INDUSTRIAL POLICIES IN PRODUCTION NETWORKS*

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Abstract

Many developing countries adopt industrial policies that push resources towards selected economic sectors. How should countries choose which sectors to promote? I answer this question by characterizing optimal industrial policy in production networks embedded with market imperfections. My key finding is that effects of market imperfections accumulate through backward demand linkages, thereby generating aggregate sales distortions that are largest in the most upstream sectors. The distortion in sectoral sales is a sufficient statistic for the ratio between social and private marginal product of sectoral inputs; therefore, there is an incentive for a well-meaning government to subsidize upstream sectors. My sufficient statistic predicts the sectors targeted by government interventions in South Korea in the 1970s and in modern-day China.

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1 Introduction

One of the oldest problems in economics is understanding how industrial policies can facilitate economic development. What is industrial policy? Broadly speaking, it is purposeful government intervention to selectively promote specific economic sectors. Industrial policies have been prominently adopted in many currently and formerly developing economies: Japan from the 1950s to 1970s, South Korea and Taiwan from the 1960s to 1980s, and modern-day China.

By their nature, these policies seek to affect the aggregate economy by targeting a few sectors; hence, cross-sector linkages are important considerations (Hirschman 1958). Loose economic reasoning suggests that it may be advantageous to subsidize or promote the development of sectors thought to serve as backbones of the economy—natural resource production, iron and steel industries, etc. Indeed, this has often been the strategy taken by countries implementing such policies. Policy documents from these interventionist governments often explicitly state "network linkages" as a criterion for choosing sectors to support.[1]

Despite their widespread use and loosely supporting intuition, economists have only a very limited formal understanding of the forms these policies should take. In this paper, I build on the production networks literature and provide the first formal analysis of industrial policy in the presence of cross-sector linkages and market imperfections. My key finding is that the effects of market imperfections accumulate through what I call "backward demand linkages", causing certain sectors to become the "sink" of distortions, thereby creating an incentive for well-meaning governments to subsidize them. The sectors in which distortions accumulate are typically designated in the networks literature as "upstream," meaning they supply to many other sectors and use few inputs from other sectors. In the data, this notion corresponds with the same sectors policymakers seem to view as important targets for intervention.

To develop my results, I start with a canonical model of production network and embed in it a generic formulation of market imperfections, which can be microfounded by a variety of underlying frictions. Market imperfections distort the use of sectoral inputs, resulting in their marginal products exceeding marginal costs. Such distortions accumulate over the production network and aggregate to alter productive sectors' equilibrium size away from their optimal size. I show that this aggregate distortion in the size of a sector is a sufficient statistic for the ratio between social and private marginal revenue products in that sector. I term the sufficient statistic "distortion centrality"—it is one scalar per sector and is defined as the ratio between sectoral influence, which

[1] See Li and Yu (1982), Kuo (1983), and Yang (1993) for Taiwan; Kim (1997) for Korea; and State Development Planning Commission of China (1995) for China.

captures sectoral size under optimal production, and sectoral sales, which is the sectoral size in equilibrium.

In the economy, the first welfare theorem holds in the absence of market imperfections; therefore, the first-best equilibrium can be trivially restored if all imperfections can be removed. On the other hand, when market imperfections cannot be directly corrected, there is room for a well-meaning government to interfere with market allocations, and distortion centrality guides optimal sectoral interventions. Specifically, I show that, holding within-sector distortions constant, a benevolent government should provide the first dollar of production subsidies to sectors with the highest distortion centrality. My results apply to marginal tax instruments that directly or indirectly expand sectoral input use; such instruments include subsidies to value-added and intermediate inputs, subsidies to sales, and transfers of working capital if market imperfections arise due to financial constraints. Furthermore, if production functions are Cobb-Douglas, distortion centrality is informative for not only marginal but also constrained-optimal subsidies to value-added input.

Perhaps surprisingly, sectors with the highest distortion centrality are not necessarily the most distorted sectors; instead, they tend to be upstream ones that supply to many distorted downstream sectors. This is because market imperfections accumulate through backward demand linkages over the production network. When a sector is distorted, the producer purchases less-than-optimal amounts of inputs from its suppliers, thereby depressing the sales of these upstream suppliers, which in turn purchase less from their own input suppliers. The effect keeps transmitting upstream through intermediate demand, and, as a result, the most upstream sector becomes the "sink" of all distortions in the economy and thus has the highest distortion centrality.

In a general production network, distortion centrality depends on market imperfections in every sector of the economy, the estimation of which is a formidable task. Indeed, a major criticism of industrial policies is that it is impossible for governments to identify the relevant sectors that are subject to market imperfections; simply put, "government cannot pick winners" (Rodrik 2008). Yet, precisely because distortions backwardly accumulate, I show that if the equilibrium input-output structure exhibits log-supermodularity—so that relatively upstream sectors use upstream inputs more intensively—then the rank ordering of sectoral distortion centrality is insensitive to the distribution of underlying market imperfections. This result suggests that it is unnecessary to precisely estimate sectoral imperfections in order to conduct welfare-improving policy interventions. In the absence of an exact intervention that directly removes market imperfections—due to either policy infeasibility or informational constraints—the second-best policy in a log-supermodular network is always to subsidize the upstream sectors, to which all distortions eventually propagate, no matter where they originate in the network.

My analysis calls for a re-evaluation of industrial policies in developing countries. Many critics of industrial policies draw on insights from the misallocation literature popularized by Hsieh and Klenow (2009) and Restuccia and Rogerson (2008), a line of work that quantitatively evaluates the loss in aggregate TFP due to firms failing to equalize the marginal revenue products of inputs. Pointing to the logical inevitability that sector-based policies generate "misallocation across sectors" and the empirical evidence that firms in the subsidized sectors tend to have lower marginal revenue products, critics conclude that sectoral interventions must lower welfare.[2] My theoretical results challenge this logic. Whereas *within-sector* dispersion in private marginal revenue products unambiguously lowers productive efficiency, as the misallocation literature suggests, my analysis shows that *cross-sector* dispersion in private marginal revenue products could enhance welfare. This is because in the presence of cross-sector linkages, social and private marginal revenue products are not equal; in fact, I provide an example in section 5 in which the rank orderings of sectoral private and social marginal revenue products are reversed. Spending in upstream sectors tends to have higher social return precisely because these sectors have high distortion centrality. In other words, to equate social marginal revenue products across sectors, the private marginal revenue products have to be lower in the upstream sectors in a distorted production network. My analysis therefore provides a counterpoint to the prevailing view that selective interventions and the consequent cross-sector misallocations must be a sign of inefficiency.

I apply my theoretical insights and empirically examine the input-output structures of South Korea during the 1970s and modern-day China, as these are two of the most salient economies with interventionist governments that have actively implemented industrial policies. I show that these economies' input-output structures approximately exhibit log-supermodularity, and, as a result, distortion centrality is insensitive to the distribution of underlying market imperfections. Further, I find that distortion centrality predicts the sectors targeted by government interventions in both of these economies. The sectors South Korea promoted in the 1970s have, on average, significantly higher distortion centrality. In modern-day China, privately-owned firms in sectors with higher distortion centrality have significantly better access to loans at more favorable interest rates, and these sectors also tend to have more state-owned enterprises, to which the government directly extends subsidies and credit in order to expand sectoral production. To be clear, these correlations by no means suggest that policies adopted by these economies were optimal: my theory abstracts away from practical aspects of policy implementation as well as the various political economy factors that affect policy choices in these economies (Krueger 1990). Nevertheless, my results suggest that there are aspects of Korean and Chinese industrial strategy that appear to be motivated by a desire to subsidize sectors that create positive network effects.

[2]For example, see Ruiz (2003), Nabli et al. (2006), Chung (2007), Sun (2009), Dabla-Norris et al. (2015), Calligaris et al. (2016), Gebresilasse (2016), and Leal (2015, 2017).

Literature Review The literature on industrial policies dates back to at least the seminal contributions by Rosenstein-Rodan (1943) and Hirschman (1958).[3] Recent contributions to this literature include Rodrik (2004, 2008), Robinson (2010), and Cheremukhin et al. (2017a, 2017b), among many others. My paper revisits Hirschman's thesis on the importance of cross-sector input-output linkages for development policies by formally analyzing the effect of government interventions in production networks with market imperfections. In a recent paper, Lane (2017) empirically studies South Korea's industrial policies during the 1970s and finds evidence for pecuniary externalities, i.e. that sectors downstream of the promoted ones experienced positive spillovers from the industrial policy program. My theoretical analysis shows that the general equilibrium effects of such pecuniary externalities can be succinctly characterized in order to design optimal interventions, and I show that my characterization predicts the sectors promoted in both historical South Korea and modern-day China.

Methodologically, my paper builds on the production networks literature. The paper to which my work most closely relates is Jones (2013), who embeds generic distortions into a Cobb-Douglas production economy with cross-sector linkages and studies the implications of distortions for aggregate output. The presence of distortions in Jones (2013) implies that sectoral influence is decoupled from sales. Following Jones (2013), there is a burgeoning literature that investigates the effects of market imperfections on aggregate output, including Bartelme and Gorodnichenko (2015), Altinoglu (2015), Bigio and La'O (2016), Baqaee (2017), Boehm (2017), and Grassi (2017). Caliendo et al. (2017) develop methodologies to identify sectoral distortions in production networks.

I make several contributions to this literature. First, I show that in a distorted production network, distortion centrality—the wedge between sectoral influence and sales—captures the ratio between social and private marginal revenue product in a sector. As a result, distortion centrality guides the optimal marginal interventions that directly or indirectly shift the use of production inputs. Second, I explicitly characterize how underlying market imperfections are aggregated into distortion centrality. I show that imperfections accumulate through backward demand linkages; therefore, the upstream sectors become the "sink" of distortions and tend to have the highest distortion centrality. Neither of these results relies on the strong Cobb-Douglas or the constant elasticity-of-substitution functional assumptions imposed by this literature.

