X}} I_{G_x}} = \sum_{x=1}^{\mathcal{X}} \gamma_x. \tag{10}$$

Thus, the sum of the output elasticities of public capital across types also pins down the output response to public investment.

In other words, in this simple economy the sum of the output elasticities of public capital across types is a sufficient statistic for both the optimal amount of public investment and the output response to a change in public investment.

3.3 Aggregate Output Elasticity

What happens if one abstracts away from multiple public capital types postulating a model economy where production only depends on a single type? In such a case, the firm's technology would be represented as

$$Y = N\, K_G^{\bar{\gamma}}, \tag{11}$$

where K_G denotes aggregate public capital, and $\bar{\gamma}$ is the output elasticity to aggregate public capital (i.e., the aggregate output elasticity henceforth). In this economy, the optimal level of aggregate public investment equals

$$\frac{I_G}{Y} = \bar{\gamma} \tag{12}$$

and the change in aggregate public investment is

$$\frac{\partial Y}{Y} \frac{I_G}{\partial I_G} = \bar{\gamma}. \tag{13}$$

Once again, the output elasticity of public capital is a sufficient statistic for the implications of public investment, with the only difference being that, in this case, what matters is the aggregate output elasticity rather than the sum of the output elasticities across types. It immediately follows that the implications of a single-type economy coincide with those of a multiple insofar the aggregate output elasticity coincides with the sum of the output elasticities across types. In other words, comparing the aggregate output elasticity with the sum of types' output elasticities is critical for determining whether there is an equivalence between a single-type and a multiple-type economy.

In fact, we can determine three different conditions. In the first case, we refer to the existence of *no bias* in the aggregate output elasticity when it exactly equals the sum of types' output elasticities.

Definition 1 (**No Bias**). *There is no bias in the aggregate output elasticity when*

$$\bar{\gamma} = \sum_{x=1}^{\mathcal{X}} \gamma_x. \tag{14}$$

In this case, considering multiple public capital types is immaterial for studying the aggregate implications of public investment, as it would generate the same predictions of a single-type model.

However, this equality may break out when the aggregate output elasticity exceeds the sum of types' output elasticities, which we refer to as the existence of a *positive bias.*

Definition 2 (**Positive Bias**). *There is positive bias in the aggregate output elasticity when*

$$\bar{\gamma} > \sum_{x=1}^{\mathcal{X}} \gamma_x. \tag{15}$$

Thus, a single-type economy overestimates the aggregate effects of public investment. Vice versa, when the aggregate output elasticity is lower than the sum of types' output elasticities, it yields to the existence of a *negative bias.*

Definition 3 (**Negative Bias**). *There is negative bias in the aggregate output elasticity when*

$$\bar{\gamma} < \sum_{x=1}^{\mathcal{X}} \gamma_x. \tag{16}$$

In this case, a single-type economy understates the effects of public investment.

To discipline the way in which we recover the aggregate output elasticity from the data, we follow exactly the estimation procedure of Bouakez et al. (2017) and Ramey (2021). This approach regresses the logarithm of observed aggregate productivity, TFP, over the logarithm of the per-capita stock of aggregate public capital, K_G, as follows:

$$\log TFP = \bar{\gamma} \log K_G. \tag{17}$$

Insofar public capital affects the productivity of private output, as defined by Equation (11), this regression identifies the elasticity of private output to aggregate public capital, $\bar{\gamma}$.

If data is generated according to our model economy with multiple public investment types, aggregate productivity can be rewritten as

$$TFP = \prod_{x=1}^{\mathcal{X}} K_{G_x}^{\gamma_x}. \tag{18}$$

Consequently, the logarithm of aggregate TFP is

$$\log TFP = \sum_{x=1}^{\mathcal{X}} \gamma_x \log K_{G_x}. \tag{19}$$

If we recover the implied elasticity of the single-type model, $\bar{\gamma}$, using data of the multiple-type economy—and thus combine Equations (17) and (19)—we find an estimate of the aggregate output elasticity which is

$$\bar{\gamma} = \sum_{x=1}^{\mathcal{X}} \theta_x \gamma_x, \tag{20}$$

where $\theta_x = \log K_{G_x} / \log K_G,\ \forall x \in \{1, \ldots, \mathcal{X}\}$. This identity states that the aggregate elasticity is a weighted sum of the output elasticities across types, where the weights θ_x are the ratios between the logarithm of the per-capita public capital stock of each type and the logarithm of the per-capita stock of aggregate public capital. As we show next, depending on the value of these weights, we may observe no bias, a positive bias, or a negative bias in the aggregate output elasticity.

3.4 Aggregate Output Elasticity Bias

To characterize the conditions under which a bias in the estimated aggregate output elasticity emerges, we need to take a stand on the measurement of aggregate public capital in the economy with multiple types. We do this as follows.

Assumption 1. *Aggregate public capital in the economy with multiple types of capital is given by*

$$K_G \equiv \left[\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}}, \tag{21}$$

where ϑ_x is the weight of the stock of public capital of type x, such that $\sum_{x=1}^{\mathcal{X}} \vartheta_x = 1$, and $\nu \geqslant 0$ is the elasticity of substitution across public capital types. We focus on the case in which $K_{G_x} \geqslant 1$, $\forall x \in \{1, \ldots, \mathcal{X}\}$.

In this way, we have a flexible representation which allows us to nests as extremes the case in which public capital is perfectly substitutable across types (i.e., $\nu \to \infty$) and the aggregate stock sums across the stock of each type, or the case in which public capital stocks are perfect complements (i.e., $\nu = 0$) and enter in fixed proportion into the aggregate public capital stock.

We can then derive four main propositions. The first one establishes an equivalence result: the estimated aggregate output elasticity is unbiased and equals the sum of types' output elasticities when the stocks of public capital are homogeneous across types. This implies that accounting for multiple types of public capital is immaterial for understanding the aggregate implications of public investment, as they can be equally recovered by a single-type model.

Proposition 1 (**Conditions for No Bias**). *If the stock of public capital is homogenous across types so that* $K_{G_x} = \bar{K}_G, \forall x \in \{1, \ldots, \mathcal{X}\}$ *, then* $\theta_x = 1, \forall x \in \{1, \ldots, \mathcal{X}\}$*, which implies that the estimated aggregate output elasticity is unbiased and it equals the sum of the individual elasticities,* $\bar{\gamma} = \sum_{x=1}^{\mathcal{X}} \gamma_x$*.*

Proof. See Appendix A. □

Proposition 1 suggests that the existence of heterogeneous stocks of public capital across types is a necessary condition for having a bias in the estimation of the aggregate output elasticity. In the next proposition, we start characterizing the case of a positive bias, which hinges on the extreme case of perfect complementarity between public capital types.

Proposition 2 (**Conditions for Positive Bias**). *If the stocks of public capital are heterogeneous and* $\nu = 0$*, there is a positive bias in the estimated aggregate output elasticity, so that* $\bar{\gamma} > \sum_{x=1}^{\mathcal{X}} \gamma_x$*.*

Proof. See Appendix A. □

Consequently, under heterogeneous and perfect complement public capital stocks, a single-type economy overstates the aggregate implications of public investment, as the aggregate output elasticity exceeds the sum of types' elasticities.

Instead, insofar as public capital stocks are imperfect complements, we can observe a negative bias. This possibility is more likely when the types of public capital with higher output elasticities have lower stock sizes. In other words, the negative bias emerges when there is no strong positive correlation between output elasticities and stock sizes across public capital types.

Proposition 3 (**Conditions for Negative Bias**). *If the stocks of public capital are heterogeneous and* $\nu > 0$*, a negative bias is more likely to emerge in the estimated aggregate output elasticity, so that* $\bar{\gamma} < \sum_{x=1}^{\mathcal{X}} \gamma_x$*, when there is no strong positive correlation between the output elasticities,* γ_x*, and the stock sizes,* K_{G_x}*, across public capital types.*

Proof. See Appendix A. □

What is the role of the elasticity of substitution across public capital types? The next proposition establishes that a positive bias is more likely to emerge for low values of it, that is, when public capital types are strong complements, whereas a negative bias arises for sufficiently high values of ν, that is, when public capital types are imperfect substitutes.

Proposition 4 (**Role of Elasticity of Substitution** ν)**.** *If the stocks of public capital are heterogeneous, for any given distribution of output elasticities, γ_x, and the stock sizes, K_{G_x}, across public capital types, higher values of the elasticity of substitution ν are more likely to result in a negative bias.*

Proof. See Appendix A. □

All together, these propositions show that when public capital stocks are homogeneous, there is no bias in the aggregate output elasticity and accounting for multiple types of public capital is inconsequential for deriving the aggregate effects of public investment. However, insofar as public capital stocks are heterogeneous, we should expect a negative bias when (*i*) public capital stocks are imperfect complements and (*ii*) there is a negative correlation between public capital stocks and output elasticities. Vice versa, the stronger the degree of complementarity across public capital types and the stronger the positive correlation between public capital stocks and output elasticities, the more likely it is that a positive bias emerges.

4 Quantitative Model

We now extend the simple framework of Section 3 into a fully-fledged model, adding different types of public investment and public capital into an otherwise standard New Keynesian economy. Specifically, we consider a representative-household model in which the fiscal authority uses lump-sum taxes to finance an exogenous stream of multiple types of public investment. Public capital stocks positively benefit private firms' production, which assembles output using private physical capital and labor. Firms choose prices subject to price-setting friction.[4] Public investment types differ in terms of: (*i*) the elasticity of private output to the stocks of public capital; (*ii*) the depreciation rate of the stocks of public capital; (*iii*) public investment shares; (*iv*) time-to-build delays; and (*v*) time-to-spend delays. Heterogeneity in public capital stocks across types comes from the differences in depreciation rates and public investment shares.

[4]Our baseline economy features price rigidities since we also want to study the heterogeneous short-run implications across public investment types. In the quantitative exercises, we also study a version of the economy with fully flexible prices.

4.1 Household

A representative household chooses consumption, C_t, labor, N_t, private investment, I_t, private physical capital, K_{t+1}, and one-period risk-free nominal bonds, B_{t+1}, to maximize its lifetime utility (22) subject to the budget constraint (23) :

$$\max_{C_t,N_t,I_t,K_{t+1},B_{t+1}} \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t \left[\frac{C_t^{1-\sigma}}{1-\sigma} - \upsilon \frac{N_t^{1+\eta}}{1+\eta} \right] \tag{22}$$

$$\text{s.t. } P_t C_t + P_t I_t + B_{t+1} + T_t = W_t N_t + R_{K,t} K_t + R_t B_t + D_t, \tag{23}$$

where β is the time discount factor, σ is the risk aversion, η is the inverse of the Frisch elasticity, υ is a labor disutility shifter, P_t denotes the price of consumption and investment, W_t is the nominal wage, $R_{K,t}$ is the nominal rental rate of private capital, R_t is the nominal return on bonds, and D_t denotes firms' nominal profits. Households finance expenditures in consumption, investment, bonds, and lump-sum taxes, T_t, with the sum of labor income, capital income, the revenue on bond holdings, and firms' profits.

Private investment accumulates to the stock of private capital subject to convex adjustment costs, so that physical capital evolves over time with the law of motion:

$$K_{t+1} = (1-\delta_K) K_t + I_t \left[1 - \frac{\Omega}{2} \left(\frac{I_t}{I_{t-1}} - 1 \right)^2 \right], \tag{24}$$

where δ_K denotes the depreciation rate of private capital, and Ω captures the magnitude of the adjustment costs.

4.2 Wholesalers

The production side consists of two types of firms: wholesalers and retailers. There is a unit measure of monopolistically competitive wholesalers, indexed by $j \in [0,1]$, which assemble output $Y_{j,t}$ with the technology

$$Y_{j,t} = N_{j,t}^{\alpha} K_{j,t}^{1-\alpha} \prod_{x=1}^{\mathcal{X}} K_{G_x,t}^{\gamma_x}, \tag{25}$$

where the private inputs are $N_{j,t}$, the labor hired by wholesaler j at time t, and $K_{j,t}$, the stock of physical capital rented from the household. The parameter α is the labor intensity. As in the simple framework, firms' technology benefits from the stocks of public capital of each type, $K_{G_x,t}$, through an extent which is defined by the output elasticities, γ_x.

Wholesalers set prices $P_{j,t}$ subject to a price setting friction à la Calvo (1983), in which prices can be reset with a probability $1-\phi$. Wholesalers chose optimal reset prices to maximize the expected discounted stream of future profits:

$$\max_{P_{j,t}} \mathbb{E}_t \left[\sum_{z=t}^{\infty} \beta^z \phi^z \frac{\Lambda_{t+1}}{\Lambda_t} \Big(P_{j,t} Y_{j,z} - W_z N_{j,z} - R_{K,z} K_{j,z} \Big) \right], \tag{26}$$

where Λ_t is the household's stochastic discount factor.