My paper also relates to the large body of macro-development literature on the misallocation of resources, including Banerjee and Duflo (2005), Restuccia and Rogerson (2008), Hsieh and Klenow (2009), Banerjee and Moll (2010), Song et al. (2011), Buera et al. (2011), Midrigan

[3] Other key references in the vast literature on industrial policies include Chenery et al. (1986), Amsden (1989), Murphy et al. (1989), Krueger (1990), Wade (1990), Westphal (1990), Page (1994), and Woo-Cumings (2001).

and Xu (2014), and Rotemberg (2017) among many others. The literature's central line of inquiry addresses the implications of micro-level market imperfections on aggregate productivity. My paper draws on this literature but shifts the focus: I study misallocation *across*—rather than *within*—sectors. I show that in the presence of input-output linkages, private and social marginal revenue products no longer coincide. As a result, equating private marginal revenue products across sectors is no longer sufficient for constrained efficiency: social marginal revenue products can still vary, and the aggregate productive efficiency can be improved if inputs are redirected to sectors with high distortion centrality.

The rest of the paper is organized as follows: Section 2 introduces a generic formulation of market imperfections into a canonical model of production network. Section 3 characterizes the distorted equilibrium. Section 4 introduces the distortion centrality measure and studies its implication for policy interventions. Section 5 characterizes how distortion centrality is shaped by underlying market imperfections and network structure. Section 6 applies the model and empirically examines the input-output relationship in historical South Korea as well as modern-day China. Section 7 concludes.

2 A Production Network With Market Imperfections

2.1 Model

This section lays out my model, which strikes a balance between generality and tractability. To focus on the policy implications of market imperfections in a production network and obtain sharp characterizations, the model deliberately features simplistic factor supply and consumption decisions.

Economic Environment The economy has a production factor in fixed supply, L, which we refer to as "labor" but can be alternatively interpreted as a composite factor consisting of labor and other factor inputs. There is a representative consumer who has non-satiated preferences and consumes a unique final good (with price normalized to one). There are S intermediate production sectors,[4] each producing a differentiated good that is used for both intermediate production and the production of the unique final good. I will refer to the output of sector i as good i and to the S goods altogether as "intermediate goods".

[4] I use the terms "sector" and "industry" interchangeably.

The final good is produced competitively by combining intermediate goods under production function

$$Y = F(Y_1, \cdots, Y_S), \tag{1}$$

where Y_i is the units of good i used for final production and Y is the aggregate output. I assume $F(\cdot)$ is differentiable, has constant-returns-to-scale, and is strictly increasing and jointly concave in its arguments.

Each intermediate good i is produced by a constant returns to scale production technology

$$Q_i = z_i F_i\left(L_i, \left\{M_{ij}\right\}_{j\in S}\right), \tag{2}$$

where L_i is the total labor employed in sector i and z_i captures the Hicks-neutral sectoral productivity. The terms $\left\{M_{ij}\right\}$ denote the amount of intermediate goods (j's) used by sector i as production inputs, and this dependence on intermediate goods captures the notion of production linkages across sectors.

Assumption 1. *Production functions F_i and F are continuously differentiable and strictly concave. Furthermore, $F_i(0, M_{i1}, \cdots M_{iS}) = 0$ and $\frac{\partial F_i(L_i, M_{i1}, \cdots M_{iS})}{\partial L_i} > 0$ at all input levels. That is, every sector needs labor to produce, and sectoral output is always strictly increasing in labor.*

Market Imperfections And Distorted Equilibrium The economic setting described thus far falls under the class of "generalized Leontief models" as defined by Arrow and Hahn (1971, pp. 40). It is well known that the First Welfare Theorem holds in this environment, and the decentralized equilibrium would be efficient if each intermediate good is produced by a price-taking representative firm. I introduce market imperfections into this economy by specifying that the allocations are "as if" chosen by a fictitious price-taking representative firm in each intermediate sector, with the fictitious firm facing input prices that are exogenously distorted upwards.

Specifically, let P_j denote the cost of purchasing good j. Market imperfections in sector i take the form of exogenous distortions χ_i^L and $\left\{\chi_{ij}\right\}_{j=1}^S$ such that equilibrium allocations are "as if" chosen by a price-taking and profit-maximizing representative firm, which faces a "shadow price" of $\left(1+\chi_i^L\right) W$ for labor and $P_j\left(1+\chi_{ij}\right)$ for input $j \in S$, with $\chi_i^L, \chi_{ij} \geq 0$.

Definition 1. Given distortions $\left\{\chi_i^L\right\}_{i=1}^S$ and $\left\{\chi_{ij}\right\}_{i,j=1}^S$, a *Distorted Equilibrium* is the collection of prices $\{P_i\}_{i=1}^S$, wage rate W, sectoral allocations $\left\{Q_i, L_i, \left\{M_{ij}\right\}_{j=1}^S\right\}_{i=1}^S$, production inputs for the final good $\{Y_i\}_{i=1}^S$, and aggregate output Y such that

1. Prices and sectoral allocations solve the cost-minimization problem of the fictitious price-

taking sectoral producers:

$$P_i = \mathscr{C}_i\left(W, \{P_j\}\right) \equiv \min_{\ell_i, \{m_{ij}\}_{j=1}^S} \left(\sum_{j \in S} \left(1+\chi_{ij}\right) P_j m_{ij} + \left(\chi_i^L\right) W \ell_i \right) \tag{3}$$

$$\text{s.t. } z_i F_i\left(\ell_i, \{m_{ij}\}_{j=1}^S\right) \geq 1,$$

and

$$L_i = Q_i \cdot \ell_i^*,$$

$$M_{ij} = Q_i \cdot m_{ij}^*,$$

where $\left\{\ell_i^*, \left\{m_{ij}^*\right\}\right\}$ is the solution to the cost minimization problem;

2. Production inputs for the final good satisfy:

$$\frac{\partial F\left(Y_1, \cdots, Y_S\right)}{\partial Y_i} = P_i; \tag{4}$$

3. Factor and intermediate goods markets clear:

$$Q_j = Y_j + \sum_{i=1}^S M_{ij}, \tag{5}$$

$$L = \sum_{i=1}^S L_i; \tag{6}$$

4. The representative consumer spend labor income on the final good:

$$C = WL = Y - \sum_{i=1}^S \left(\sum_{j \in S} \left(1+\chi_{ij}\right) P_j M_{ij} + \left(1+\chi_i^L\right) W L_i \right). \tag{7}$$

Discussion The definition of Distorted Equilibrium requires only that allocations are as-if chosen by a price-taking firm, and the definition is deliberately agnostic about both the actual market structure and the source of price distortions. My theoretical results in sections 3, 4, and 5 apply to any microfoundation that induces equilibrium prices and allocations that coincide with this generic definition of Distorted Equilibrium. The next subsection provides microfoundations of the Distorted Equilibrium under various market imperfections and market structures.

Equation (7) specifies that payments associated with the market imperfections are not rebated to the representative consumer, whose consumption C is equal to the value of total factor payments WL. Instead, the distortion payments correspond to deadweight losses in the economy, such as excess entry or real costs incurred with pecuniary transactions across sectors, and are therefore subtracted from the aggregate output. The specification also nests the interpretation that these distortion payments are made to agents other than the representative consumer. My theoretical analyses in sections 3 and 4 study the impact of various policy instruments on C, the aggregate consumption of the representative consumer; hence, my results apply to both interpretations.

2.2 Microfoundations

To make discussions concrete, in this subsection I provide four different microfoundations for the Distorted Equilibrium. Distortion payments are modeled as deadweight losses in all four cases. Readers who are more interested in directly seeing the main theoretical results can skip ahead to section 3.

The first two microfoundations are based on financial frictions with deadweight losses generated by, respectively, the excess entry of constrained firms and the monitoring cost for the repayment of working capital. Market imperfections in the third microfoundation are based on monopolistic markups, and the fourth builds on Marshallian externalities. Although market imperfections in these four microfoundations come from varying sources and productions are based on different market structures, all four microfoundations induce equilibrium prices and allocations that coincide with those in Definition 1.

Financial Frictions - Working Capital Constraints The first microfoundation is based on financial frictions. I assume each producer faces an exogenous working capital constraint on the purchase of certain intermediate inputs $D_i \subset S$, and the distortion $\chi_{ij} \equiv \chi_i$ for all $j \in D_i$ in this case corresponds to either the shadow value on working capital or the Lagrange multiplier on the constraint in sector i.

Specifically, intermediate production is modeled as a two-stage entry game. In the first stage, a large measure of identical and atomistic potential entrants choose whether to set up a firm in any sector, paying a fixed cost κ_i (in units of the final good) if they decide to enter in sector i. In the second stage, firms in sector i produce the identical and perfectly substitutable good i according to a constant-returns-to-scale production function

$$q_i = z_i F_i\left(\ell_i, m_{i1}, \cdots, m_{iS}\right) \tag{8}$$

while taking prices as given and facing a working capital constraint

$$\sum_{j \in D_i} P_j m_{ij} \leq \Gamma_i, \tag{9}$$

where Γ_i denotes the exogenous amount of working capital available to each firm in sector i. (Note that I use lower-case letters to denote firm-level variables while, as before, the corresponding upper-case letters denote sectoral and aggregate variables.)

I now argue that the decentralized equilibrium in this environment has sectoral prices and allocations that coincide with those in Definition 1. Each firm takes prices as given and maximizes variable profit:

$$\max_{\ell_i, \{m_{ij}\}} P_i z_i F_i \left(\ell_i, \{m_{ij}\}\right) - W \ell_i - \sum_{j \in S} P_j m_{ij} \quad \text{subject to (9)}.$$

Let χ_i be the constraint's Lagrange multiplier, which captures firms' willingness to pay for additional working capital. The term $(1+\chi_i)$ captures the ratio between marginal product and marginal cost of the constrained inputs. To pin down χ_i, an endogenous object, I note that the variable profit accrued to each firm is $\pi_i = \chi_i \Gamma_i$. These positive profits in turn lead to excessive entry and deadweight losses in equilibrium, with $\pi_i = \kappa_i$ as ensured by the free-entry condition. The Lagrange multiplier χ_i is therefore equal to κ_i / Γ_i. The unconstrained inputs are not subject to distortions according to this microfoundation.

The total sectoral output and inputs are equal to

$$Q_i = N_i q_i, \;\; L_i = N_i \ell_i, \;\; M_{ij} = N_i m_{ij}. \tag{10}$$

Since $F_i(\cdot)$ features constant-returns-to-scale, we can write

$$Q_i \;\; = \;\; N_i z_i F_i \left(\ell_i, \{m_{ij}\}\right) = z_i F_i \left(L_i, \{M_{ij}\}\right). \tag{11}$$

Sectoral allocations and prices therefore coincide with those in Definition 1, with $\chi_{ij} = \kappa_i / \Gamma_i$ for all $j \in D_i$ and $\chi_{ij} = 0$ otherwise. The amount of final good used for consumption is equal to the aggregate output net of entry cost $\kappa_i N_i = \chi_i \sum_{j \in D_i} P_j M_{ij}$, satisfying condition 7.

Under this microfoundation, inputs in D_i require working capital to purchase, and these inputs can be thought of as capital goods (e.g. machinery, equipments, and computers) or services that can be subject to hold-up problems (such as outsourced R&D services), for which trade credit is difficult to obtain and costs must be incurred upfront. The unconstrained inputs can be thought of as material or commodity inputs—such as intermediate materials for the production of consumer goods (e.g. textiles) and commoditized services—for which trade credit is more available (Fisman 2001) such that the input cost can be paid after production.

Financial Frictions - Monitoring Costs The second and perhaps simplest microfoundation for the Distorted Equilibrium assumes there is a representative firm in each intermediate sector with production technology specified in (2), and each firm i must borrow working capital in order to finance the purchases of certain intermediate inputs $j \in D_i \subset S$. There is a representative financial institution (lender) that extends working capital to intermediate producers and incurs a proportional (linear) expense χ in terms of the final good while doing so. The expense χ can be thought of as monitoring costs that must be incurred to ensure working capital is repaid after production. The lender behaves competitively and makes zero profit, charging a flat net interest rate that is equal to the expense χ for each unit of working capital.

In this setting, producer i's profit maximization problem is

$$\max_{L_i, \{M_{ij}\}} P_i z_i F_i \left(L_i, \{M_{ij}\}\right) - W L_i - \sum_{j \in S} P_j M_{ij} - \chi \Gamma_i \quad \text{s.t.} \sum_{j \in D_i} P_j M_{ij} \leq \Gamma_i.$$

Market clearing conditions imply that total factor payments are equal to the total output net of monitoring costs:

$$WL = F\left(Y_1, \cdots, Y_S\right) - \sum_{i=1}^{S} \chi \left(\sum_{j \in D_i} P_j M_{ij} \right).$$

This microfoundation induces equilibrium sectoral allocations and prices that coincide with those in definition 1, with $\chi_{ij} = \chi$ for all $i \in S$, $j \in D_i$.

Monopoly Distortions The third microfoundation of the Distorted Equilibrium is based on monopoly markups. Consider the two-stage entry game as in the first microfoundation, but with two modifications. First, firms no longer face any working capital constraints. Second, firms within each sector i produce differentiated goods that combine into intermediate good i through a constant-returns-to-scale Dixit-Stiglitz aggregator with constant elasticity of substitution $\sigma_i > 1$, and firms behave monopolistically to maximize profits, taking their residual demand curves as given.

Specifically, a large measure of potential entrants in each sector can choose to pay a fixed cost κ_i units of the final good in order to enter. Upon entry, each firm v produces a differentiated good according to production function in (8), and these varieties can be combined into intermediate good

i by

$$Q_i = N_i^{\frac{1}{1-\sigma_i}} \left(\int_0^{N_i} q_i(\nu)^{\frac{\sigma_i - 1}{\sigma_i}} d\nu \right)^{\frac{\sigma_i}{\sigma_i - 1}}.$$

The first multiplicative term $N_i^{\frac{1}{1-\sigma_i}}$ in the aggregator is introduced to neutralize the taste-for-variety effect so that sectoral production features constant-returns-to-scale. In equilibrium, all firms within each sector make identical quantity choices $\{\ell_i, \{m_{ij}\}\}$, and the sectoral production technology aggregates to (2). Monopolistic pricing induces each producer to charge a constant and multiplicative markup $\frac{\sigma_i}{\sigma_i - 1}$ over marginal costs. The variable profit is $\frac{1}{\sigma_i}$ fraction of the sales revenue, and by the free-entry condition, is equal to the fixed cost of entry:

$$\kappa_i N_i = \frac{1}{\sigma_i} P_i Q_i = \frac{1}{\sigma_i - 1} \left(W L_i + \sum_{j \in S} P_j M_{ij} \right).$$

This microfoundation induces sectoral allocations and prices as in Definition 1 with $\chi_{ij} = \frac{1}{\sigma_i - 1}$ for all $j \in S$.

Marshallian Externality The last microfoundation adopts Marshallian externality, the idea that individual firms' intensive production could impose positive spillovers and raise other firms' productivity in the sector. I capture this spillover effect by writing the productivity of firms in each sector as a function of the average firm-level output in that sector. Specifically, consider again a large measure of potential entrants that can pay a fixed cost κ_i to enter each sector. Upon entry, firms in sector i produce the identical and perfectly substitutable good i according to the production function

$$q_i = z_i \left(\frac{Q_i}{N_i} \right)^{1-\alpha_i} F_i \left(\ell_i, \{m_{ij}\} \right)^{\alpha_i},$$

where $F_i(\cdot)$ is homogeneous of degree one and $\alpha_i \in (0,1)$. The multiplicative term $\left(Q_i / N_i \right)^{1-\alpha_i}$ captures the component of Hicks-neutral productivity that each firm takes as exogenous but is nevertheless dependent on the average output quantity of firms in the sector. The exponential coefficients α_i and $(1-\alpha_i)$ control the relative strength of Marshallian externality in the sector, and they are parametrized to sum to one in order to ensure aggregate sectoral constant-returns-to-scale while keeping each firm's profit maximization objective function concave. The market structure is such that each firm takes prices as given and chooses input quantities $\{\ell_i, \{m_{ij}\}\}$ in order to maximize profit:

$$\pi_i = \max_{\ell_i, \{m_{ij}\}} P_i z_i \left(\frac{Q_i}{N_i} \right)^{1-\alpha_i} F_i \left(\ell_i, \{m_{ij}\} \right)^{\alpha_i} - W \ell_i - \sum P_j m_{ij}.$$

As in the case for exogenous working capital and monopoly distortion, the free-entry condition pins down variable profit at $\kappa_i = \pi_i$. Sectoral allocations and prices in this economy coincide with those in Definition 1, with $\chi_{ij} \equiv \alpha_i / (1 - \alpha_i)$ for all $j \in S$.

3 Distorted Equilibrium

In this section I characterize the distorted equilibrium. Because the economy features aggregate constant returns to scale, the marginal cost of production in any given sector depends only on the prices of inputs and is not affected by sectoral output levels. The unit cost $\mathscr{C}_i$ of producing good i, as a function of the input price vector $\left(\tilde{W}, \left\{\tilde{P}_j\right\}\right)$, is the solution to the distorted cost-minimization problem in (3). Similarly, the unit cost $\mathscr{C}^F$ of producing the final good is

$$\mathscr{C}^F \left(\left\{\tilde{P}_j\right\}\right) \equiv \min_{\{y_j\}} \sum_j p_j y_j \text{ s.t. } F\left(\left\{y_j\right\}_{j=1}^S\right) \geq 1.$$

Equilibrium price vector $\left(W, \left\{P_j\right\}\right)$ is the fixed point that solves the set of equations

$$\begin{aligned} \mathscr{C}_i\left(W, \left\{P_j\right\}\right) &= P_i \text{ for all } i \quad (12) \\ \mathscr{C}^F\left(\left\{P_j\right\}\right) &= 1, \quad (13) \end{aligned}$$

where (13) reflects the normalization that the final good's price is unity.

My model is nested in the class of generalized Leontief models, and standard arguments for the existence and uniqueness of the equilibrium price vector in this class of models also apply to my setting (e.g., see Stiglitz 1970 and Arrow and Hahn 1971). Specifically, under Assumption 1, that sectoral output always strictly increases in labor, the Jacobian matrix of the mapping that represents the system of unit cost equations has the dominant diagonal property, which ensures the global uniqueness of solution by the univalence theorem of Gale and Nikaido (1960).

The price vector $\left(W, \left\{P_j\right\}\right)$ completely pins down equilibrium allocations. To see this, note that the wage rate pins down aggregate consumption, since $C = WL$. The sectoral distorted first-order conditions uniquely pin down sectoral expenditure shares on inputs for all producers:

$$\omega_{ij} \equiv \frac{P_j M_{ij}}{P_i Q_i}, \quad \omega_i^L \equiv \frac{WL_i}{P_i Q_i}, \quad \beta_j \equiv \frac{P_j Y_j}{Y}, \quad (14)$$

where ω_{ij} and ω_i^L respectively denote sector i's expenditure share on input j and on labor, and β_j denotes the final producer's expenditure share on good j. I define $\gamma_i \equiv \frac{P_i Q_i}{WL}$ to be the total sales of sector i relative to aggregate consumption, and I refer to the stacked $S \times 1$ vector $\gamma \equiv \left[\frac{P_i Q_i}{WL}\right]$ as the sales vector. The next lemma shows that the sales vector can be expressed as a function of expenditure shares and, as a result, one can solve for sectoral output as $Q_i = \gamma_i \frac{WL}{P_i}$ and solve for all production input allocations in the distorted equilibrium through expenditure shares in (14).

Lemma 1. *(Sales) The sales vector γ is*

$$\gamma' = \frac{\beta' (I - \Omega)^{-1}}{\beta' (I - \Omega)^{-1} \omega^L}, \tag{15}$$

where $\Omega \equiv \left[\omega_{ij}\right]$ is the matrix of expenditure shares with rows denoting input-using industries, columns denoting input-producing industries, and $\omega^L \equiv \left[\omega_i^L\right]$ is the vector of sectoral expenditure shares on labor.

The object $(I - \Omega)^{-1} = I + \Omega + \Omega^2 + \cdots$ is the Leontief inverse of the input-output expenditure share matrix Ω. This object summarizes the flow of goods across sectors through the infinite hierarchy of production linkages. The common denominator in the sales vector reflects the fact that only a fraction of the final good accrues to consumption $C = WL$ while the remaining fraction is incurred as the deadweight losses due to market imperfections.