4.3 Retailer

A perfectly competitive retailer purchases the different varieties $Y_{j,t}$ from wholesalers and assemble them into final output Y_t as follows

$$Y_t = \left[\int_0^1 Y_{j,t}^{\frac{\epsilon-1}{\epsilon}} \mathrm{d}j \right]^{\frac{\epsilon}{\epsilon-1}}, \tag{27}$$

where ϵ is the elasticity of substitution across varieties. This aggregator implies that the price of final goods equals

$$P_t = \left[\int_0^1 P_{j,t}^{1-\epsilon} \mathrm{d}j \right]^{\frac{1}{1-\epsilon}}. \tag{28}$$

The retailer sells the final goods to the household, as private consumption and investment, and to the fiscal authority, as the different types of public investment. Consequently, the resource constraint reads

$$Y_t = C_t + I_t + \sum_{x=1}^{\mathcal{X}} I_{G_x,t}. \tag{29}$$

4.4 Fiscal Authority

The fiscal authority faces an exogenous stream of planned public investment expenditures in each type, $A_{G_e,x}$, which follows the auto-regressive process:

$$\log A_{G_x,t} = (1-\rho) \log I_{G_x} + \rho \log A_{x,t-1} + \varepsilon_{x,t} + \varepsilon_t, \tag{30}$$

where ρ is the persistence of the process, and I_{G_x} is the steady-state values of public investment of type x. The variation in these steady-state values defines the heterogeneity in public investment shares, that is, the extent to which each public investment type accounts for total public investment.

We consider two types of shocks: an idiosyncratic shock which raises public investment in only one specific type and is denoted by $\varepsilon_{x,t}$; and a common shock, ε_t, which raises total public investment while preserving constant the composition in planned spending across all types.

As in Leeper et al. (2010), Ramey (2021), and Peri et al. (2024), planned public investment turns into actual spending only with a lag, the so called time-to-spend delay. Specifically, actual public investment spending in type x is defined as

$$I_{G_x,t} = \frac{1}{\tau_x} \sum_{z=1}^{\tau_x} A_{x,t+1-z}. \tag{31}$$

This specification implies that current spending in public investment averages planned lagged expenditures. The parameter τ_x denotes the length of the time-to-spend delays. Importantly, the delays vary across types.

Current public investment accrues to the stock of public capital according to the law of motion

$$K_{G_x,t+1} = (1-\delta_x) K_{G_x,t} + I_{G_x,t-\zeta_x}, \tag{32}$$

where δ_x is the depreciation rate and ζ_x denotes the duration of the time-to-build delays for each type of public capital. Both the depreciation rates and the durations of the time-to-build delays are allowed to vary across types.

The government finances the stream of public investment via means of a lump-sum tax on the household, so that the budget constraint is

$$T_t = P_t \sum_{x=1}^{\mathcal{X}} I_{G_x,t}. \tag{33}$$

4.5 Monetary Authority

A monetary authority sets the nominal interest rate according to a Taylor rule that responds to inflation, π_t, and the output gap, Y_t/Y_t^f, where Y_t^f denotes the output level in a counterfactual version of the economy with perfectly flexible prices. The Taylor rule reads

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\varphi_r} \left[\pi_t^{\varphi_\pi} \left(\frac{Y_t}{Y_t^f}\right)^{\varphi_y}\right]^{1-\varphi_r} \tag{34}$$

where R denotes the steady-state level of the interest rate, φ_r captures the degree of interest rate inertia, and φ_π and φ_y denote the degree of responsiveness of the nominal interest rate to inflation and the output gap, respectively.

5 Quantitative Analysis

This section presents the results of the analysis based on the quantitative model introduced above. We start by detailing the calibration of the model—and especially the disciplining of heterogeneity across public investment types—in Section 5.1, and then we study the estimation bias for the aggregate output elasticity in Section 5.2. Next, we measure the differences in the implications of our multiple-type economy vis-à-vis the single-type model regarding the optimal levels of public investment and public capital, in Section 5.3, and the fiscal multipliers, in Section 5.4. Finally, Section 5.5 evaluates how feeding the model with actual variation in public investment composition both over time and across government levels leads to large changes in the size of the fiscal multiplier.

5.1 Calibration

We calibrate the model to the U.S. economy. We log-linearize the model around a zero inflation rate steady-state, and set one time period to coincide with a quarter.

We set the time discount factor to $\beta = 0.99$ so that the annualized real interest rate is 4%. The risk aversion is $\sigma = 2$, and we consider a unit Frisch elasticity, so that $\eta = 1$.[5] We set the preference shifter to $\upsilon = 0.1192$ to guarantee that labor supply in steady state equals one.

[5] We study the implications of different calibrations of the Frisch elasticity in Appendix C.3.

We fix the depreciation rate of private physical capital to 0.0205, which is derived by taking information from the BEA, dividing by the current-cost depreciation of private fixed assets on their lagged current-cost net stock, and averaging it over the period 1950-2019. This implies an annual depreciation rate of 7.95%. We set the adjustment cost parameter to 4.0840, so that the relative standard deviation of private investment in terms of the standard deviation of output in a model specification featuring aggregate TFP shocks is 2.6675, as in the data.

For the production side, the labor intensity equals to $\alpha = 0.6$ and the Calvo probability is $\phi = 0.75$ to imply an average duration of prices of 4 quarters. The elasticity of substitution across varieties is $\epsilon = 4$ in line with the markups of around 30% documented in recent decades by De Loecker et al. (2020).

We calibrate the Taylor rule parameters following the empirical evidence of Clarida et al. (2000): the degree of inertia is $\phi_r = 0.8$, and the degrees of responsiveness of the nominal interest rate to inflation and the output gap are $\phi_\pi = 1.5$ and $\phi_y = 0.2$, respectively. Then, we set the persistence of the auto-regressive processes of public investment to $\rho = 0.9$.[6]

5.1.1 Calibration of Public Investment Types

When bringing the model to the data, we set $\mathcal{X} = 3$ and consider three types of public investment: equipment (e), structures (s), and IPP (i), so that $x \in \{e, s, i\}$. We do so to strike a balance between having enough variety and heterogeneity across types with the necessity of calibrating the extent of the output elasticities. Our focus on public equipment, structures, and IPP allows us to leverage previous evidence provided by the literature to guide the calibration of the output elasticities.

Let us dig deeper on how we discipline the different sources of heterogeneity across the three public investment types. First, we start with the depreciation rates and the public investment shares, which determine the variation in the size of the public capital stocks across types. We set the depreciation rates following the same procedure of the depreciation rate of private capital, using information from the BEA, and find $\delta_e = 0.033$, $\delta_s = 0.005$, and $\delta_i = 0.046$. These values imply annual depreciation rates of 12.4% for equipment, 1.9% for structures, and 17.0% for IPP. The public investment shares are pinned down by the values of public investment at the steady state. To do so, we derive in the data the average share of public equipment, public structures, and public IPP for the general government as a fraction of GDP, for the period 1950-2023. We find that public equipment account for 1.28% of GDP, whereas this ratio is 1.45% for public IPP and 2.25% for public structures. We set the steady-state values for each type accordingly. This implies that equipment, structures, and IPP account for 26%,

[6] Appendix C.3 reports the results of a model specification in which we set the persistence up to $\rho = 0.94$, which coincides with the persistence estimated by Leeper et al. (2010).

45%, and 29% of total public investment, respectively. The combination of the depreciation rates and the public investment shares implies that the lion's share of total public capital consists of structures, whereas equipment and IPP only account for 7% and 6%, respectively, of the total public capital stock.

Second, we choose the output elasticities to public capital starting from that of IPP. A recent paper by Fieldhouse and Mertens (2023) finds that the output elasticity of non-defense R&D is 0.12, whereas that of defense R&D is not statistically different from zero. Since non-defense R&D accounts on average for 55% of total defense and non-defense R&D between 1950 and 2022, we set the output elasticity of IPP to $\gamma_i = 0.07 = 0.55 \times 0.12$. Then, we take the stand that the stock of public equipment is productive but at the minimum level possible, by choosing an elasticity of $\gamma_e = 0.005$. Finally, we set $\gamma_s = 0.05$, so that structures have a large effect on the productivity of private inputs, but relatively lower than that of IPP. This choice coincides with that of Ramey (2021) in the analysis on infrastructure investment, as well as with the calibration of Baxter and King (1993) and Leeper et al. (2010). Appendix B.1 provides empirical evidence in the spirit of Bouakez et al. (2017) and Ramey (2021) in which we estimate output elasticities for equipment, structures, and IPP and show that they are roughly in line with those defined in the calibration of the model. In fact, if anything, our calibration of the elasticity of IPP capital is conservative.[7] Furthermore, in the next section, we show that our calibrated model implies an output elasticity of aggregate public capital which is remarkably in line with empirical estimates provided by the literature.

Regarding the time-to-build and time-to-spend delays, we do the following. We start with equipment, since this is the investment type which is likely to be less affected by these lags. Accordingly, we set the time-to-build delay to one quarter, $\zeta_e = 1$, and the time-to-spend to two quarters, $\tau_e = 2$. For IPP, we assume slightly larger time-to-spend delays, with $\tau_i = 4$, but substantially prolonged time-to-build ones, with $\zeta_i = 12$. This is consistent with the fact that according to the U.S. Patent Office, the procedures of getting a patent approved take around 22 months. Structures feature the longest delays, with six quarters for time-to-spend, $\tau_s = 6$, and four years for the time-to-build, $\zeta_s = 16$. The first choice is in line with Ramey (2021), who show that time-to-spend delays of 5 quarters can account for the lags in the allocation of ARRA funds, as documented by Leduc and Wilson (2013). The time-to-build lag follows evidence from the U.S. Government Accountability Office, indicating that infrastructure construction may take between 2 and 6 years.

[7]We study the robustness of our results to alternative calibration choices for the output elasticities in Appendices C.2 and C.3.

5.1.2 Calibration of the Single-Type Economy

In the quantitative analysis, we compare the implications of our baseline model in Section 4 with the calibration choices defined above to one which completely abstracts from heterogeneity in the composition of public investment: an economy with only one type of public investment and public capital. Throughout the paper, we refer to the baseline model as the "Multiple-Type" economy, and to the homogeneous public capital case as the "Single-Type" economy.

To discipline the "Single-Type" economy, we follow the same strategy used for the calibration of our baseline model. First, we compute again the depreciation rate using information from the BEA, with the difference that we focus on information on aggregate public capital. We find a depreciation rate of $\bar{\delta} = 0.011$, that is, an annual rate of 4.4%. Second, we set the share of public investment in GDP as the sum of the shares of public investment in equipment, structures, and IPP in GDP, which equals 4.98%. Third, we set the time-to-build delays to 10 quarters, which is the average value of the delays across the three types. Fourth, we fix the time-to-spend delay to 4 quarters, which is the average value of the delays across the three types. Finally, the next section discusses how we estimate the output elasticity of the aggregate stock of public capital.

5.2 Aggregate Output Elasticity Bias

To measure the aggregate output elasticity bias, we simulate the "Multiple-Type" model, and take the values of the observed aggregate total factor productivity and the stocks of public capital in equipment, structures, and IPP. As in our analytical derivations, we compute aggregate public capital as

$$K_{G,t} = \left[\omega_e K_{G_e,t}^{\frac{\nu-1}{\nu}} + \omega_s K_{G_s,t}^{\frac{\nu-1}{\nu}} + \omega_i K_{G_i,t}^{\frac{\nu-1}{\nu}}\right]^{\frac{\nu}{\nu-1}} \tag{35}$$

where ω_e, ω_s, and ω_i are the weights of each type, and ν is the elasticity of substitution across public capital stocks. We set the weights such that they equal the share of each type of public capital into the sum of public capital across types, and calibrate the elasticity of substitution to $\nu = 1.5$. This value is consistent with a prima-facie estimation of the elasticity of substitution, reported in Appendix B.2, in which we find evidence in favor of values above 1, and close to 1.5.

Given this parametrization, we take the values of aggregate total factor productivity and aggregate public capital implied by our "Multiple-Type" model and estimate regression (17). We find that the econometrician recovers an implied elasticity of private output to the aggregate stock of public capital of $\bar{\gamma} = 0.0718$. This value is remarkably in line with the estimates provided by the literature, which exactly focuses on aggregate information on total public capital. For instance, Bouakez et al. (2017) find a value of 0.0652. As we mentioned above, the fact that the model is consistent with estimates based on the aggregate stock of public capital corroborates our calibration choices for the output elasticities to public equipment, structures, and IPP.