I next introduce the notion of sectoral influence, which is a centrality measure that captures the elasticity of aggregate consumption with respect to sectoral TFP shocks. Let σ_{ij} denote the equilibrium elasticity of the production function in sector i with respect to input j:

$$\sigma_{ij} \equiv \frac{\partial \ln F_i \left(L_i, \left\{ M_{ij} \right\}_{j \in S} \right)}{\partial \ln M_{ij}}.$$

As a direct application of the Envelope theorem, σ_{ij} also captures the elasticity of the unit cost of production $\mathscr{C}_i$ in sector i with respect to the price of input j, as summarized by the following Lemma.

Lemma 2. $\sigma_{ij} = \frac{\partial \ln \mathscr{C}_i \left(W, \{P_k\}_{k=1}^S \right)}{\partial \ln P_j}$.

Definition 2. **(Influence)** The influence of sector i is defined as the i-th element of the vector

$$\mu' \equiv \beta' (I - \Sigma)^{-1}$$

where $\Sigma \equiv \left[\sigma_{ij}\right]$ is the matrix of the production elasticities, with rows representing the input-using industries and columns representing the input-supplying industries.

Proposition 1. *1. The elasticity vector of prices with respect to productivity in sector i is*

$$\frac{d\ln \mathbf{P}}{d\ln z_i} = (I-\Sigma)^{-1}\left(\frac{d\ln W}{d\ln z_i}\cdot\sigma^L - \mathbf{e}_i\right),$$

where $\mathbf{P} \equiv (P_1,\cdots,P_S)$, $\sigma^L \equiv \left(\sigma_1^L,\cdots,\sigma_S^L\right)$, *and* $\mathbf{e}_i$ *is the unit vector with its i-th element being one and all other elements zero.*

2. Influence captures the elasticity of wage rate W and aggregate consumption C with respect to sectoral productivity shock:

$$\mu_i = \frac{d\ln W}{d\ln z_i} = \frac{d\ln C}{d\ln z_i}.$$

The proposition can be understood as follows. A one-percent increase in productivity z_j directly lowers the price of good j by one percent, which, according to Lemma 2, lowers the prices of all goods i's that use good j as a production input by σ_{ij} percent, the ij-th entry of the input-output elasticity matrix Σ. The productivity shock also propagates downstream, resulting in higher-round effects that are captured by higher powers of the elasticity matrix. Holding wage rate constant, the total effect of the shock on prices is captured by $-(I-\Sigma)^{-1}\mathbf{e}_i$. Since the final good's price is normalized to unity, the wage rate must rise and feeds back into sectoral prices. The proportional changes in W as well as in C are captured by the influence of sector i, $\mu_i = \beta'(I-\Sigma)^{-1}\mathbf{e}_i$ because β' is the elasticity of $C^F(\cdot)$ with respect to the sectoral price.

Relationship to Hulten (1978) The celebrated result of Hulten (1978) states that, in the absence of market imperfections, sectoral sales capture the elasticity of aggregate output with respect to sectoral TFP shocks ($\gamma_i = d\ln Y/d\ln z_i$). Hulten's theorem can be seen as a corollary to Proposition 1: without distortions and deadweight losses, sectoral influence is equal to sales and aggregate output is equal to aggregate consumption. Proposition 1 shows that in a distorted equilibrium, Hulten's theorem breaks down for two reasons: 1) sectoral influence and sectoral sales are no longer equal ($\mu \neq \gamma$), and 2) deadweight losses drive apart aggregate output and aggregate consumption ($Y \neq C$).[5]

Effect of Market Imperfections Market imperfections generate within-sector distortions and affect sectoral prices and aggregate consumption similarly to input-augmenting productivity shocks.

[5] A special case of the distorted equilibrium (c.f. Definition 1) often seen in the literature (e.g. Jones 2013 and Bartelme and Gorodnichenko 2016) is when production functions are Cobb-Douglas so that the local elasticities and expenditure shares become globally constant. Under this assumption, Y is always proportional to C even in the presence of market imperfections and, as a result, $\mu_i = \frac{d\ln Y}{d\ln z_i}$ in a distorted equilibrium.

Holding input prices constant, a marginal increase in distortion raises the cost of producing good i. The effect travels downstream by raising the cost of goods that directly or indirectly use good i for production and ultimately lowers the wage rate and aggregate consumption, as summarized by the next lemma.

Lemma 3. *1. The elasticity vector of sectoral prices with respect to distortions in sector i is*

$$\frac{d\ln \mathbf{P}}{d\ln\left(1+\chi_{ij}\right)} = (I-\Sigma)^{-1}\left(\frac{d\ln W}{d\ln\left(1+\chi_{ij}\right)}\cdot\sigma^{L}+\sigma_{ij}\cdot\mathbf{e}_{i}\right);$$

2. The elasticity of wage rate and aggregate consumption with respect to distortions in sector i is

$$\frac{d\ln W}{d\ln\left(1+\chi_{ij}\right)} = \frac{d\ln C}{d\ln\left(1+\chi_{ij}\right)} = -\mu_{i}\cdot\sigma_{ij}.$$

Production elasticities and expenditure shares are both local properties of the distorted equilibrium and are functions of equilibrium prices; therefore distortions indirectly affect production elasticities and expenditure shares through prices. Furthermore, distortions also directly affect sectoral demand for intermediate inputs. In the absence of distortions, $\sigma_{ij}=\omega_{ij}$ for all sectors and all inputs, and influence is consequently equal to sales for all sectors.[6] Market imperfections in a sector drive apart intermediate expenditure shares and elasticities, with $\sigma_{ij}=\omega_{ij}\left(1+\chi_{ij}\right)$. Contrary to the downstream travel of productivity effect, this demand effect instead travels upstream through backward demand linkages: distortions in sector i reduce the use of inputs in the sector, thereby lowering the sales of input suppliers. The sectors that produce these inputs in turn purchase fewer inputs from their own upstream suppliers, which also end up with lower sales. These demand effects aggregate over production linkages and cumulatively generate a wedge between sectoral influence and sales. This wedge is the central object of this paper. In the next section 4, I formally define the wedge as a sector's *distortion centrality*, and I show that it guides marginal sectoral interventions by capturing how an intermediate good's social value relates to its private value.

Acemoglu et al. (2012), Baqaee (2015), and Acemoglu and Akcigit (2016) observe that in a production network with Cobb-Douglas technologies, productivity shocks travel downstream through input-output linkages from suppliers to buyers, while demand shocks travel upstream. My analysis shows that their results do not rely on functional form assumptions: under constant-returns-to-scale production, demand shocks affect equilibrium quantities by traveling upstream and have no effect on prices, while productivity shocks affect prices by traveling downstream

[6] The common denominator $\beta'(I-\Omega)^{-1}\omega^{L}$ in equation (15) is equal to one absent distortion.

as shown by Proposition 1. Furthermore, my analysis shows that market imperfections serve as shocks to both productivity and the intermediate demand that emanates from the distorted sectors. The productivity effect propagates downstream by raising prices and ultimately reducing aggregate consumption, while the demand effect propagates upstream and distorts sectoral sales away from influence.

4 Distortion Centrality and Sectoral Policies

In this section I introduce the distortion centrality measure, which is defined as the ratio between sectoral influence and sales. I show that distortion centrality captures how sectoral output's social value relates to its private value and that this measure guides marginal sectoral interventions. Unless explicitly noted, all discussions and formal claims are based on the generic model introduced in section 1 without appealing to a specific microfoundation of the distortion.

4.1 Distortion Centrality

Distortions within Sectors Holding all prices constant, the ratio between the elasticity and expenditure share on input j, σ_{ij}/ω_{ij}, captures the ratio between the marginal revenue of input j (accrued to producer i) and its price P_j in a decentralized equilibrium. To see this, start from the distorted equilibrium and suppose producer i purchases additional $dM_{ij} \equiv d\tau \cdot M_{ij}$ units of input j for production at a cost of $d\tau \cdot P_j M_{ij}$. The additional inputs lead to a sectoral output expansion of $dQ_i = d\tau \cdot \sigma_{ij} Q_i$ units, which translates into additional revenue of $dR_i = P_i dQ_i$ if the all prices are held fixed. Collecting terms, this calculation shows that the ratio between marginal revenue and marginal cost is

$$\frac{dR_i}{d\tau \cdot P_j M_{ij}} = \frac{d\tau \cdot \sigma_{ij} P_i Q_i}{d\tau \cdot P_j M_{ij}} = \frac{P_i}{P_j}\frac{\partial Q_i}{\partial M_{ij}} = \frac{\sigma_{ij}}{\omega_{ij}}.$$

I label this ratio as the private marginal return to expenditures.

Definition 3. (**Private Marginal Return**) The *private marginal return to* expenditures on input j in sector i, PR_{ij}, is defined as the ratio between input j's marginal revenue product and its undistorted price P_j:

$$PR_{ij} \equiv P_i \frac{\partial Q_i}{\partial M_{ij}} \Big/ P_j.$$

In the absence of any market imperfections, the private marginal return to expenditures is equal to one for all inputs used in all sectors. Market imperfections manifest themselves at the sector level by decoupling elasticities from expenditure shares and by driving the sectoral private marginal return to expenditures above unity to $\left(1+\chi_{ij}\right)$.

Linkages and Distortion Centrality The earlier definition of private marginal return is a partial equilibrium notion that captures the benefits accrued to the sectoral producer from one dollar of additional expenditure on inputs while *holding all prices constant*. In the presence of cross-sector input-output linkages, marginal expenditure in any sector could potentially affect prices and allocations in every other sector of the economy under general equilibrium. As more inputs are used for production in sector i, the output of good i rises, and its price must fall in order to clear the market. The changes in P_i alter the cost of production for all sectors that directly and indirectly use good i as an input; in turn, these shifts in cost of production induce further changes in allocations. These general equilibrium effects ultimately affect aggregate consumption and the welfare of the representative consumer.

To analyze partial equilibrium private marginal returns, one simply starts from the distorted equilibrium allocations in a sector and considers a marginal change in input quantities while holding all prices constant. On the other hand, to analyze the general equilibrium effect of marginal expenditures, one must consider price changes as well as the reallocation of goods, and this earlier approach is no longer viable. To make progress, I model marginal expenditures through small subsidies given to firms for purchasing inputs. Specifically, consider a small subsidy τ_{ik} such that the fictitious producer i faces unit price $\frac{P_k}{1+\tau_{ik}}$ on input k, where the subsidy is given as a transfer to firms in terms of the final good. The subsidy perturbs the unit cost of production in sector i to

$$\mathscr{C}_i\left(W,\left\{P_j\right\}\right) \equiv \min_{\ell_i,\left\{m_{ij}\right\}_{j=1}^S}\left(\sum_{j\in S}\frac{\left(1+\chi_{ij}\right)P_j m_{ij}}{1+\tau_{ik}\cdot\mathbf{1}\left(j=k\right)}+\left(1+\chi_i^L\right)W\ell_i\right) \tag{16}$$

$$\text{s.t. } z_i F_i\left(\ell_i,\left\{m_{ij}\right\}_{j=1}^S\right)\geq 1.$$

The distorted first-order condition in sector i on input k becomes

$$P_i z_i\frac{\partial F_i\left(L_i,\left\{M_{ij}\right\}_{j\in S}\right)}{\partial M_{ik}}=\frac{P_k\left(1+\chi_{ik}\right)}{1+\tau_{ik}}. \tag{17}$$

On the one hand, the perturbation of the cost function $\mathscr{C}_i(\cdot)$, through general equilibrium changes in prices and allocations, affects aggregate consumption C. On the other hand, implementing the subsidy requires resources, which amounts to $P_k M_{ik}\cdot\frac{\tau_{ik}}{1+\tau_{ik}}$ units of the final good in equilibrium. Assume for now that such resources come from outside the economy and that all market clearing conditions remain the same as in Definition 1, so that the only change to the distorted equilibrium is the cost-minimization problem as in (16). It will soon become clear why this exercise is meaningful for studying policy experiments.

Definition 4. (Social Marginal Return) The *social marginal return* to expenditures on input k in sector i, SR_{ik}, is defined as the ratio between the marginal change in aggregate consumption and the marginal resources required to finance the small subsidy to input k in sector i:

$$SR_{ik} \equiv \frac{dC/d\tau_{ik}}{d\left(P_k M_{ik} \cdot \frac{\tau_{ik}}{1+\tau_{ik}}\right)/d\tau_{ik}}\bigg|_{\tau_{ik}=0}.$$

The social marginal return SR_{ik} provides the answer to the following question: starting from the distorted equilibrium, if the economy receives a marginal dollar's worth of additional resource and spends it on input k in sector i, then how much can aggregate consumption increase? The main theoretical result of this paper succinctly characterizes this object.

Definition 5. (**Distortion Centrality**) The distortion centrality ξ_i of sector i is the ratio between its influence and sales:

$$\xi_i \equiv \frac{\mu_i}{\gamma_i}.$$

Theorem 1. *The (general equilibrium) social marginal return to expenditures on input k in sector i is equal to the (partial equilibrium) private marginal return times the distortion centrality of sector i:*

$$SR_{ik} = PR_{ik} \times \xi_i.$$

The private return PR_{ik} summarizes the value of one-dollar spending on input k that is captured by producer i while the social return SR_{ik} summarizes the value of marginal spending to the final consumer. Theorem 1 states that distortion centrality, which is obtained by dividing influence by the sales of a sector, captures the ratio between social and private marginal return to expenditures in the sector. The object ξ_i is a centrality measure because it depends on the distribution of market imperfections in the economy as well as the network structure that links across sectors, which I characterize in section 5.

Since influence is equal to sales absent market imperfections, one can interpret the influence vector as representing the potential or undistorted size of intermediate sectors under *optimal production* at equilibrium prices, while the sales vector captures the actual and distorted size of sectors under *distorted equilibrium production*. The distortion centrality ξ_i captures the ratio between the potential and actual size of sector i, and Theorem 1 shows that this ratio reveals how social marginal returns of inputs in sector i relate to the private marginal returns.

There is another way to interpret this result. Pecuniary externalities in the production economy—a drop in P_i benefits users of good i and hurts its producer, with the two effects cancelling one another in the absence of market imperfections—do not net out in a distorted general equilibrium. As P_i drops, deadweight loss decreases in the downstream sectors in which producers have to purchase good i with distortions. While producer i values its own output at the equilibrium price P_i, the social value of sectoral production differs from P_i due to these pecuniary externalities. Theorem 1 shows that distortion centrality summarizes the net pecuniary externalities from sector i's production and is a sufficient statistic for calculating how the social value of good i relates to its private value P_i. The social value of marginal expenditure on any input k in sector i is therefore the private value PR_{ik} times the distortion centrality ξ_i of the production sector.

4.2 Marginal Interventions

I now discuss how distortion centrality can be informative for marginal sectoral interventions. I first state my result in terms of direct subsidies to production inputs. To then illustrate how my result can be used to understand other policy instruments that shift the use of production inputs, I examine two applications: 1) government grant of working capital and 2) subsidies to sectoral sales.

In Definition 4 of social marginal return, I assume the resources required to implement the marginal subsidy τ_{ik} come from outside the economy. In fact, the interpretation can be minimally modified so that the resources come from within the production network and the economy remains closed. To this end, I introduce a government with real expenditure E financed by lump-sum tax T into the distorted equilibrium. The expenditure E can be interpreted as public consumption. I accordingly update the definition for a distorted equilibrium to reflect the fact that 1) some aggregate output is expensed by the government, and 2) consumers consume post-tax labor income.

Definition 6. Given distortions $\left\{\chi_i^L\right\}_{i=1}^S$ and $\left\{\chi_{ij}\right\}_{i,j=1}^S$, a *Distorted Equilibrium with Public Expenditure* is the collection of lump-sum tax T, government expenditure E, prices $\left\{\{P_i\}_{i=1}^S, W\right\}$, and allocations $\left\{\left\{Q_i, L_i, \{M_{ij}\}_{j=1}^S, Y_i\right\}_{i=1}^S, Y\right\}$ such that prices and sectoral allocations solve the distorted cost-minimization problem as in (3); production inputs for the final good satisfy condition (4); factor and intermediate goods markets clear as in (5) and (6); the government finances expenditure via lump-sum tax $(E = T)$; the representative consumer consumes post-tax labor income

$(C = WL - T)$; and lastly, the market for the final good clears:

$$C + E = Y - \sum_{i=1}^{S} \left(\sum_{j \in S} \left(1 + \chi_{ij}\right) P_j M_{ij} + \left(1 + \chi_i^L\right) W L_i \right).$$

The discussions in this subsection use the equilibrium in Definition 6. I first consider marginal sectoral intervention in the form of a proportional subsidy τ_{ik} given to sector i when purchasing input k. The subsidy changes the distorted first-order condition as in equation (17), and I specify that the government finances the subsidies by holding the lump-sum tax T constant while cutting back public consumption E:

$$E\left(\tau_{ik}\right) = T - \frac{\tau_{ik}}{1 + \tau_{ik}} P_k M_{ik}.$$

Definition 7. (Social Marginal Return in Distorted Equilibrium with Public Expenditure) The *social marginal return* to expenditures on input k in sector i in a distorted equilibrium with public expenditure E is defined as the ratio between the marginal change in private consumption C and the marginal decrease in public expenditure E required to finance the small subsidy to input k in sector i, holding the lump-sum tax T constant:

$$SR_{ik} \equiv - \left. \frac{dC/d\tau_{ik}}{dE/d\tau_{ik}} \right|_{\tau_{ik}=0, T \text{ constant}}.$$

I abuse notation and use SR_{ik} to denote social marginal return in both definitions 4 and 7 because as the next result shows, SR_{ik} under these two definitions are equivalent.

Theorem 2. *The social marginal return of expenditure in sector i on input k in a distorted equilibrium with public expenditure is equal to the private marginal return times the distortion centrality of sector i:*

$$SR_{ik} = PR_{ik} \times \xi_i.$$

Theorem 2 shows that the social marginal return to input expenditures is informative for marginal policy interventions because it can be interpreted as a *revenue-neutral fiscal multiplier*; it tells the government how much private consumption can be improved by cutting back one dollar of public consumption and spending the saved resources on sectoral input subsidies while holding the fiscal revenue (lump-sum tax) constant. While standard intuitions might suggest that, to improve productive efficiency, subsidies should be directed towards the sectors that are most distorted, i.e. those with the highest private returns, my result suggests that this economic reasoning is flawed in the presence of market imperfections and sectoral linkages. In a distorted equilibrium, the social and private return to working capital are not necessarily equal, with the ratio between the two precisely captured by the distortion centrality measure.

Knowing the social returns to a set of fiscally accessible subsidy instruments, a benevolent government should implement marginal policy reforms by adopting subsidies with the higher social returns. The rankings of social returns $\{SR_{ik}\}_{i,k}$ directly translates into the social preference ordering over the subsidies $\{\tau_{ik}\}_{i,k}$ regardless of how the government marginally trades off between private and public consumption. To see this, let $U(C,E)$ be the social welfare function over private and public consumption and assume $U(\cdot)$ is increasing and differentiable in both arguments. The marginal change in social welfare U following a marginal intervention τ_{ik}, financed by cutting back E by one dollar, is

$$\frac{dU/d\tau_{ik}}{dE/d\tau_{ik}} = \frac{\partial U}{\partial E} + \frac{\partial U}{\partial C} \times SR_{ik}.$$

It is apparent $\frac{dU/d\tau_{ik}}{dE/d\tau_{ik}} \geq \frac{dU/d\tau_{jm}}{dE/d\tau_{jm}}$ if and only if $SR_{ik} \geq SR_{jm}$ for all i,k,j,m. Furthermore, if the planner has access to flexible lump-sum taxes, it must be the case that $\frac{\partial U}{\partial E} = \frac{\partial U}{\partial C}$ and, therefore, any marginal interventions with social return exceeding unity would result in higher social welfare, and vice versa.

The result embodied in Theorem 2 can seem surprising and counterintuitive. Contrary to the conventional wisdom in the misallocation literature that dispersions in marginal product of inputs necessarily lower welfare, I show in subsequent analyses that cross-sector dispersions in marginal product induced by policy interventions can enhance welfare. Furthermore, I show in section 5 that, perhaps paradoxically, sectors with the most distortions in a production network could have the lowest distortion centrality and that the rank orderings of sectoral private and social marginal revenue products are reversed. As a result, subsidizing the most privately distorted sector could result in the least welfare gain and could in fact lead to welfare loss.