Table 1: Aggregate Output Elasticity Bias - Heterogeneity in Public Capital Stocks.

Multiple-Type Economy	Estimated Value	No Bias Value	Implied Bias
Baseline	0.0718	0.1250	-0.0545
Homogeneous Public Capital Stocks	0.1250	0.1250	0.0000
Homogeneous Depreciation Rates	0.1247	0.1250	-0.0003
Homogeneous Public Investment Shares	0.0798	0.1250	-0.0452
Low Depreciation Rate IPP	0.1214	0.1250	-0.0026

Note: The table reports the estimated aggregate output elasticity and the implied bias with respect to the sum of the output elasticities across types associated with the baseline economy with four cases which consider (*i*) homogeneous public capital stocks (i.e., homogeneous depreciation rates and public investment shares), (*ii*) homogeneous depreciation rates, (*iii*) homogeneous public investment shares, or (*iv*) a low depreciation rate for the stock of public IPP capital.

Importantly, the estimated value of the aggregate output elasticity of $\bar{\gamma} = 0.0718$ is substantially lower than the sum of the output elasticities across types, which equals 0.125. In other words, recovering the output elasticity of aggregate output yields a substantial negative bias. This is because there is a close to zero correlation between the stocks of public capital and the output elasticities across types. Indeed, IPP is the type with the highest output elasticity, with a value of 0.07, but its extremely high depreciation rate (almost ten times higher than that of structures), and low public investment share, make it having just 6% of the total public capital stock. Consistently with our analytical results of Section 3, insofar there is no strong positive correlation between the stocks of public capital and the output elasticities, the estimated aggregate output elasticity tends to be lower than the sum of the output elasticities across types.

Table 1 digs into the determinants of the negative bias, by starting from an economy in which the size of the public capital stocks are homogeneous across the three types. As in our analytical derivations, in this case, we find no bias whatsoever, confirming that heterogeneity in public capital stocks is the necessary condition to generate a bias in the aggregate output elasticity. In our model, heterogeneity in public capital stocks hinges on two traits: variation in either depreciation rates or public investment shares. We disentangle the relevance of these two dimensions by considering two alternative economies in which either depreciation rates are homogeneous across types but public investment shares are not, or vice versa. In these two cases, the stocks of public capital vary across the three types.

When we set homogeneous depreciation rates, we find that the estimated aggregate output elasticity virtually coincides with the sum of the output elasticities across types, so that there is no bias whatsoever. Instead, homogeneous public investment shares result in severe negative bias, since we estimate an aggregate output elasticity of 0.0798, not far away from our baseline estimated value of 0.0718. This exercise shows that in the model the key dimension that drives heterogeneity in public capital stocks—and in turn the aggregate output elasticity bias—is heterogeneity in depreciation rates, while differences in public investment shares are immaterial.

To close this first exercise, we consider a case in which we reduce substantially the depreciation rate of IPP capital, from a 17% annual rate to 2%, in line with the depreciation rate of structures. As a result, the size of the stock of IPP capital rises substantially, generating a strong positive correlation of 0.76 between output elasticities and capital stocks across types. This case reduces substantially the negative bias and actually implies an estimated aggregate output elasticity which virtually coincides with the sum of the output elasticities across types.

Next, we further corroborate the robustness of the negative bias of the estimated aggregate output elasticity with an additional exercise. We estimate the aggregate output elasticity in a series of economies with different calibrations for the output elasticities across public capital types: (*i*) an economy with halved output elasticities with respect to the baseline values, so that $\gamma_e = 0.005, \gamma_s = 0.05, \gamma_i = 0.07$; (*ii*) an economy with a lower output elasticity for the stock of

Table 2: Aggregate Output Elasticity Bias - Different Output Elasticities across Types.

Multiple-Type Economy	Output Elasticities by Type	Estimated Value	No Bias Value	Implied Bias
Baseline	$\gamma_e = 0.0050, \gamma_s = 0.0500, \gamma_i = 0.0700$	0.0718	0.1250	-0.0532
Halved Elasticities	$\gamma_e = 0.0025, \gamma_s = 0.0250, \gamma_i = 0.0350$	0.0340	0.0625	-0.0285
Low Equipment Elasticity	$\gamma_e = 0.0000, \gamma_s = 0.0500, \gamma_i = 0.0700$	0.0701	0.1200	-0.0499
High Equipment Elasticity	$\gamma_e = 0.0200, \gamma_s = 0.0500, \gamma_i = 0.0700$	0.0769	0.1400	-0.0631
High Structures Elasticity	$\gamma_e = 0.0050, \gamma_s = 0.0700, \gamma_i = 0.0700$	0.0956	0.1450	-0.0494
High IPP Elasticity	$\gamma_e = 0.0050, \gamma_s = 0.0500, \gamma_i = 0.0900$	0.0772	0.1450	-0.0678
Only Productive Structures	$\gamma_e = 0.0000, \gamma_s = 0.1250, \gamma_i = 0.0000$	0.1332	0.1250	0.0082

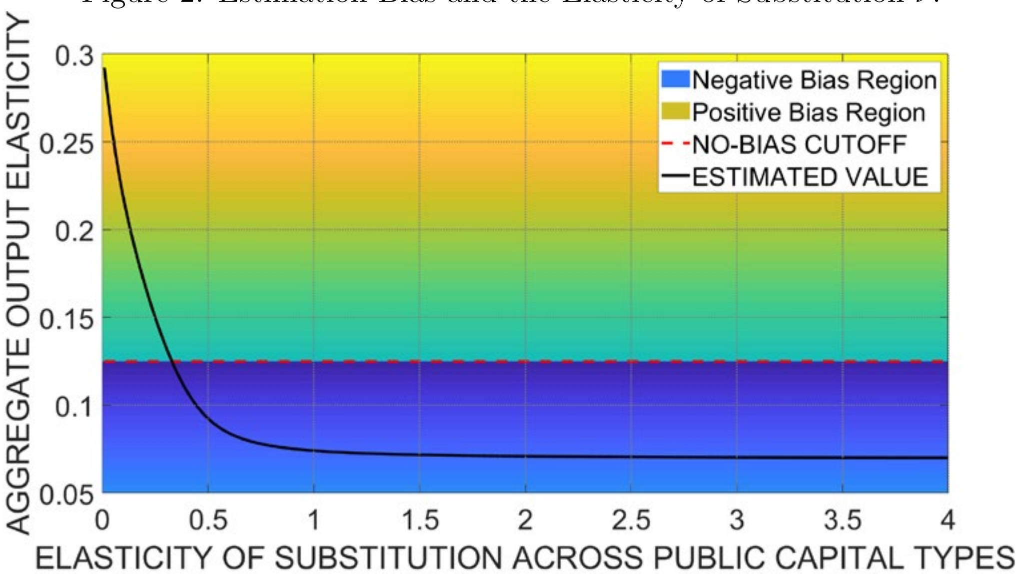
Note: Panel (A) of the table reports the estimated aggregate output elasticity and the implied bias with respect to the sum of the output elasticities across types associated with the baseline economy (i.e., $\gamma_e = 0.005, \gamma_s = 0.05, \gamma_i = 0.07$), and a series of multiple-type economies with alternative calibrations for the output elasticities of public capital: (*i*) a case with halved elasticities (i.e., $\gamma_e = 0.0025, \gamma_s = 0.025, \gamma_i = 0.035$), (*ii*) a case with a lower output elasticity of the stock of public equipment (i.e., $\gamma_e = 0, \gamma_s = 0.05, \gamma_i = 0.07$), (*iii*) a case with a higher output elasticity of the stock of public equipment (i.e., $\gamma_e = 0.02, \gamma_s = 0.05, \gamma_i = 0.07$), (*iv*) a case with a higher output elasticity of the stock of public structures (i.e., $\gamma_e = 0.005, \gamma_s = 0.07, \gamma_i = 0.07$), (*v*) a case with a higher output elasticity of the stock of public IPP (i.e., $\gamma_e = 0.005, \gamma_s = 0.05, \gamma_i = 0.07$), and (*vi*) a case in which only the stock of public structures is productive (i.e., $\gamma_e = 0, \gamma_s = 0.125, \gamma_i = 0$).

public equipment, so that $\gamma_e = 0, \gamma_s = 0.05, \gamma_i = 0.07$; (iii) an economy with a higher output elasticity for the stock of public equipment, so that $\gamma_e = 0.02, \gamma_s = 0.05, \gamma_i = 0.07$; (iv) an economy a higher output elasticity for the stock of public structures, so that $\gamma_e = 0.005, \gamma_s = 0.07, \gamma_i = 0.07$; (v) an economy a higher output elasticity for the stock of public IPP, so that $\gamma_e = 0.005, \gamma_s = 0.05, \gamma_i = 0.09$; and (vi) an economy in which we tilt all the baseline values of the output elasticities to the stock of public structures, while making equipment and IPP to be not productive, so that $\gamma_e = 0, \gamma_s = 0.125, \gamma_i = 0$. We report the results in Table 2.

We then move into evaluating the robustness of the estimation bias, and start by focusing on the role of the elasticity of substitution across public capital types, ν. To do so, we report in Figure 2 the estimated aggregate output elasticity as a function of different values of ν. In line with our analytical results, low values of ν are associated with a positive bias, whereas high values of ν yield a negative bias. However, we find that to achieve a positive bias requires counterfactually low values of ν: the estimated aggregate output elasticity equals the sum of the output elasticities across types when $\nu = 0.3292$, so that the positive bias emerges for $\nu < 0.3292$, whereas the negative bias exists insofar $\nu > 0.3292$. Even if we consider an elasticity of substitution as low as $\nu = 0.5$, we find evidence in favor of a severe negative bias: in this case the aggregate output elasticity is around 0.09.

All in all, these results corroborate that heterogeneity in public investment composition yields a negative estimation bias for the aggregate output elasticity, and the magnitude of this bias barely depends on the exact value of the elasticity of substitution across public capital types as long as we exclude counterfactually low values of ν (i.e., we exclude values of ν below 0.5).

Figure 2: Estimation Bias and the Elasticity of Substitution ν.



Note: The figure reports the estimated aggregate output elasticity as a function of different values of the elasticity of substitution across public capital types, ν. The dashed line reports the value of the aggregate output elasticity which coincides with the sum of the output elasticities across types, that is, the no-bias value of the aggregate output elasticity.

We find a severe negative bias for the aggregate output elasticity, as it is always substantially below the sum of the output elasticities of equipment, structures, and IPP. This finding holds irrespectively even when moving the output elasticities across types around the baseline values. In line with our derivations, we find that raising the output elasticity of IPP further exacerbate the negative bias. Instead, the opposite applies when raising the value of the output elasticity of public structures. We also showcase that a positive bias can emerge when public structures are highly productive with a value that equals the sum of the elasticity across the three types, i.e. $\gamma_s = 0.125$, while equipment and IPP are not productive.

Importantly, Appendix C.1 shows additional strong evidence in favor of a sizable negative bias for the aggregate output elasticity even in case either we halve the elasticity of substitution across public capital types to $\nu = 0.75$, or we reduce it even further to $\nu = 0.5$. All in all, these results highlight that abstracting from heterogeneity across public equipment, structures, and IPP leads to a large negative bias in the estimation of the aggregate output elasticity so that it is substantially lower than the sum of the output elasticity across the three types. In what follows, we quantify the implications of this negative bias for the derivation of optimal public investment and the public investment multiplier, by comparing the predictions of the "Multiple-Type" and "Single-Type" economies.

5.3 Optimal Public Investment

Similarly to Section 3.2, we derive the optimal levels of public capital and public investment, by maximizing household's utility at the steady state. In doing so, we compare the optimal levels implied by our baseline "Multiple-Type" economy with those of the "Single-Type" model. Since we focus on the steady state of these two economies, we abstract from the role of time-to-spend and time-to-build delays. In addition, the derivation of the optimal levels abstracts from the actual values of the public investment shares. Accordingly, for the sake of the results of this section, in the "Multiple Type" economy, public equipment, structures, and IPP differ in terms of output elasticities and depreciation rates.

We report the results of this exercise in Table 3. While in the "Single-Type" economy the ratios of optimal public capital and public investment over (annualized) GDP are 133.45% and 5.82%, respectively, they are substantially larger when in the "Multiple-Type" model. Indeed, our baseline economy predicts levels of optimal capital and investment, which equal 213.50% and 10.34%. In other words, the negative bias in the aggregate output elasticity makes heterogeneity in public investment composition to double the optimal level of public investment.[8]

[8] To be precise, moving from the "Single Type" to the "Multiple Type" model raises the optimal level of public capital by 60%, and the optimal level of public investment by 78%.