The result in Theorem 2 also extends beyond input-specific subsidies and is indeed applicable to other policy instruments that directly or indirectly affect the equilibrium use of production inputs. In the next subsection, I next consider two alternative policy instruments as applications of Theorem 2. Given the pervasiveness of credit subsidies and targeted sectoral loans in industrial policy episodes, the first application microfounds market imperfections with working capital constraints (i.e. the first microfoundation in section 2.2) and considers a policy that marginally transfers working capital to firms. Because of the prominence of revenue distortions in the misallocations literature, I study sales subsidies in the second application. The policy interventions in these applications are isomorphic to sectoral subsidies that apply to a group of inputs within each sector, with $\tau_{ik} = \tau_i$ for all $k \in \Theta_i \subseteq S$. The subsidy τ_i modifies the distorted first-order condition in sector i to (17) for all inputs $k \in \Theta_i$. The following result on τ_i is a direct corollary of Theorem 2.

Corollary 1. *The social marginal return of subsidy τ_i on inputs $k \in \Theta_i$ in a distorted equilibrium with public expenditure is equal to the private marginal return times the distortion centrality of sector i:*

$$SR_i = PR_i \times \xi_i,$$

where

$$SR_i \equiv -\frac{dC/d\tau_i}{dE/d\tau_i}\Big|_{\tau_i=0,T\ constant}, \quad PR_i \equiv \left(\sum_{k\in\Theta_i}\frac{\partial \ln Q_i}{\partial \ln M_{ik}}\right) \Big/ \frac{\sum_{k\in\Theta_i} P_k M_{ik}}{P_i Q_i} = \frac{\sum_{k\in\Theta_i}\sigma_{ik}}{\sum_{k\in\Theta_i}\omega_{ik}}.$$

That is, the private return captures the partial-equilibrium benefit that accrues to producer i for one-dollar spending on inputs $k \in \Theta_i$, with the marginal expenditure allocated to each input k being proportion to $P_k M_{ik}$.

4.3 Application: Transfer of Working Capital

Consider an economy distorted by financial frictions, as in the first microfoundation of section 2.2, and a policy instrument that transfers working capital to firms. Specifically, consider lump-sum transfers η_i to each producer in sector i after they enter but before production takes place, so that each producer's working capital constraint becomes

$$\sum_{j\in D_i} P_j m_{ij} \le \Gamma_i + \eta_i. \tag{18}$$

The variable profit earned by each firm in production is,

$$\pi_i = \max_{\ell_i,\{m_{ij}\}} P_i z_i F_i\left(\ell_i,\{m_{ij}\}\right) - W\ell_i - \sum_{j\in S} P_j m_{ij} + \eta_i, \quad \text{subject to (18)}.$$

The government finances the transfers by cutting back on public consumption (recall that N_i is the measure of firms that enter to produce in sector i in equilibrium):

$$E(\eta_i) = T - \eta_i N_i.$$

Let χ_i be the Lagrange multiplier on constraint (18) when $\eta_i = 0$. As discussed in section 2.2,

$\chi_i = \kappa_i / \Gamma_i$ where κ_i is the fixed cost of entry in sector i. Holding all prices constant, the partial equilibrium private value of working capital, which is defined as the increase in variable profit captured by a producer in sector i for a marginal transfer η_i, is

$$PR_i^K \equiv \left.\frac{\partial \pi_i}{\partial \eta_i}\right|_{\eta_i=0} = 1 + \chi_i.$$

I define the social value of working capital as

$$SR_i^K \equiv \left.\frac{dC/d\eta_i}{dE/d\eta_i}\right|_{\eta_i=0, T \text{ constant}}.$$

Proposition 2. *The (general equilibrium) social value of working capital is*

$$SR_i^K = PR_i^K \times \xi_i.$$

The transfer of working capital η_i effectively induces firms to marginally expand their use of production inputs that are subject to the working capital constraint (18). The private and social value of working capital can therefore be seen as the value captured by the sectoral producer and by the final consumer, respectively, for one dollar of expenditure on constrained inputs. For this reason, Proposition 2 can be seen as a corollary of Theorem 2. The result shows that in a production network with financial frictions, a benevolent planner should not blindly direct working capital toward the most constrained sectors (as measured by PR); rather, the productive efficiency gain is highest if the marginal dollar of working capital goes to sectors with the highest social returns.

Connection to the misallocation literature

Proposition 2 reveals a flaw in applying conclusions from the misallocation literature, popularized by Hsieh and Klenow (2009) and Restuccia and Rogerson (2008), to economies with cross-sector input-output linkages. Specifically, this literature spells out and quantitatively evaluates the aggregate TFP losses due to firms failing to equalize marginal products of production inputs. Critics of industrial policies often refer to this literature when arguing that sector-based policies inevitably generate "misallocation across sectors"; therefore, such critics conclude, these policies are detrimental to aggregate productive efficiency and welfare.[7]

[7] See footnote 2 for citations.

My analysis challenges this logic. While within-sector dispersions in private marginal revenue products unambiguously lower efficiency, as the misallocation literature suggests, policy instruments that generate cross-sector dispersions in private marginal revenue products could enhance welfare in a distorted equilibrium. To see this, consider an economy in which the private returns to working capital are equalized across all firms in all sectors, but firms are still constrained ($\chi_i = \chi > 0$ for all i). According to the conventional view, which ignores cross-sector production linkages, this economy might not warrant any interventions: the fact that marginal returns to working capital are equalized can be seen as a sign of a well-functioning private credit market. Furthermore, firms' ongoing constraints could reflect real costs in the credit market, for example the monitoring cost associated with delivering working capital (the second microfoundation in section 2.2) or that the economy only has a fixed amount of funds available as working capital. However, Proposition 2 illustrates that in this economy, the social value of working capital would not be the same across sectors. Instead, the social value is ranked precisely by the distortion centrality measure, and a benevolent government should marginally disturb the privately optimal allocations of working capital, under which private value is equated across sectors, and re-direct working capital to sectors with the highest distortion centrality. In fact, to equate social marginal value of working capital in a generic economy with production linkages and market imperfections, the private value has to be different across sectors.

4.4 Application: Sales Subsidy

Many real world economies adopt sector-specific sales taxes, and these taxes also feature prominently in the misallocation literature as a potential source of distortions (e.g. see Hsieh and Klenow 2009 and Jones 2013). As the second application of Theorem 2, I study marginal subsidies to sales revenue. Specifically, consider a subsidy by which firms in sector i receive a transfer of τ_i from the government for every dollar of revenue the firms generate. Under the subsidy, firms value each unit of sectoral output at $(1+\tau_i) P_i$, and the distorted first-order conditions with respect to inputs become

$$(1+\tau_i) P_i z_i \frac{\partial F_i\left(L_i, \{M_{ij}\}_{j\in S}\right)}{\partial M_{ij}} = P_j \left(1+\chi_{ij}\right) \text{ for all } j \in S,$$

$$(1+\tau_i) P_i z_i \frac{\partial F_i\left(L_i, \{M_{ij}\}_{j\in S}\right)}{\partial L_i} = W \left(1+\chi_i^L\right).$$

The government again finances the subsidy by cutting back on public consumption:

$$E(\tau_i) = T - \tau_i P_i Q_i.$$

All other conditions in the distorted equilibrium c.f. Definition 6 remain unchanged.

Starting from the equilibrium allocation, one dollar of government expenditure on sales subsidy accrues exactly one dollar of profit to the producer, hence the private return to expenditures on sales subsidies is exactly one in all sectors. Similar to my previous analysis in this section, I define the social return to sales subsidies as the change in aggregate consumption in response to one dollar of expenditure on the subsidies:

$$SR_i^{Sales} \equiv \left.\frac{dC/d\tau_i}{dE/d\tau_i}\right|_{\tau_i=0,T\text{ constant}}.$$

Proposition 3. *The social marginal return to expenditures on sales subsidy τ_i is*

$$SR_i^{Sales} = \xi_i.$$

Holding input prices constant, a marginal sales subsidy τ_i effectively lowers sectoral output price while inducing firms to produce with the same input expenditure shares as in the decentralized equilibrium. In this sense, SR_i^{Sales} captures the social value of equilibrium production in sector i relative to its price P_i, the private value captured by sectoral producers. According to Proposition 3, SR_i^{Sales} is exactly equal to the distortion centrality in sector i.

4.5 Optimal Value-Added Subsidies Under Cobb-Douglas Technologies

My next result pertains to optimal (as opposed to marginal) linear subsidies to sectoral value-added. Under Cobb-Douglas production technologies, both the input-output elasticity and expenditure matrices are stable under value-added subsidies. In this case, the product between private return to labor inputs and sectoral distortion centrality captures not only the social marginal return to labor, but also the constrained-optimal value-added subsidies if the planner can freely choose any level of τ_i^L.

Theorem 3. *Suppose all production functions are iso-elastic, with*

$$F_i\left(L_i, \{M_{ij}\}\right) = L_i^{\alpha_i^L} \prod_{i=1}^{S} M_{ij}^{\sigma_{ij}}$$

$$F\left(\{Y_i\}\right) = \prod_{i=1}^{S} Y_i^{\beta_i}.$$

The optimal value-added subsidies, i.e. the solution to the planning problem

$$\vec{\tau}^L \equiv \arg\max_{\{\tilde{\tau}_i^L\}} W\left(\left\{\tilde{\tau}_i^L\right\}\right)$$

satisfies

$$1+\tau_i^L \propto \xi_i \times \left(1+\chi_i^L\right). \tag{19}$$

The result as stated is on the proportionality of $\left(1+\tau_i^L\right)$ because the levels are not pinned down: having access to unrestricted value-added taxes is a substitute for either lump-sum taxation on consumers or a uniform tax on wages, as the planner can always scale $\left(1+\tau_i^L\right)$ by a constant and adjust the lump-sum tax accordingly to balance the budget.

5 Distortion Centrality and Network Structure

My discussion thus far has illustrated that distortion centrality is informative for marginal policy interventions in a distorted equilibrium. But how do market imperfections aggregate over a production network? In this section, I show that imperfections accumulate to upstream sectors through backward demand linkages. As a result, sectors with the highest distortion centrality tend to be those that are upstream and supply to many distorted sectors, which in turn supply to many other distorted sectors, and so on. To build intuition for this result, I begin with a stylized example before characterizing distortion centrality in general production networks.

Example: Vertical Production Networks Consider the following stylized example. There are $S=3$ intermediate production sectors that form a vertically connected network: good 1 is produced upstream and linearly from labor, good 2 is produced midstream by combining good 1 and labor, and good 3 is produced downstream by combining good 2 and labor. The final good is produced linearly from the downstream good 3. The flow of input and output in the network is represented in Figure I. Producers in sector i face distortion χ_i on all input purchases.

The influence and sales vector of this economy follow

$$\Big(\mu_1,\ \mu_2,\ ,\mu_3\Big) \propto \Big(\sigma_3\sigma_2,\ \ \sigma_3,\ \ 1\Big),$$

$$\Big(\gamma_1,\ \gamma_2,\ ,\gamma_3\Big) \propto \left(\frac{\sigma_3}{(1+\chi_3)}\cdot\frac{\sigma_2}{(1+\chi_2)},\ \ \frac{\sigma_3}{1+\chi_3},\ \ 1\right).$$

Correspondingly, the vector of distortion centrality is

$$\left(\xi_1,\ \xi_2,\ \xi_3\right) \propto \left(\ (1+\chi_3)\,(1+\chi_2)\,,\ \ (1+\chi_3)\,,\ \ 1\right).$$

Distortions in downstream sector 3 decouple the expenditure share from the production elasticities of the intermediate input, good 2, thereby lowering total demand for good 2 in the economy. The drop in demand leads to lower sales of good 2 relative to the influence of this sector. Sales of upstream sector 1 can be written as

$$P_1 Q_1 = P_1 M_{21} = \omega_{21} \cdot P_2 Q_2.$$

It is apparent that the sales of upstream good 1 are in turn distorted even further relative to the sectoral influence, via two channels. Firstly, a drop in the sector 2 sales, due to distortions in sector 3, translates into lower demand for sector 2's production inputs: labor and good 1. Secondly, distortions in sector 2 further decouple the sectoral expenditure share on good 1 from the production elasticities.

This example shows that market imperfections within each sector accumulate across the network into distortion centrality through backward demand linkages. I emphasize two intuitions. First, a sector has depressed sales and consequently higher distortion centrality not because of distortions within the sector but because of distortions faced by that sector's customers who use this good as a production input. In the example, it is the market imperfections in downstream that raise midstream's distortion centrality, and it is the market imperfections in midstream as well as in downstream that raise the distortion centrality of the upstream sector. Second, a sector's distortions and distortion centrality accumulate onto its upstream suppliers through backward linkages. The further upstream a sector is and the more layers of production linkages the sectoral good must travel before reaching the final consumer, the higher that sector's distortion centrality.

Perhaps surprisingly, the distortion centrality is always highest in upstream sector 1 and lowest in downstream sector 3 ($\xi_1 \geq \xi_2 \geq \xi_3$), regardless of the underlying distortions in each sector. Furthermore, the social returns of sectoral expenditure on the value-added input follow

$$\left(SR_1^L,\ SR_2^L,\ SR_3^L\right) \propto \left(\ (1+\chi_1)\,(1+\chi_2)\,(1+\chi_3)\,,\ \ (1+\chi_2)\,(1+\chi_3)\,,\ \ (1+\chi_3)\ \right).$$

That is, the rank order of social marginal return to expenditures on labor can even be the complete reversal of the rank order of private marginal returns, which follow

$$\left(PR_1^L,\ PR_2^L,\ PR_3^L\right) \propto \Bigg((1+\chi_1),\ (1+\chi_2),\ (1+\chi_3)\Bigg).$$

According to my earlier results, subsidies in this economy should be directed towards sector 1 over the other two sectors regardless of distortion size in those sectors, and subsidies given to sector 2 are still preferable to subsidies given to sector 3, no matter how distorted firms are in sector 3. This seemingly perverse result is again due to the upstream accumulation of distortions: distortions in sector 3 get passed onto the distortion centrality of sector 2, which is further passed on to form the distortion centrality of sector 1, so that the marginal social product of inputs is always highest in sector 1.

5.1 Distortion Centrality in General Production Networks

I now formalize intuitions from the previous example and characterize the distortion centrality measure for general production network structures. Let

$$\hat{\omega}_{ij} \equiv \frac{M_{ij}}{Q_j} = \omega_{ij}\frac{P_iQ_i}{P_jQ_j}.$$

Recall ω_{ij} captures the expenditure share of sector i on good j and can be interpreted as the equilibrium importance of j as a *supplier* for i. On the other hand, $\hat{\omega}_{ij}$ captures the share of good j used sector i as a fraction of total output of sector j. In other words, $\hat{\omega}_{ij}$ captures the equilibrium importance of sector i for the total demand of good j. For this reason, I refer to $\hat{\Omega} \equiv \left[\hat{\omega}_{ij}\right]$ as the $S\times S$ input-output *demand* matrix. Let $\hat{\omega}_j^F \equiv \frac{Y_j}{Q_j}$ capture the importance of the final good producer as a buyer of good j, and I refer to $\hat{\omega}^F \equiv \left[\hat{\omega}_j^F\right]$ as the $S\times 1$ *final demand* vector. Note that the market clearing condition for good j implies that $\hat{\omega}_j^F = 1-\sum_{i\in S}\hat{\omega}_{ij}$.

Theorem 4. *The distortion centrality ξ_j of sector j can be written as*

$$\xi_j = \hat{\omega}_j^F\cdot\delta + \sum_{i\in S}\xi_i\cdot\left(1+\chi_{ij}\right)\cdot\hat{\omega}_{ij} \tag{20}$$

for scalar $\delta = \frac{WL}{Y}$. In matrix form,

$$\xi' \propto \left(\hat{\omega}^F\right)'\left(I-\mathbf{D}\circ\hat{\Omega}\right)^{-1}$$

where $\mathbf{D}$ is an $S\times S$ matrix that encodes distortions with $\mathbf{D}_{ij}\equiv 1+\chi_{ij}$, and $\circ$ denotes the Hadamard *product.*

Note that the order of subscripts in (20) is "ij", where i indexes for the buyers of good j. To interpret this result, consider sector j that *supplies to* sector i's with distortion centrality ξ_i's. Distortions within each sector i depress demand for good j, and the distortion $\left(1+\chi_{ij}\right)$ is then magnified by the distortion centrality (ξ_i) of the input-using sector, weighted by the importance of sector i's demand for good j $(\hat{\omega}_{ij})$ and passed onto the supplier sector j to ultimately contribute to j's distortion centrality ξ_j. This is the sense in which market imperfections accumulate through *backward demand linkages.* Distortions in sector j and centrality ξ_j are then passed onto j's input-supplying sectors, further traveling upstream through backward linkages. The equilibrium vector of distortion centrality is the fixed point in equation (20). The constant $\delta < 1$ ensures that the distortion centrality cannot be above one in all intermediate sectors, and $(1-\delta)$ captures the aggregate share of deadweight losses in the economy.

5.2 Distortion Centrality in Monotone Hierarchical Networks

Theorem 4 shows that in order to uncover sectoral distortion centrality in general production networks, one must know both the equilibrium input-output demand matrix $\hat{\Omega}$ and the distortion matrix $\mathbf{D}$. Yet, Theorem 4 and the earlier example also suggest that the network structure $\hat{\Omega}$ alone can be highly informative regarding the distortion centrality measure and that if the equilibrium input-output structure is vertical (with $\hat{\omega}_{i,i-1} = 1$ and $\hat{\omega}_{i,j} = 0$ otherwise), distortion centrality is always higher in a relatively upstream sector regardless of the underlying market imperfections and production technologies that induce the vertical structure in equilibrium. I now show that this intuition can be generalized and that the rank ordering of distortion centrality across sectors is insensitive to distortions $\mathbf{D}$ for a class of equilibrium network structures $\hat{\Omega}$.

Definition 8. (Monotone Hierarchy) An $S \times S$ non-negative square matrix B exhibits *monotone hierarchy* (MH) property if the following conditions hold:

1. Column sums do not exceed one:

$$\sum_{k=1}^{S} B_{ki} \leq 1 \text{ for all } i,$$

2. B_{mi} is log-supermodular in (m,i):

$$B_{mi}B_{nj} \geq B_{mj}B_{ni} \text{ for all } m < n, i < j, \tag{21}$$

3. For all m and $i < j$,

$$B_{mi}\left(1-\sum_{k=1}^{S}B_{kj}\right) \geq B_{mj}\left(1-\sum_{k=1}^{S}B_{ki}\right)$$

A production network is said to be MH if there exists an indexation of sectors such that the equilibrium input-output demand matrix $\hat{\Omega}$ has the MH property. In MH networks, sector i is said to be *upstream* of sector j whenever $i \leq j$.

To understand the MH property, consider the $(S+1)\times S$ matrix $\tilde{B}$, which is defined by extending B with an additional $(S+1)$-th row such that all column sums are equal to one:

$$\tilde{B}_{mj} \equiv \begin{cases} B_{mj} & \text{for all } m, j \leq S, \\ 1-\sum_{k=1}^{S} B_{kj} & \text{for } m = S+1. \end{cases}$$

The MH property is equivalent to log-supermodularity of the extended matrix $\tilde{B}$. In a production network, this extended row is precisely the final demand vector $\hat{\omega}^F$, and MH essentially requires that relatively upstream sectors demand more strongly from other upstream sectors, with the final producer interpreted as the most downstream. Upstreamness generates a total order over sectors in an MH network and can be translated into the rank ordering of distortion centrality under certain conditions.