When disentangling the implications of our model on optimal public capital across the three types, we find that the optimal amount of public capital and investment as a fraction of GDP equal 3.72% and 0.46% for equipment, 171% and 3.27% for structures, and 38.78% and 6.61% for IPP. These moments imply that IPP is the type with the highest ratio of optimal public investment over GDP. This is due to its combination of a high output elasticity of public capital and a high depreciation rate. Instead, the very low depreciation rate of structures—coupled with its relatively high output elasticity—implies a large fraction of public capital in its type as a share of GDP.

Interestingly, there are large differences between the model implications on optimal public investment by type and the actual shares of public investment in GDP in the data. According to the model, IPP is most under-invested type: the optimal GDP share of public investment in IPP is five times that in the data, 6.61% vs. 1.31%. Public structures are slightly under-invested, with an optimal share of 3.27% compared to the 2.25% in the data. On the contrary, the optimal levels of equipment are slightly below to those observed in the data.[9]

Appendix C.2 shows that heterogeneity in the public investment composition substantially rises the optimal amount of total public investment even if we consider different calibration strategies for the output elasticities of public capital by type. Thus, notwithstanding the exact specification of the output elasticities by type, insofar there is a substantial negative bias in the aggregate output elasticity, a model with multiple types of public capital predicts strikingly larger optimal

Table 3: Optimal Public Capital and Public Investment.

		Total	Equipment	Structures	IPP
Optimal Public Capital (% of GDP)	Single-Type	133.45	-	-	-
	Multiple-Type	213.50	3.72	171.00	38.78
Data		73.82	9.44	57.63	6.65
Optimal Public Investment (% of GDP)	Single-Type	5.82	-	-	-
	Multiple-Type	10.34	0.46	3.27	6.61
Data		4.84	1.28	2.25	1.31

Note: The table reports the optimal public capital and optimal public investment—in percentage terms with respect to annual GDP—for the "Single-Type" economy and the "Multiple-Type" economy, and compare them to the values observed in the data. The statistics are computed for total public investment, as well as for each public investment type: equipment, structures, and IPP.

[9]Using the shares of public investment by type observed in the data, we can back out the implied output elasticities. We find values of $\gamma_e = 0.017$, $\gamma_s = 0.07$, $\gamma_i = 0.018$, so that their sum equals 0.105. If we feed in these output elasticities in the model, we estimate an aggregate output elasticity of 0.0845. In other words, the negative bias holds on even if we set the output elasticities by type so to match the ratio of public investment to GDP observed in the data.

levels of public investment. We also corroborate the validity of our results to the case in which public investment is financed via a distortionary labor income tax, rather than a lump-sum one.

5.4 Fiscal Multipliers

5.4.1 Measurement

We now turn to the positive implications of the composition of public investment by measuring how the fiscal multiplier varies when accounting for heterogeneity in public investment composition. To do so, we follow Mountford and Uhlig (2009) and compute the fiscal multiplier in present-value terms at horizon $\mathcal{H}$:

$$\mathcal{M}_{\mathcal{H}} = \frac{\sum_{t=0}^{\mathcal{H}} \beta^t \left(Y_t - Y\right)}{\sum_{t=0}^{\mathcal{H}} \beta^t \left(X_t - X\right)}, \tag{36}$$

where X_t denotes a generic type of public investment. When we study the effects of the aggregate shock that preserves the composition of public investment, ε_t, the denominator uses the variation in total public investment, $X_t = I_{G_e,t}+I_{G_s,t}+I_{G_i,t}$. Instead, when we focus on the type-specific public investment shocks, $\varepsilon_{e,t}$, $\varepsilon_{s,t}$, and $\varepsilon_{i,t}$, the denominator uses public investment in either equipment (i.e., $X_t = I_{G_e,t}$), structures, (i.e., $X_t = I_{G_s,t}$), or IPP, (i.e., $X_t = I_{G_i,t}$).

Equation (36) posits that the fiscal multiplier, $\mathcal{M}_{\mathcal{H}}$, equals the ratio between the discounted sum of the deviations from steady state of GDP and the discounted sum of the deviations from steady state of public investment up to quarter $\mathcal{H}$. In what follows, we focus on the short-run and long-run implications of public investment by computing the multiplier both at the 1-year horizon (i.e., $\mathcal{H} = 4$) and throughout the entire response of output to the public investment shock (i.e., $\mathcal{H} = \infty$), which we refer to as the long-run multiplier.

5.4.2 The Role of the Public Investment Composition

We start by reporting in Columns (1) and (2) of Table 4 the 1-year and long-run multipliers for the "Single-Type" and "Multiple-Type" economies. In the short run, we find very muted effects of public investment: the multiplier of total public investment at the 1-year horizon is 0.19 in both economies. This is consistent with the findings of Boehm (2020), in which public investment has limited stimulus effect on impact. In our case, this limited effect hinges on the time-to-build and time-to-spend delays.[10] Thus, heterogeneity in the public investment composition is immaterial for the measurement of the fiscal multiplier in the short run.

When looking at the multipliers for each type of public investment, we find that public equipment generates the strongest output response, with a 1-year multiplier of 0.42. Instead, the multiplier for structures is 0.07, and that of IPP is even negative, -0.02. Again, this is due to the heterogeneous incidence of the

[10] Appendix C.3 shows that the 1-year multiplier for the "Multiple-Type" economy becomes 0.70 when abstracting from the time-to-build and time-to-spend delays.

time-to-build and time-to-spend delays: since they characterize relatively more the investment in structures—and to a lower extent that of IPP—these lags curb substantially their output response. Instead, public investment in equipment is implemented and accrues to the stock of capital almost immediately, so that private inputs can benefit even in the short run from this type of spending.

The multiplier increases significantly at longer horizons: the long-run multiplier in the "Multiple-Type" economy is 1.54, in line with the values reported in the literature (Boehm, 2020; Ramey, 2021; Peri et al., 2024). Instead, the long-run multiplier for the "Single-Type" model is much lower and even below 1, as it equals 0.72. This comparison highlights the second key quantitative result of the paper: the severe negative bias in the estimated aggregate output elasticity makes heterogeneity in public investment composition to double the long-run fiscal multiplier.

Again, there is substantial variation in the long-run multipliers between equip-

Table 4: Fiscal Multipliers.

		Total	Equipment	Structures	IPP
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.19	-	-	-
	Multiple-Type	0.19	0.42	0.07	-0.02
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.72	-	-	-
	Multiple-Type	1.54	0.45	0.58	3.99

Note: This table reports fiscal multipliers, at the horizon of 1 year and in the long run. The table compares the multipliers associated with the "Single-Type" economy, which abstracts from heterogeneity in the public investment composition and considers only one type of public investment, and the "Multiple-Type" economy, which is the baseline model with public investment in equipment, structures, and IPP.

ment, structures, and IPP: the multiplier ranges from 0.45 for equipment to 0.58 for structures, and then up to 3.99 for IPP. From this perspective, should the government want to maximize the bang for the buck, public investment plans should be titled toward investment in intellectual property products.

5.4.3 Robustness Checks

Appendix C.3 validates the implications of public investment composition on the size of the fiscal multipliers in an extensive battery of robustness checks. Specifically, we consider: (i) a lower Frisch elasticity (i.e., $\eta = 2$, so that the Frisch elasticity is 0.5 as in Chetty et al., 2013), (ii) a higher Frisch elasticity (i.e., $\eta = 0.5$, so that the Frisch elasticity is 2 as in Erosa et al., 2016), (iii) lower markups (i.e., $\epsilon = 6$ so that markups equal 20%), (iv) higher persistence of the AR(1) processes of public investment appropriations (i.e., $\rho = 0.94$ in line with the estimate of Leeper et al., 2010), (v) a higher time discount factor (i.e.,

$\beta = 0.995$ so that the real return at steady state is 2%), (vi) a stronger response of the Taylor rule to inflation (i.e., $\phi_\pi = 5$), (vii) no private investment adjustment costs (i.e., $\Omega = 0$), (viii) prolonged time-to-build delays for private investment with a lag of 10 quarters, (ix) no time-to-spend delay (i.e., $\tau_e = \tau_s = \tau_i = 0$), (x) no time-to-build delay (i.e., $\zeta_e = \zeta_s = \zeta_i = 0$), and (xi) no delay at all (i.e., $\tau_e = \tau_s = \tau_i = \zeta_e = \zeta_s = \zeta_i = 0$), (xii) distortionary taxes as in Leeper et al. (2010), (xiii) sticky wages as in Erceg et al. (2000), (xiv) flexible prices (i.e., $\phi = 0$ so that prices are reset in each period).

Next, we also evaluate the implications of different values for the output elasticities: (i) halved elasticities (i.e., $\gamma_e = 0.0025$, $\gamma_s = 0.025$, $\gamma_i = 0.035$), (ii) a higher equipment elasticity (i.e., $\gamma_e = 0.02$), (iii) a lower equipment elasticity (i.e., $\gamma_e = 0$), (iv) a higher structure elasticity (i.e., $\gamma_s = 0.07$), (v) a higher IPP elasticity (i.e., $\gamma_s = 0.09$) and (vi) implied elasticities to match the ratio of public investment over GDP by type observed in the data (i.e., $\gamma_e = 0.017$, $\gamma_s = 0.07$, $\gamma_i = 0.018$).

In addition, we study also how the difference in the multiplier between the "Single-Type" and "Multiple-Type" economies varies with the distinct sources of heterogeneity across types in the baseline model. To do so, we consider "Multiple-Type"economies in which we abstract each time from a dimension of heterogeneity. Consistently with the fact that the variation in the depreciation rates is the key feature that determines heterogeneity in public capital stocks—and thus is the necessary condition for the existence of the negative bias in the estimated aggregate output elasticity—we find that the long-run multipliers coincide in "Single-Type" and "Multiple-Type" economies in case we consider homogeneous depreciation rates in the latter. However, in all other cases we still find that a substantial amplification in the size of the long-run multiplier moving from the "Single-Type" to the "Multiple-Type" economy, with an increase in the range of 95%-163%.

All in all, this analysis shows that accounting for heterogeneity in the public investment composition substantially amplifies the long-run fiscal multiplier relative to the economy with a homogeneous stock of public capital.

5.5 Changes in the Public Investment Composition

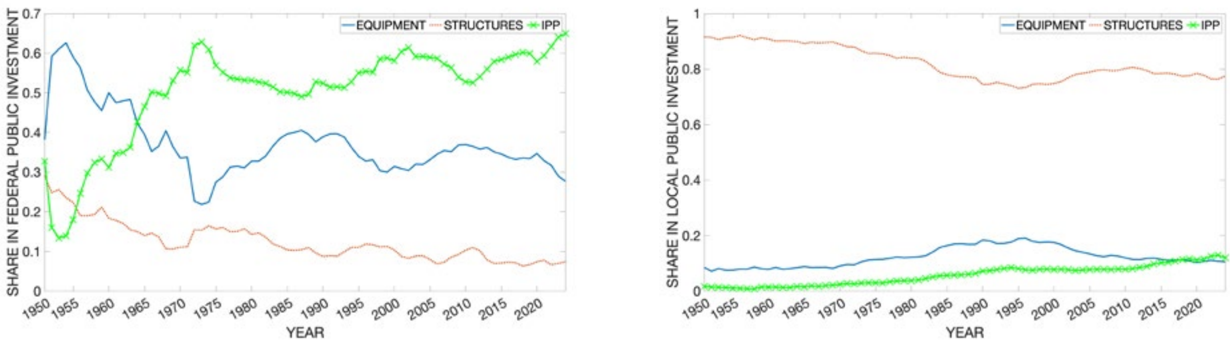
The previous section has established that long-run multipliers vary substantially across types. This observation implies that changes in the composition public investment between equipment, structures, and IPP varies both across government levels and over time imply stark differences in the multiplier of total public investment. We uncover this fact with a final exercise that leverages the observed variation in the composition of public investment of the U.S. general, federal, and local government between 1950 and 2023.

First of all, we replicate the same decomposition exercise of Figure 1, but this time focusing on the public investment of the federal and local government, rather than that of the general government. Figure 3 highlights that the composition of public investment changes both over time and across government levels. Interestingly, the relevance of IPP has increased in recent decades, especially in the case of the federal government.

We evaluate the implications of these differences and shifts by feeding them

Figure 3: Composition of Public Investment across Government Levels

(a) Federal Government (b) Local Government



Note: The figures show the shares of equipment, structures, and IPP in total public investment from 1950 to 2023 for the federal government, in Panel (a), and the local government, in Panel (b).

into the model. Specifically, we consider that each point of time our economy is hit by a sequence of shocks to public investment in equipment, structures, and IPP that feature the same composition observed for each level of the government over each year, between 1950 and 2023. To do so, we run a model specification for each combination of government level and year in a three-step process. First, we modify the law of motions of planned public investment expenditures of Equations (30) by focusing solely on the common shock, and add type-specific loadings χ_x, as follows:

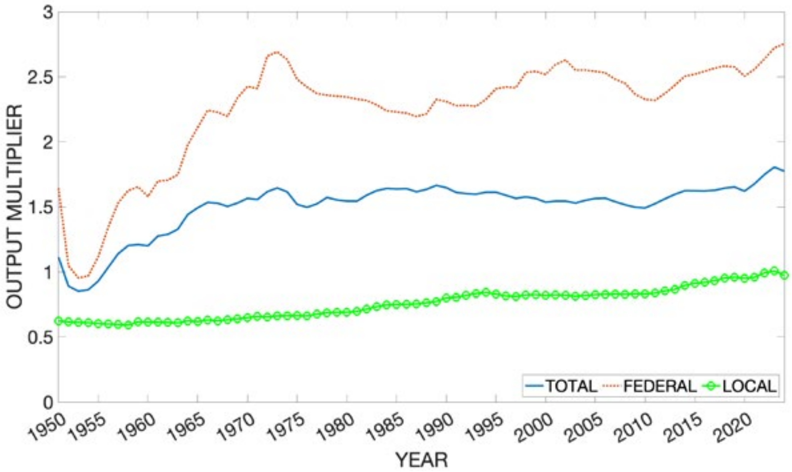
$$\log A_{G_x,t} = (1-\rho)\log I_{G_x} + \rho \log A_{x,t-1} + \chi_x \varepsilon_t. \tag{37}$$

Second, we set the loading parameters to ensure the composition of total public investment coincides with that of the government level of interest in the year of interest. Third, we shock the economy and measure the implied long-run multiplier.[11] We show the results of this exercise in Figure 4.

The overall variation in the long-run multipliers is very substantial. On the low end, the public investment multipliers of the local government are low and smoothly increasing over time around values always below one, from 0.59 in 1957 to 1.01 in 2022. On the high end, public investment of the federal government has the highest multipliers, as it consists mainly of IPP. The ability of this government level in triggering a large output response has been varying considerably over time: the long-run multiplier was 1.64 in 1950, shrunk to 0.95 in 1952, and

[11] Although the elasticity of output to public capital may differ when comparing spending of different government levels, in this exercise, we keep fixed the quantitative relevance of the different dimensions of heterogeneity across public investment types, as defined in the calibration of Section 5.1.

Figure 4: Public Investment Composition and Long-Run Fiscal Multipliers



Note: The figures show the long-run fiscal multipliers implied by a composition of public investment that resembles that of different government levels, as it varies year by year in the data, between 1950 and 2023.

rose steadily up to 2.69 in 1972. After that, the multiplier has been around 2.3, and only recently increased again, reaching the maximum value of 2.75 exactly in 2023. Interestingly, although the long-run multiplier of the general government conceals a large deal of the heterogeneity between the federal and local government, it still ranges between 0.85 and 1.81.

Overall, the results of this section corroborate the notion that the composition of public investment has a first-order quantitative bearing on the size of the fiscal multiplier, so that the output response tends to be larger whenever spending is tilted towards IPP investment, as it is the case for the federal government, especially over the most recent years.

6 Conclusion

This paper argues that the composition of public investment across types is critical to understand the aggregate implications of this type of spending. First, we show analytically that whenever there is heterogeneity in the size of stocks of public capital across types, recovering the output elasticity of aggregate public capital yields to a bias. The direction of this bias depends on the correlation between output elasticities and public capital stock sizes across types: a strong positive correlation yields to a positive bias, whereas the opposite applies with a negative or mildly positive correlation. As a result, focusing on singly homogeneous type of public capital may misestimates the aggregate effects of public investment.

We then introduce three types of public investment—equipment, structures, and IPP—into an otherwise standard New Keynesian economy. We discipline the model by considering heterogeneity across types in the output elasticities to public capital, depreciation rates, time-to-build and time-to-spend delays, as well as steady-state shares of each type of spending in total GDP. When we calibrate the model, we find that although IPP is the most productive type of public capital, it features the lowest stock size. This rules out a positive correlation between output elasticities and public capital stock sizes across types, and thus implies the existence of a negative bias for the aggregate output elasticity. We find this bias to be severe.

The large negative bias makes a single-type economy to substantially underestimate the aggregate effects of public investment. We show that a multiple-type economy generates optimal levels of public investment and long-run public investment multipliers which are twice as large as those associated with a single-type economy.

Finally, we feed the model with actual variation in public investment composition both over time, between 1950 and 2023, and across government levels, considering the composition of public investment of the general, federal, and local government. This exercise highlights that changes in the composition alter substantially the multiplier, and also uncover that the public investment of federal government has the strongest ability in spurring a surge in output, as this type of spending is tilted more towards IPP investment.

References

Acemoglu, Daron, Ufuk Akcigit and William Kerr. (2016). "Networks and the macroeconomy: An empirical exploration". *NBER Macroeconomics Annual,* 30(1), pp. 273–335. https://doi.org/10.1086/685961

Baqaee, David, and Emmanuel Farhi. (2019). "The microeconomic foundations of aggregate production functions". *Journal of the European Economic Association,* 17(5), pp. 1337–1392. https://doi.org/10.1093/jeea/jvz050

Barattieri, Alessandro, Susanto Basu and Peter Gottschalk. (2014). "Some evidence on the importance of sticky wages". *American Economic Journal: Macroeconomics,* 6(1), pp. 70–101. https://doi.org/10.1257/mac.6.1.70

Basso, Henrique S., and Omar Rachedi. (2024). "The carbon-adjusted fiscal multiplier". Unpublished.

Baxter, Marianne, and Robert King. (1993). "Fiscal policy in general equilibrium". *American Economic Review,* 83(3), pp. 315–334. https://www.jstor.org/stable/2117521

Boehm, Christoph. (2020). "Government consumption and investment: Does the composition of purchases affect the multiplier?". *Journal of Monetary Economics,* 115, pp. 80–93. https://doi.org/10.1016/j.jmoneco.2019.05.003

Bouakez, Hafedh, Michel Guillard and Jordan Roulleau-Pasdeloup. (2017). "Public investment, time to build, and the zero lower bound". *Review of Economic Dynamics,* 23, pp. 60–79. https://doi.org/10.1016/j.red.2016.09.001

Bouakez, Hafedh, Michel Guillard and Jordan Roulleau-Pasdeloup. (2020). "The optimal composition of public spending in a deep recession". *Journal of Monetary Economics,* 114, pp. 334–349. https://doi.org/10.1016/j.jmoneco.2019.03.006

Bouakez, Hafedh, Omar Rachedi and Emiliano Santoro. (2023). "The government spending multiplier in a multi-sector economy". *American Economic Journal: Macroeconomics,* 15(1), pp. 209–239. https://doi.org/10.1257/mac.20200213

Bouakez, Hafedh, Omar Rachedi and Emiliano Santoro. (2024). "The sectoral origins of the spending multiplier". https://doi.org/10.2139/ssrn.4996004

Calvo, Guillermo. (1983). "Staggered prices in a utility-maximizing framework". *Journal of Monetary Economics,* 12(3), pp. 383–398. https://doi.org/10.1016/0304-3932(83)90060-0

Chetty, Raj, Adam Guren, Day Manoli and Andrea Weber. (2013). "Does indivisible labor explain the difference between micro and macro elasticities? A meta-analysis of extensive margin elasticities". *NBER Macroeconomics Annual,* 27(1), pp. 1–56. https://doi.org/10.1086/669170

Clarida, Richard, Jordi Gali and Mark Gertler. (2000). "Monetary policy rules and macroeconomic stability: Evidence and some theory". *Quarterly Journal of Economics,* 115(1), pp. 147–180. https://doi.org/10.1162/003355300554692

Cox, Lydia, Gernot Müller, Ernesto Pasten, Raphael Schoenle and Michael Weber. (2024). "Big G". *Journal of Political Economy,* 132(10), pp. 3260–3297. https://doi.org/10.1086/730426

De Loecker, Jan, Jan Eeckhout and Gabriel Unger. (2020). "The rise of market power and the macroeconomic implications". *Quarterly Journal of Economics*, 135(2), pp. 561–644. https://doi.org/10.1093/qje/qjz041

Erceg, Christopher, Dale Henderson and Andrew Levin. (2000). "Optimal monetary policy with staggered wage and price contracts". *Journal of Monetary Economics*, 46(2), pp. 281–313. https://doi.org/10.1016/S0304-3932(00)00028-3

Erosa, Andrés, Luisa Fuster and Gueorgui Kambourov. (2016). "Towards a micro-founded theory of aggregate labour supply". *Review of Economic Studies*, 83(3), pp. 1001–1039. https://doi.org/10.1093/restud/rdw010

Fernald, John. (1999). "Roads to prosperity? Assessing the link between public capital and productivity". *American Economic Review*, 89(3), pp. 619–638. https://doi.org/10.1257/aer.89.3.619

Fernald, John. (2014). "A quarterly, utilization-adjusted series on total factor productivity". Paper Series, 2012-19, Federal Reserve Bank of San Francisco, pp.1-28. https://doi.org/10.24148/wp2012-19

Fieldhouse, Andrew, and Karel Mertens. (2023). "The returns to government R&D: Evidence from US appropriations shocks". https://doi.org/10.24149/wp2305

Fisher, Franklin M. (1965). "Embodied technical change and the existence of an aggregate capital stock". *Review of Economic Studies*, 32(4), pp. 263–288. https://doi.org/10.2307/2295835

Gomme, Paul, and Peter Rupert. (2007). "Theory, measurement and calibration of macroeconomic models". *Journal of Monetary Economics*, 54(2), pp. 460–497. https://doi.org/10.1016/j.jmoneco.2005.09.005

Hall, Robert. (2009). "By how much does GDP rise if the government buys more output?". *Brookings Papers on Economic Activity*, 2009(2), pp. 183–231. https://doi.org/10.1353/eca.0.0069

Ilzetzki, Ethan, Enrique Mendoza and Carlos A. Végh. (2013). "How big (small?) are fiscal multipliers?". *Journal of Monetary Economics*, 60(2), pp. 239–254. https://doi.org/10.1016/j.jmoneco.2012.10.011

Jorgenson, Dale Weldeau, and Zvi Griliches. (1967). "The explanation of productivity change". *Review of Economic Studies*, 34(3), pp. 249–283. https://doi.org/10.2307/2296675

Koh, Dongya, Raül Santaeulàlia-Llopis and Yu Zheng. (2020). "Labor share decline and intellectual property products capital". *Econometrica*, 88(6), pp. 2609–2628. https://doi.org/10.3982/ECTA17477

Leduc, Sylvain, and Daniel J. Wilson. (2013). "Roads to prosperity or bridges to nowhere? Theory and evidence on the impact of public infrastructure investment". *NBER Macroeconomics Annual*, 27(1), pp. 89–142. https://doi.org/10.1086/669173

Leeper, Eric, Michael Plante and Nora Traum. (2010). "Dynamics of fiscal financing in the United States". *Journal of Econometrics*, 156(2), pp. 304–321. https://doi.org/10.1016/j.jeconom.2009.11.001

Leeper, Eric, Todd Walker and Shu-Chun Yang. (2010). "Government investment and fiscal stimulus". *Journal of Monetary Economics*, 57(8), pp. 1000–1012. https://doi.org/10.1016/j.jmoneco.2010.09.002

Malley, James, and Apostolis Philippopoulos. (2023). "The macroeconomic effects of funding US infrastructure". *European Economic Review*, 152, p. 104334. https://doi.org/10.1016/j.euroecorev.2022.104334

Moro, Alessio, and Omar Rachedi. (2022). "The changing structure of government consumption spending". *International Economic Review*, 63(3), pp. 1293–1323. https://doi.org/10.1111/iere.12568

Mountford, Andrew, and Harald Uhlig. (2009). "What are the effects of fiscal policy shocks?". *Journal of Applied Econometrics*, 24(6), pp. 960–992. https://doi.org/10.1002/jae.1079

Peri, Alessandro, Omar Rachedi and Iacopo Varotto. (2024). "Public investment in a production network: Aggregate and sectoral implications". *Review of Economics and Statistics.* Forthcoming. https://doi.org/10.1162/rest_a_01391

Ramey, Valerie. (2021). "Chapter 4. The macroeconomic consequences of infrastructure investment". In University of Chicago Press, *Economic Analysis and Infrastructure Investment*, pp. 219–276. https://doi.org/10.7208/chicago/9780226800615.003.0005

Roulleau-Pasdeloup, Jordan. (2022). "The public investment multiplier: Insights from a new analytical framework". Unpublished.

Solow, Robert. (1955). "The production function and the theory of capital". *Review of Economic Studies*, 23(2), pp. 101–108. https://doi.org/10.2307/2296293

Sraffa, Piero. (1960). *Production of commodities by means of commodities. Prelude to a Critique of Economic Theory.* Cambridge University Press. https://doi.org/10.2307/139694

Wilson, Daniel J. (2009). "IT and beyond: The contribution of heterogeneous capital to productivity". *Journal of Business & Economic Statistics*, 27(1), pp. 52–70. https://doi.org/10.1198/jbes.2009.0005

Woodford, Michael. (2011). "Simple analytics of the government expenditure multiplier". *American Economic Journal: Macroeconomics*, 3(1), pp. 1–35. https://doi.org/10.1257/mac.3.1.1

A More on the Analytical Derivations

Proof of Proposition 1

Proof. If $K_{G_x} = \bar{K}_G \;\; \forall x \in \{1, \ldots, \mathcal{X}\}$, then $K_G \equiv \left[\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}}\right]^{\frac{\nu}{\nu-1}} = \bar{K}_G$. As such $\log K_{G_x} / \log K_G = 1 \;\; \forall x \in \{1, \ldots, \mathcal{X}\}$, which also implies that $\theta_x = 1 \;\; \forall x \in \{1, \ldots, \mathcal{X}\}$. Using Equation (20), it then follows that $\bar{\gamma} = \sum_{x=1}^{\mathcal{X}} \gamma_x$. These results are irrespective of the value of the elasticity of substitution across public capital types, ν. □

Proof of Proposition 2

Proof. When $K_{G_x} \neq \bar{K}_G \;\; \forall x \in \{1, \ldots, \mathcal{X}\}$ and $\nu \to 0$, then $K_G = \left[\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}}\right]^{\frac{\nu}{\nu-1}}$ converges to $\min[K_{G_1}, \ldots, K_{G_{\mathcal{X}}}]$. As such, $\frac{\log K_{G_x}}{\log K_G} \geqslant 1 \; \forall x \in \{1, \ldots, \mathcal{X}\}$. Using Equation (20), it follows that $\bar{\gamma} < \sum_{x=1}^{\mathcal{X}} \gamma_x$. □

Proof of Proposition 3

Proof. Consider the case in which $\nu \to \infty$, so that $K_G \to \sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}$. Let $\underline{K}_G \equiv \min\{K_{G_x}\}$ and $\bar{K}_G \equiv \max\{K_{G_x}\}$. It follows that $\log(\underline{K}_G) \leqslant \log(K_G) \leqslant \log(\bar{K}_G)$. Therefore, we have that $\frac{\log K_{G_x}}{\log K_G} \geqslant 1$ for those public capital types x for which $K_G \leqslant K_{G_x} \leqslant \bar{K}_G$ and $\frac{\log K_{G_x}}{\log K_G} \leqslant 1$ for public capital types x for which $\underline{K}_G \leqslant K_{G_x} \leqslant K_G$. As a result, one can always find a set of $\gamma_x^\star \;\; \forall x \in \{1, \ldots, \mathcal{X}\}$, such that $\bar{\gamma} = \sum_{x=1}^{\mathcal{X}} \frac{\log K_{G_x}}{\log K_G} \gamma_x^\star = \sum_{x=1}^{\mathcal{X}} \gamma_x^\star$. Then, decreasing the output elasticity $\gamma_{\bar{x}}$ for a specific type $x \equiv \bar{x} \in \{1, \ldots, \mathcal{X}\}$ which is such that $\frac{\log K_{G_{\bar{x}}}}{\log K_G} \geqslant 1$ (decreasing their correlation), yields a negative bias, so that $\bar{\gamma} < \sum_{x=1}^{\mathcal{X}} \gamma_x$. Vice versa, increasing the output elasticity of the same type $x \equiv \bar{x} \in \{1, \ldots, \mathcal{X}\}$ leads to a positive bias, so that $\bar{\gamma} > \sum_{x=1}^{\mathcal{X}} \gamma_x$. Finally, as long as, $\nu > 0$ then $K_G > \underline{K}_G$ (using the results in proposition 2 and 4), completing the proof. □

Proof of Proposition 4

Proof. First we show that $K_G \equiv \left[\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}}\right]^{\frac{\nu}{\nu-1}}$ increases with the value of the elasticity of substitution across public capital types, ν.

$$
\begin{aligned}
\frac{\partial K_G}{\partial \nu} &= K_G \Bigg\{ \frac{-1}{(\nu-1)^2} \left[\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}} \log(\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}}) + \\
&\quad + \frac{1}{(\nu-1)\nu} \left[\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}-1} \sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}} \log(K_{G_x}) \Bigg\} = \\
&= \frac{K_G^2}{(\nu-1)^2} \left[-\log(\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}}) + \frac{\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}} \log(K_{G_x}^{\frac{\nu-1}{\nu}})}{\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}}} \right] \approxeq \\
&\approxeq \frac{K_G^2}{(\nu-1)^2} \left[-(1+\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}}) + \frac{\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}} (1+K_{G_x}^{\frac{\nu-1}{\nu}})}{\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}}} \right] \approxeq \\
&\approxeq \frac{K_G^2}{(\nu-1)^2} \left[\frac{-(\sum_{x=1}^{\mathcal{X}} K_{G_x}^{\frac{\nu-1}{\nu}})^2 + \sum_{x=1}^{\mathcal{X}} \vartheta_x (K_{G_x}^{\frac{\nu-1}{\nu}})^2}{\sum_{x=1}^{\mathcal{X}} \vartheta_x K_{G_x}^{\frac{\nu-1}{\nu}}} \right] \geqslant 0
\end{aligned}
$$

The last inequality holds due to Jensen's inequality $[\sum_{x=1}^{\mathcal{X}} \vartheta_x f(z) \geqslant f(\sum_{x=1}^{\mathcal{X}} \vartheta_x z)]$ for any z if $f(\cdot)$ is convex.

As in the proof of Proposition 3, if we define $\underline{K}_G \equiv \min\{K_{G_x}\}$ and $\bar{K}_G \equiv \max\{K_{G_x}\}$, then as ν increases $\log(\underline{K}_G) \leqslant \log(K_G) \leqslant \log(\bar{K}_G)$. Consequently, as we decrease the elasticity γ_x for high capital stock types, for which $\frac{\log K_{G_x}}{\log K_G} \geqslant 1$, and increase the elasticity γ_x for low capital types, for which $\frac{\log K_{G_x}}{\log K_G} \leqslant 1$, or in general, decrease the correlation between elasticities and the stock of capital across types, it is more likely that $\bar{\gamma} = \sum_{x=1}^{\mathcal{X}} \frac{\log K_{G_x}}{\log K_G} \gamma_x < \sum_{x=1}^{\mathcal{X}} \gamma_x$. □

B Empirical Evidence

This section provides prima-facie evidence that supports the calibration of two dimensions of the model: (i) the output elasticities of public equipment, structures, and IPP, and (ii) the elasticity of substitution of public capital across types. Section B.1 extends the standard approach in the estimation of the aggregate output elasticity to the case of public equipment, structures, and IPP, respectively, whereas Section B.2 takes the first order condition of the aggregate public capital aggregator to the data.

B.1 Output Elasticities of Public Capital across Types

In Section 5.1, we discuss the calibration choices of the model regarding the output elasticities to public capital for equipment, structures, and IPP, which are based on values derived in the literature. Section 5.2 corroborates these decisions by showing that the model implies an estimated elasticity of private output to public capital which is remarkably in line with values found in the literature. In this section, we provide further support to our calibration by providing novel empirical evidence in line with our choices for the output elasticities.

To do so, we extend the econometric analysis of Bouakez et al. (2017) and Ramey (2021) by focusing each time on a different type of public capital, rather than considering total public capital. Specifically, we estimate the following regression

$$\log TFP_t = \gamma_e \log K_{G_e,t} + \mathbf{X}'_t\theta + \epsilon_t, \tag{B.1}$$

$$\log TFP_t = \gamma_s \log K_{G_s,t} + \mathbf{X}'_t\theta + \epsilon_t, \tag{B.2}$$

$$\log TFP_t = \gamma_i \log K_{G_i,t} + \mathbf{X}'_t\theta + \epsilon_t, \tag{B.3}$$

where υ_e, υ_s, and υ_i are the values of the elasticity of private output to public investment in equipment, structures, and IPP, respectively, as observed in the data, TFP_t is a measure of capacity-adjusted productivity, $\mathbf{X}'_t$ is a set of covariates, and $K_{G_e,t}$, $K_{G_s,t}$, and $K_{G_i,t}$ are the stocks of public capital for the three types. Note that insofar our model is the true data generator process of the data, then the three stocks of public capital are orthogonal to each other, and thus we can recover the type-specific output elasticities by estimating regressions (B.1), (B.2), and (B.3) one by one, without incurring in any omitted variable bias. Regarding the covariates, Bouakez et al. (2017) and Ramey (2021) argue about the importance of incorporating factors that capture variation in both human capital and private R&D, so that the regressions can uniquely pin down the effect of public capital on productivity.

To run the estimation, we take the very same data used in Bouakez et al. (2017) and Ramey (2021) which refer to the U.S. economy from 1950 on at the annual frequency, and extend them with information on public capital for equipment, structures, and IPP. Specifically, Bouakez et al. (2017) and Ramey (2021) consider data from the U.S. BEA on the current-cost stock of total public capital of the general government, civilian non-institutional population above the age of 16, data from the Federal Reserve Economic Data of the St. Louis Federal Reserve Bank on the GDP deflator, the GDP component of research and development, and the personal consumption expenditures in education services. The series of seasonally-adjusted TFP comes from Fernald (2014). We add to this information by merging it with data from the U.S. BEA on the current-cost stocks of public capital in equipment, structures, and IPP.

We then compute the real stock of public capital for each stock per capita, by dividing the current-cost stocks by the product of the GDP deflator and population. We do the same for both R&D and education expenditures. With this data, we estimate the relationships (B.1), (B.2), and (B.3) as cointegrating regressions using Dynamic Ordinary Least Squares, using two leads and no lags as in Bouakez et al. (2017) and Ramey (2021). We find that the estimate of the output elasticity of equipment is $\hat{\gamma}_e = -0.0035$ with a standard deviation of 0.0904 and a p-value of 0.969, the estimate of the output elasticity of structures is $\hat{\gamma}_s = 0.0447$ with a standard deviation of 0.0259 and a p-value of 0.084, and the estimate of the output elasticity of IPP is $\hat{\gamma}_i = 0.1354$ with a standard deviation of 0.0663 and a p-value of 0.041.

These values imply that our calibration choice for equipment slightly overstates its output elasticity, as we set $\gamma_e = 0.005$ while we cannot reject the null hypothesis that it is zero in the data. The estimated output elasticity for structures is 0.0447, in line with our calibration choice of $\gamma_s = 0.05$. Actually, we cannot reject the null hypothesis that the estimate $\hat{\upsilon}_s$ equals 0.05 at the 10% level (the test yields a p-value of 0.8372). Finally, while the point estimate of the elasticity of IPP is $\hat{\upsilon}_i = 0.1354$ and larger than our calibration choice of $\gamma_s = 0.07$, given the standard error of the estimate we cannot reject the null hypothesis that $\hat{\upsilon}_i$ equals 0.07 at the 10% level (the test yields a p-value of 0.3241). All in all, these empirical results further corroborate the validity of our calibration strategy for the output elasticity to public capital for equipment, structures, and IPP.

Furthermore, consistently with the findings of Fieldhouse and Mertens (2023), we find that the high values of the output elasticity are associated with the stocks of public capital of the defense federal government spending. Instead, all the stocks of public capital of non-defense spending—including the stock of IPP—are not statistically different from zero. Although our empirical approach is different both in terms of data and approach from that of Fieldhouse and Mertens (2023), the fact that we find very similar results provide further support to our calibration strategy.

B.2 Elasticity of Substitution of Public Capital Types

This section gives prima-facie evidence on the elasticity of substitution across public capital types. Let us restate the function that bundles public of Equation (35):

$$K_{G,t} = \left[\sum_{x=1}^{\mathcal{X}} \omega_x K_{G_x,t}^{\frac{\nu-1}{\nu}} \right]^{\frac{\nu}{\nu-1}}, \tag{B.4}$$

where ω_x is the weight of each public capital type, and ν is our parameter of interest, that is, the elasticity of substitution across public capital types.

How can we estimate the elasticity of substitution in the data? Let us take the first order conditions associated to a given type x:

$$K_{G_x,t} = \omega_x^{\nu} \left(\frac{P_{K_{G,t}}}{P_{K_{G_x,t}}} \right)^{\nu} K_{G,t}, \tag{B.5}$$

where $P_{K_{G,t}}$ is the implied price of aggregate public capital and $P_{K_{G_x,t}}$ is the implied price of public capital in type x.

We then implement two manipulations: multiply both sides by $\frac{P_{K_{G_x,t}}}{P_{K_{G,t}} K_{G,t}}$ and then take the logarithm. Accordingly, Equation (B.5) turns into the following

$$\log \left(\frac{P_{K_{G_x,t}} K_{G_x,t}}{P_{K_{G,t}} K_{G,t}} \right) = \log \left(\omega_x^{\nu} \right) + (1-\nu) \log \left(\frac{P_{K_{G_x,t}}}{P_{K_{G,t}}} \right), \tag{B.6}$$

which relates the share of the value of public capital in a given type x (in terms of the total value of public capital) as a function of a constant, and the interaction between a function of the elasticity of substitution and the logarithm of the price of the stock of public capital of type x relative to the price of the stock of aggregate public capital. As a result, we can regress the logarithm of the share of public capital of type x on a constant and the relative price of the stock of public capital of type x, and in this way estimate implicitly the elasticity of substitution ν.

If we focus on the three types of public capital—equipment, structures, and IPP—so that $x \in \{e, s, i\}$, and apply the same manipulations described above, we can specify the panel regression:

$$\log \left(\frac{P_{K_{G_x,t}} K_{G_x,t}}{P_{K_{G,t}} K_{G,t}} \right) = \log \left(\omega_x^{\nu} \right) + (1-\nu) \log \left(\frac{P_{K_{G_x,t}}}{P_{K_{G,t}}} \right) + \kappa_x + \kappa_t + \epsilon_{x,t}, \tag{B.7}$$

where κ_x denotes type-specific fixed effects and κ_t are time fixed effects. To bring regression (B.7) to the data, we get information on the current-cost net stock of aggregate public capital, public capital in equipment, public capital in structures, and public capital in IPP of the general government from the Fixed Assets Tables of the BEA, at the annual frequency from 1950 to 2022. Unfortunately, there is no direct measurement of the price of the stocks of public capital. We then use as a proxy the price index of aggregate public investment and public investment for the three types from the BEA.

When we estimate the panel regression (B.7), we find a value of $(1-\nu)$ that equals -0.64 (with a p-value of 0.5%), which implies an estimate of the elasticity of substitution of $\hat{\nu} = 1.64$. If we test for the estimate of $(1-\nu)$ to equal -0.5, so that the estimated elasticity of substitution is 1.5 as in our parametrization, we cannot reject the null hypothesis with a p-value of 54%. Accordingly, our prima-facie evidence on the elasticity of substitution across public capital types implies a very mild degree of substitutability, and justifies our calibration choice.

C Quantitative Analysis: Additional Results

This section provides an extensive battery of robustness checks that corroborate the validity of our three main quantitative findings: (i) the existence of the negative bias in the estimation of the aggregate output elasticity in Section C.2, (ii) the fact that accounting for heterogeneity in public investment composition raises substantially the optimal level of public investment in Section 5.3, and (iii) the fact that accounting for heterogeneity in public investment composition doubles the long-run public investment multiplier in Section C.3.

C.1 More on the Aggregate Output Elasticity Bias

The existence of a severe negative bias in the estimation of the output elasticity of aggregate public capital does not vary when perturbing the values of the output elasticities of each type around their baseline values even when considering a substantially lower elasticity of substitution of public capital.

To establish this result, we alter the elasticity of substitution from our preferred value of 1.5 to either 0.75 or 0.5. In this way, we can evaluate how the negative bias varies when we halve the elasticity of substitution or even divide it by three. Specifically, we report in Panel A of Table C.1 the estimated aggregate output elasticity in the baseline economy and in the set of alternative calibrations of the output elasticities by type considered in Table 2 when the elasticity of substitution is set to 0.75, and do the similar analysis for the elasticity of substitution of 0.5 in Panel B.

The results indicate that while in the baseline the negative bias (i.e., the difference between the estimated aggregate output elasticity and the sum of output elasticities across types) is -0.0532, it becomes -0.0470 when we halve the elasticity of substitution, and -0.0325 when $\nu = 0.5$. In other words, the extent of the negative bias barely varies even when we reduce substantially the elasticity of substitution, and the same holds for all the different specifications of the output elasticities by type.

In addition, the last row of either Panel shows that when counterfactually attributing the entire extent of the productivity of public capital to structures, so that $\gamma_e = \gamma_i = 0$ and $\gamma_s = 0.125$, we observe a positive bias which instead rises sharply as the elasticity of substitution shrinks. While with $\nu = 1.5$ the positive bias of this counterfactual specification of the output elasticities is 0.0082, it becomes as high as 0.0411 when $\nu = 0.5$. From this perspective, this result confirms our analytical derivations showing that a strong positive correlation between the

Table C.1: Aggregate Output Elasticity Bias.

Multiple-Type Economy	Output Elasticities by Type	Estimated Value (1)	No Bias Value (2)	Implied Bias (3)
Low Elasticity of Substitution across Public Capital Types: $\nu = 0.75$				
Baseline	$\gamma_e = 0.0050, \gamma_s = 0.0500, \gamma_i = 0.0700$	0.0780	0.1250	-0.0470
Halved Elasticities	$\gamma_e = 0.0025, \gamma_s = 0.0250, \gamma_i = 0.0350$	0.0372	0.0625	-0.0253
Low Equipment Elasticity	$\gamma_e = 0.0000, \gamma_s = 0.0500, \gamma_i = 0.0700$	0.0762	0.1200	-0.0438
High Equipment Elasticity	$\gamma_e = 0.0200, \gamma_s = 0.0500, \gamma_i = 0.0700$	0.0836	0.1400	-0.0564
High Structures Elasticity	$\gamma_e = 0.0050, \gamma_s = 0.0700, \gamma_i = 0.0700$	0.1035	0.1450	-0.0415
High IPP Elasticity	$\gamma_e = 0.0050, \gamma_s = 0.0500, \gamma_i = 0.0900$	0.0839	0.1450	-0.0611
Only Productive Structures	$\gamma_e = 0.0000, \gamma_s = 0.1250, \gamma_i = 0.0000$	0.1433	0.1250	0.0183
Low Elasticity of Substitution across Public Capital Types: $\nu = 0.5$				
Baseline	$\gamma_e = 0.0050, \gamma_s = 0.0500, \gamma_i = 0.0700$	0.0925	0.1250	-0.0325
Halved Elasticities	$\gamma_e = 0.0025, \gamma_s = 0.0250, \gamma_i = 0.0350$	0.0447	0.0625	-0.0178
Low Equipment Elasticity	$\gamma_e = 0.0000, \gamma_s = 0.0500, \gamma_i = 0.0700$	0.0905	0.1200	-0.0295
High Equipment Elasticity	$\gamma_e = 0.0200, \gamma_s = 0.0500, \gamma_i = 0.0700$	0.0989	0.1400	-0.0411
High Structures Elasticity	$\gamma_e = 0.0050, \gamma_s = 0.0700, \gamma_i = 0.0700$	0.1216	0.1450	-0.0234
High IPP Elasticity	$\gamma_e = 0.0050, \gamma_s = 0.0500, \gamma_i = 0.0900$	0.0992	0.1450	-0.0458
Only Productive Structures	$\gamma_e = 0.0000, \gamma_s = 0.1250, \gamma_i = 0.0000$	0.1661	0.1250	0.0411

Note: Panel (A) and (B) report analogous moments of Table 2 with the only difference that we have reduced the elasticity of substitution of public capital across types in the aggregator of total public capital from $\nu = 1.5$ to $\nu = 0.75$, and from $\nu = 1.5$ to $\nu = 0.5$, respectively.

output elasticities and the public capital stock sizes across types yields a positive bias especially when there is a sufficiently low elasticity of substitution across public capital types.

C.2 Optimal Public Capital: Robustness Checks

To ascertain the robustness of the model implications on the optimal levels of public investment and public capital at the steady state, we consider five alternative calibration choices for the elasticities of private output to the three types of public capital. We report all the results of this exercise in Table C.2. Importantly, for every specification of the multiple type economy that we consider in this robustness analysis, we define the corresponding single-type model with its associated implied aggregate output elasticity.

In the first case, we halve the three output elasticities from their baseline values, which implies that the values for equipment, structures, and IPP become $\gamma_e = 0.0025$, $\gamma_s = 0.025$, and $\gamma_i = 0.035$, respectively. Note that this setting implies a sum of the output elasticities across types of 0.0625, but when we estimate the aggregate output elasticity we find a value of 0.0334, confirming the existence of a severe negative bias. As a result, moving from the "Single-Type" to the "Multiple-Type" economy substantially raises the levels of both the optimal public capital (from 63.28% to 106.75%, a 69% increase) and the optimal public investment (from 2.76% to 5.17%, a 87% increase).

In the second case, we consider the baseline output elasticities for structures and IPP, but make public equipment to be not productive, so that $\gamma_e = 0$. Since this case barely reduces the negative bias, as indicated by the estimated reported in Table 2, accounting for heterogeneity in public investment composition still substantially increases the optimal levels of public capital (from 130.47% to 209.78%, a 61% increase) and public investment (from 5.69% to 9.88%, a 74% increase). Then, we do the opposite and make public equipment much more productive than in the baseline, so that $\gamma_e = 0.02$. In this case, moving from the "Single-Type" to the "Multiple-Type" economies increases the optimal levels of public capital by 57% (from 143.13% to 224.67%) and public investment by 88% (from 6.24% to 11.73%).

In the fourth case, we consider a higher output elasticity of public structures, with a value of $\gamma_s = 0.07$. Although this calibration reduces the negative bias as it boosts the productivity of the type with the largest stock of capital—thus raising the positive correlation between output elasticities and stock sizes across types, we still find a significant amplification due to heterogeneity in the public investment composition: moving from the "Single-Type" to the "Multiple-Type" economy substantially changes the levels of both the optimal public capital (from 177.93% to 281.90%, a 58% increase) and the optimal public investment (from 7.76% to 11.65%, a 50% increase).

Vice versa, in the last case we consider a higher output elasticity of public IPP, which exacerbates the negative bias. As a result, accounting for heterogeneity in the public investment composition raises the optimal level of public capital

Table C.2: Optimal Public Capital and Public Investment - Robustness Checks.

		Total	Equipment	Structures	IPP
Panel A: Halved Elasticities					
Optimal Public Capital (% of GDP)	Single-Type	63.28	-	-	-
	Multiple-Type	106.75	1.86	85.50	19.39
Optimal Public Investment (% of GDP)	Single-Type	2.76	-	-	-
	Multiple-Type	5.17	0.23	1.64	3.30
Panel B: Low Equipment Elasticity					
Optimal Public Capital (% of GDP)	Single-Type	130.47	-	-	-
	Multiple-Type	209.78	0.00	171.00	38.78
Optimal Public Investment (% of GDP)	Single-Type	5.69	-	-	-
	Multiple-Type	9.88	0.00	3.27	6.61
Panel C: High Equipment Elasticity					
Optimal Public Capital (% of GDP)	Single-Type	143.13	-	-	-
	Multiple-Type	224.67	14.89	171.00	38.78
Optimal Public Investment (% of GDP)	Single-Type	6.24	-	-	-
	Multiple-Type	11.73	1.85	3.27	6.61
Panel D: High Structures Elasticity					
Optimal Public Capital (% of GDP)	Single-Type	177.93	-	-	-
	Multiple-Type	281.90	3.72	239.40	38.78
Optimal Public Investment (% of GDP)	Single-Type	7.76	-	-	-
	Multiple-Type	11.65	0.46	4.58	6.61
Panel E: High IPP Elasticity					
Optimal Public Capital (% of GDP)	Single-Type	143.69	-	-	-
	Multiple-Type	224.58	3.72	171.00	49.86
Optimal Public Investment (% of GDP)	Single-Type	6.27	-	-	-
	Multiple-Type	12.23	0.46	3.27	8.50

Note: The table reports the optimal public capital and optimal public investment—in percentage terms with respect to annual GDP—for the "Single-Type" economy and the "Multiple-Type" economy associated with different calibrations of the output elasticities of public capital by type. Panel A halves the elasticities with respect to the baseline calibration, Panel B considers a lower value of the output elasticity of public equipment so that $\gamma_e = 0$, Panel C considers a higher value of the output elasticity of public equipment so that $\gamma_e = 0.02$, Panel D considers a higher value of the output elasticity of public structures so that $\gamma_s = 0.07$, and Panel E considers a higher value of the output elasticity of public IPP so that $\gamma_i = 0.09$.

by 56% (from 143.69% to 224.58%) and that of public investment by 95% (from 6.27% to 12.23%).

Finally, we corroborate the validity of our results to the case in which public investment is financed via a distortionary labor income tax, rather than a lump-sum one. The social planner now takes into account that increasing public investment creates a distortion on labor supply but as public investment increases the productivity of both private capital and labor, optimal investment reduces by only 4% due to the distortions relative to the case where the social planner uses lump-sum taxes. Results are displayed in table C.3.

Table C.3: Optimal Public Capital and Investment: Lump-sum versus Distortionary Taxes.

		Total	Equipment	Structures	IPP
Optimal Public Capital	Single-Type	133.45	-	-	-
with lump-sum taxes (% of GDP)	Multiple-Type	213.50	3.72	171.00	38.78
Optimal Public Capital	Single-Type	130.39	-	-	-
with distortionary taxes (% of GDP)	Multiple-Type	204.61	3.57	163.88	37.17
Data		73.82	9.44	57.63	6.65
Optimal Public Investment	Single-Type	5.82	-	-	-
with lump-sum taxes (% of GDP)	Multiple-Type	10.34	0.46	3.27	6.61
Optimal Public Investment	Single-Type	5.69	-	-	-
with distortionary taxes (% of GDP)	Multiple-Type	9.91	0.44	3.14	6.33
Data		4.84	1.28	2.25	1.31

Note: The table reports the optimal public capital and optimal public investment—in percentage terms with respect to annual GDP—for the "Single-Type" economy and the "Multiple-Type" economy when government finances investment with lump-sum or distortionary taxes on labor income and compare them to the values observed in the data. The statistics are computed for total public investment, as well as for each public investment type: equipment, structures, and IPP.

C.3 Fiscal Multipliers: Robustness Checks

We turn into the robustness checks of the model implications on fiscal multipliers. While the previous section only studied the role of the output elasticities to public capital—since these are the dimensions that determine the optimal levels—we now consider a much wider array of alternative calibration choices and model specifications. We report the 1-year and long-run multipliers in the "Single-Type" and "Multiple-Type" economies for each of these robustness checks in Tables C.4-C.6.

Panels A and B of Table C.4 look into the value of the Frisch elasticity, which is set to one in the baseline calibration. The Frisch elasticity is a key parameter for the transmission of public spending: as discussed by Hall (2009), fiscal multipliers increase in the value of the Frisch elasticity so that a more elastic labor supply may be required to generate a relatively stronger output response to public investment. In the first robustness check, we reduce it to 0.5, so that $\eta = 2$, in line with the the evidence on the elasticity at the individual level provided by Chetty et al. (2013). In the second case, we instead increase the Frisch elasticity to 2, so that $\eta = 0.5$. This choice is closer to the value of 4 considered by Baxter and King (1993) and Ramey (2021), and in line with the macro-level elasticity of labor supply derived in Erosa et al. (2016).

Panel C evaluates the role of the markup. In the baseline model, we set the elasticity of substitution across varieties to $\epsilon = 4$, so that the markup is 30%, in line with De Loecker et al. (2020). In this check, we reduce the markup to 20%, which implies a value of the elasticity of substitution of $\epsilon = 6$. Then, Panel D considers the role of the persistence of the AR(1) processes for planned public investment in each type. While in the baseline we set $\rho = 0.9$, we now consider a higher degree of persistence so that $\rho = 0.94$, in line with the estimate of Leeper et al. (2010).

Panel E studies the role of the time discount factor. In the baseline case, we set $\beta = 0.99$ to get an annualized real interest rate is 4%. Given the decline in real rates in recent decades, and the fact that the measurement of fiscal multipliers in Equation (36) implies that the time discount factor directly affects it, by modulating the discounting of the deviations from steady state of GDP and public investment, we consider a case in which we the time discount factor rises to $\beta = 0.995$, which implies an annual real interest rate of 2%.

Moving to Table C.5, Panel F ascertains the role of the monetary policy stance, as Woodford (2011) demonstrates that the level of the multiplier shrinks if the monetary authority is relatively more reactive to changes in inflation. We address this possibility by raising the inflation sensitivity of nominal interest rates in the Taylor rule from $\phi_\pi = 1.5$ to $\phi_\pi = 5$

In Panel G, we considers the role of the adjustment costs of private investment. Indeed, the results of Ramey (2021) indicate that the presence of adjustment costs is not innocuous, as they hinder the crowding out effect on investment, raising the multiplier. Accordingly, we abstract from the adjustment costs in private

Table C.4: Fiscal Multipliers - Robustness Checks.

		Total	Equipment	Structures	IPP
Panel A: Low Frisch Elasticity					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.04	-	-	-
	Multiple-Type	0.07	0.28	-0.09	-0.07
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.52	-	-	-
	Multiple-Type	1.44	0.22	0.38	4.16
Panel B: High Frisch Elasticity					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.33	-	-	-
	Multiple-Type	0.30	0.54	0.23	0.03
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.87	-	-	-
	Multiple-Type	1.63	0.65	0.75	3.86
Panel C: Low Markups					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.18	-	-	-
	Multiple-Type	0.19	0.42	0.07	-0.03
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.73	-	-	-
	Multiple-Type	1.57	0.46	0.59	4.07
Panel D: High AR(1) Persistence					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.18	-	-	-
	Multiple-Type	0.17	0.40	0.08	-0.08
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.79	-	-	-
	Multiple-Type	1.57	0.52	0.68	3.89
Panel E: High Discount Factor					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.16	-	-	-
	Multiple-Type	0.16	0.40	0.04	-0.08
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	1.00	-	-	-
	Multiple-Type	2.04	0.44	0.90	5.22

Note: This table reports fiscal multipliers, at the horizon of 1 year and in the long run. The table compares the multipliers associated with the "Single-Type" economy, which abstracts from heterogeneity in the public investment composition and considers only one type of public investment, and the "Multiple-Type" economy, which is the baseline model with public investment in equipment, structures, and IPP.

Table C.5: Fiscal Multipliers - Robustness Checks (cont).

		Total	Equipment	Structures	IPP
Panel F: High Taylor Rule Response to Inflation					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.13	-	-	-
	Multiple-Type	0.14	0.32	0.11	-0.10
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.66	-	-	-
	Multiple-Type	1.48	0.40	0.55	3.89
Panel G: No Private Investment Adjustment Cost					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.66	-	-	-
	Multiple-Type	0.49	0.41	1.00	0.09
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.68	-	-	-
	Multiple-Type	1.46	0.37	0.60	3.76
Panel H: Long Time-to-Build for Private Investment					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.21	-	-	-
	Multiple-Type	0.23	0.43	0.08	0.08
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.85	-	-	-
	Multiple-Type	1.68	0.55	0.73	4.15
Panel I: No Time-to-Build Delays					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.23	-	-	-
	Multiple-Type	0.38	0.43	0.06	0.61
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.87	-	-	-
	Multiple-Type	2.04	0.46	0.77	5.43
Panel J: No Time-to-Spend Delays					
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.54	-	-	-
	Multiple-Type	0.53	0.57	0.55	0.45
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.83	-	-	-
	Multiple-Type	1.69	0.54	0.69	4.25

Note: This table reports fiscal multipliers, at the horizon of 1 year and in the long run. The table compares the multipliers associated with the "Single-Type" economy, which abstracts from heterogeneity in the public investment composition and considers only one type of public investment, and the "Multiple-Type" economy, which is the baseline model with public investment in equipment, structures, and IPP.

investment, setting $\Omega = 0$. Instead, in Panel H, we keep the adjustment costs but set a prolonged time-to-build as we do for public investment. Specifically, we take the time-to-build for each type of public investment, get the share of equipment, structures, and IPP in total private investment, and derive the implied duration of the time-to-build delay. We find that the composition of private investment across types is very similar to that of public investment, so that the implied duration of the time-to-build delay is 10 quarters.

We then study the implications of the time-to-build and time-to-spend delays for public investment. Specifically, Panel I abstracts from the time-to-build delays, $\zeta_e = \zeta_s = \zeta_i = 0$, Panel J abstracts from the time-to-spend delays, so that $\tau_e = \tau_s = \tau_i = 0$, and Panel K of Table C.5 abstracts from either type of delay, so that $\zeta_e = \zeta_s = \zeta_i = \tau_e = \tau_s = \tau_i = 0$.

Panel L alters the fiscal system by positing that changes in public investment from the steady state are financed through a distortionary tax on both labor income and capital income, in the spirit of Leeper et al. (2010). Specifically, we change the household borrowing constraint of Equation (23) as follows

$$P_t C_t + P_t I_t + B_{t+1} + T_t = (1 - \tau_t) W_t N_t + (1 - \tau_t) R_{K,t} K_t + R_t B_t + D_t, \quad \text{(C.8)}$$

where τ_t denotes the distortionary tax rate. Then, the government budget constraint of Equation (33) becomes

$$T + \tau_t \left[W_t N_t + R_{K,t} K_t \right] = \sum_{x=1}^{\mathcal{X}} I_{G_x,t}. \quad \text{(C.9)}$$

where the lump-sum tax equals total public investment at the steady state, $T = \sum_{x=1}^{\mathcal{X}} I_{G_x,t}$.

Panel M studies a version of the model with nominal wage rigidity as in Erceg et al. (2000). To do so, we consider that households supply differentiated varieties of labor, indexed by $\mu \in [0, 1]$, which are imperfectly substitutable among themselves. This implies a labor aggregator that reads

$$N_t = \left(\int_0^1 N_{\mu,t}^{\frac{\epsilon_w - 1}{\epsilon_w}} \mathrm{d}\mu \right)^{\frac{\epsilon_w}{\epsilon_w - 1}}, \quad \text{(C.10)}$$

where $N_{\mu,t}$ denotes a specific variety of labor, and ϵ_w is the elasticity of substitution. Total labor is then sold to the wholesalers at a wage, which is set according to a Calvo price-setting protocol, in which the probability of adjusting it equals to $1 - \phi_w$. We set the elasticity to substitution to $\epsilon_w = 4$, so that is equals the value of the elasticity of substitution across wholesalers' goods varieties, while the probability of not adjusting the wage is $\phi_w = 2/3$, in line with the evidence on the frequency of wage adjustments documented by Barattieri et al. (2014).

Finally, Panel N considers a version of the model that abstracts from price rigidity, by setting the Calvo provability to zero, that is, $\phi = 0$, which implies that firms can always reset their price optimally.

In all cases, we find that although the different specifications alter the role of heterogeneity in public investment composition for the fiscal multiplier in the short run, these differences are not economically significant. Instead, this extensive battery of robustness checks confirms that the "Multiple-Type" economy implies a substantially larger long-run public investment multiplier than the "Single-Type" model. In all these cases, the minimum change in the size of the long-run multiplier across the two economies is 87%, which is associated with the high Frisch elasticity models in Panel B.

Table C.6: Fiscal Multipliers - Robustness Checks (cont.).

		Total	Equipment	Structures	IPP
		Panel K: No Delay			
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.58	-	-	-
	Multiple-Type	0.70	0.58	0.57	1.00
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.99	-	-	-
	Multiple-Type	2.18	0.54	0.89	5.63
		Panel L: Distortionary Taxation			
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	-0.43	-	-	-
	Multiple-Type	-0.40	-0.03	-0.71	-0.64
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	-0.15	-	-	-
	Multiple-Type	0.66	-0.38	-0.33	3.12
		Panel M: Sticky Wages			
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.15	-	-	-
	Multiple-Type	0.16	0.45	-0.06	-0.04
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.74	-	-	-
	Multiple-Type	1.59	0.50	0.59	4.11
		Panel N: Flexible Prices			
1-Year Multiplier, $\mathcal{M}_4$	Single-Type	0.36	-	-	-
	Multiple-Type	0.30	0.40	0.41	0.05
Long-run Multiplier, $\mathcal{M}_\infty$	Single-Type	0.69	-	-	-
	Multiple-Type	1.50	0.40	0.57	3.90

Note: This table reports fiscal multipliers, at the horizon of 1 year and in the long run. The table compares the multipliers associated with the “Single-Type” economy, which abstracts from heterogeneity in the public investment composition and considers only one type of public investment, and the “Multiple-Type” economy, which is the baseline model with public investment in equipment, structures, and IPP.

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