Proposition 4. *Consider a production network with equilibrium input-output demand matrix $\hat{\Omega}$.*

Case 1. If there exist scalars a and b such that $a \cdot \mathbf{D} \circ \hat{\Omega}$ and $b \cdot \left(\mathbf{D} \circ \hat{\Omega} - \hat{\Omega}\right)$ satisfy the MH property, then

$$\xi_i \geq \xi_j \;\text{ for all } i < j.$$

Case 2. Suppose $\hat{\Omega}$ exhibits the MH property and is lower-triangular. Suppose that for $i \neq j$, (a) conditional on the diagonal entries $\{\chi_{kk}\}_{k=1}^{S}$, χ_{ij}'s are i.i.d. with distribution function $\mathscr{F}$ and finite support over $[0, \bar{\chi}]$, and (b) $\chi_{ij} \geq \chi_{ii}$ almost surely, then

$$\mathbb{E}\left[\xi_i\right] \geq \mathbb{E}\left[\xi_j\right] \;\text{ for all } i < j.$$

Case 1 of the proposition shows that upstream sectors always have higher distortion centralities under the condition that $\mathbf{D} \circ \hat{\Omega}$ and $\left(\mathbf{D} \circ \hat{\Omega} - \hat{\Omega}\right)$ both satisfy MH. To understand this, suppose $\hat{\Omega}$ is itself MH. The condition is trivially satisfied when distortions are constant in the economy, $\chi_{ij} = \chi$ for all i, j, with $a \equiv \frac{1}{1+\chi}$ and $b \equiv \frac{1}{\chi}$. When $\chi_{ij}'s$ are not constant, the condition thus requires that the variation in χ_{ij}'s around the mean has to be such that the MH property of $\hat{\Omega}$ is still preserved under the Hadamard product with χ_{ij}'s as well as with $(1+\chi_{ij})$'s.

Case 2 of the proposition takes the *equilibrium* demand relationship $\hat{\Omega}$ as fixed and imposes joint stochasticity on the underlying production technology and market imperfections that generate $\hat{\Omega}$. It shows that when $\hat{\Omega}$ is MH and lower-triangular, relatively upstream sectors always have higher distortion centralities in expectation if within-sector transactions are always less distorted than cross-sector ones and that the latter are i.i.d. conditional on the former.

As an illustration, Figure II shows a hypothetical MH network with a lower-triangular input-output demand matrix. The rows represent *input-using* industries and columns represent *input-supplying* industries. Each entry in the matrix is drawn in proportion to the strength of the input-output relationship $\hat{\omega}_{ij}$. The log-supermodularity condition, that upstream industries demand upstream inputs more intensively, is manifested in the figure by sparse entries in the bottom-left and dense entries just below the diagonal.

6 The Role of Linkages in Industrial Policy Episodes

Industrial policies are ubiquitously adopted in developing economies, and interventionist governments often publish documents that explicitly state "network linkages" as a criterion for choosing sectors to support.[8] My analyses thus far show that subsidizing sectors with high distortion centralities can indeed improve productive efficiency, but how does one identify which sectors have high distortion centrality?

In a general production network, distortion centrality depends on the size of market imperfections in *every* sector of the economy. Credibly identifying distortions in the entire economy, with any degree of precision and certainty, is a virtually impossible task for both policymakers and econometricians: microeconometric studies can only recover distortions in specific industries, and macro methods have to rely on extremely strong assumptions. Pack and Saggi (2006) suggest that effective industrial policy is impossible precisely because of the informational requirements; Rodrik (2008) writes that "in the absence of omniscience—that is, almost always—an activist government will miss its targets... and waste the economy's resources."

Yet, my analysis from section 5.2 shows that network structures play a crucial role in shaping the distortion centrality measure, and the rank ordering of distortion centrality across sectors could be insensitive to the distribution of underlying market imperfections precisely because market im-

[8] See Li and Yu (1982), Kuo (1983), and Yang (1993) for Taiwan; Kim (1997) for Korea; and State Development Planning Commission of China (1995) for China.

perfections accumulate through backward demand linkages. Leveraging this insight, I empirically examine the input-output demand structures of South Korea during the 1970s and modern-day China, which are two of the most salient economies with interventionist governments that actively implement industrial policies. I show that both economies' input-output demand matrices approximately satisfy the MH property, under which the upstreamness of sectors can be unambiguously defined. Consequently, I simulate distortion centrality using various specifications for market imperfections and show that, for each economy, the sectoral distortion centrality is almost perfectly correlated and has an extremely stable rank ordering across all specifications. This finding confirms that the cross-sector variation in distortion centrality indeed originates from the near-MH network structure and that it is unnecessary to precisely estimate sectoral market imperfections in order to conduct welfare-improving interventions. Lastly, I show that distortion centrality predicts the sectors targeted by government interventions in both of these economies, suggesting that certain aspects of their industrial strategy appear to be motivated by a desire to subsidize sectors that could create positive network effects.

6.1 MH Property and Stability of Distortion Centrality

I start with the equilibrium input-output demand matrices ($\hat{\Omega} \equiv \left[\hat{\omega}_{ij}\right]$) of South Korea in 1970 and China in 2007. These matrices are derived from national input-output tables and are respectively disaggregated at 152 and 135 three-digit industries; $\hat{\omega}_{ij}$ is computed as the share of overall supply of good j demanded by sector i in the economy.[9] To illustrate the MH property of these real-world input-output demand matrices, I first need to order industries not by the respective national industry classification codes but instead re-arrange them according to some notion of upstreamness. To this end, I define ξ_i^{Ref} as the benchmark sectoral distortion centrality under the assumption that distortions are uniform across all sectors with $\chi_{ij} = 10\%$ for all i, j,[10] and I re-index industries in decreasing order of ξ_i^{Ref} for both economies.

Figures III and IV show the input-output demand matrices of South Korea and China, respectively. Rows represent *input-using* industries and columns represent *input-supplying* industries, thus the ij-th entry in each figure corresponds to $\hat{\omega}_{ij}$, the importance of sector i for the demand of good j. For ease of visualization, each entry is drawn proportionally in size to $\hat{\omega}_{ij}$ and is truncated below at 5%, so that only important intermediate demand relationships are represented in these figures.

[9] I thank Nathaniel Lane for graciously sharing the input-output table of South Korea in 1970.

[10] The level of constant distortion is chosen arbitrarily at 10%, but as I later show in Table II, this choice does not affect the rank ordering of sectoral distortion centrality precisely because of the MH property.

The input-output demand matrices of both economies bear a striking resemblance to the hypothetical lower-triangular MH network depicted in Figure II. Once arranged by the benchmark distortion centrality ξ_i^{Ref}, industries in both economies appear to have a hierarchical order and highly asymmetric input-output relationships. The downstream industries purchase heavily from the upstream ones, but the reverse is not true, manifested in both matrices with dense entries below the diagonal and sparse above: the lower-triangular entries average to 0.81% and 0.83% for South Korea and China, respectively, and are an order of magnitude larger than those above the diagonal, which average to 0.13% and 0.33%, respectively. Most importantly, both input-output matrices in Figures III and IV exhibit the MH property: upstream producers in both economies seem to rely more heavily on upstream inputs than downstream producers do, as evidenced by the sparse bottom-left entries and the dense entries just below the diagonal.

To formally assess the MH property of these economies, I exhaustively test the inequalities in the definition of MH (Definition 8) over all possible combinations of industries. Among the over 100 million unique inequalities for each of these economies, 86% hold true for South Korea while 72% hold true for China, as shown in Table I. Furthermore, almost all inequality violations involve minuscule entries of the demand matrices $\hat{\Omega}$, which represent unimportant demand relationships and do not contribute very much to distortion centrality (c.f. Theorem 4). Once small entries $\hat{\omega}_{ij} \leq 0.001$ are truncated to zero, 97% and 92% of the MH inequalities hold true for, respectively, South Korea and China. This is strong evidence that the production networks of both economies are approximately MH—only 50% of the inequalities would have held true if demand linkages were randomly and independently generated.

The MH network structures of these economies imply that the rank ordering of sectoral distortion centrality is insensitive to the distribution of market imperfections, as my results from section 5.2 suggest. To verify this, I simulate market imperfections from a range of distributions, and I examine the stability of distortion centrality in both economies. Specifically, I randomly generate market imperfections from truncated normal, uniform, or exponential distributions, using various parameters for each distribution.[11] In every specification, I perform 10,000 simulations, each time drawing χ_{ij}'s independently, and I compute distortion centrality using Theorem 4. I also examine the stability of distortion centrality with respect to different levels of economy-wide constant distortions.

For both South Korea and China, the sectoral distortion centrality is close to being perfectly correlated across all simulations in all specifications, and their rank ordering is extremely stable. As shown in Table II, the average Pearson and Spearman-rank correlation between the benchmark

[11] Only thin-tailed distributions are used for the simulations because constant-returns-to-scale implies $\sum_j \hat{\omega}_{ij}(1+\chi_{ij}) = 1$; hence, distortions cannot be arbitrarily large conditioning on equilibrium $\hat{\omega}_{ij}$'s.

and simulated distortion centrality is close to one in all specifications; this is despite the fact that underlying distortions are uncorrelated across simulations. Note also that these simulations do not follow the specific assumptions in Proposition 4, in that $\mathbf{D} \circ \hat{\Omega}$ is not necessarily MH in any simulation draw, and the off-diagonal distortions (χ_{ij}'s) do not almost surely exceed the diagonal ones (χ_{ii}'s). This is intentional: whereas Proposition 4 provides the conditions under which distortion centrality is perfectly rank-correlated for different distributions of market imperfections, my simulations show that the correlation is still nearly perfect even when the assumptions are violated. The rank-stability of distortion centrality is precisely due to the near-MH network structure and the backward accumulation of market imperfections. These average correlations would have all been zero if demand linkages were randomly and independently generated.[12]

The rank-stability of sectoral distortion centrality suggests that it is unnecessary to precisely estimate sectoral imperfections in order to conduct welfare-improving policy interventions. In the absence of an exact intervention that directly removes market imperfections—due to either policy infeasibility or informational constraints—policies that marginally subsidize the upstream sectors, to which all distortions eventually propagate, could potentially improve welfare. I now show that the benchmark distortion centrality indeed predicts the sectors targeted by government interventions in both of these economies.

South Korea Between 1973 and 1979, South Korea implemented a government-led, large-scale industrialization program, officially named the "Heavy-Chemical Industry" (HCI) drive. The program targeted six broad sectors, including those producing metal products, machineries, electronics, petrochemicals, automobiles, and shipbuilding. Firms that operated in the promoted industries received substantially favorable policy incentives (Woo 1991; Kim 1997; Lane 2017), and some of the largest modern South Korean manufacturing conglomerates originated in this era. The list of three-digit industries targeted by the HCI drive is provided in Appendix Table B.2.

The HCI industries were all upstream, as can be visualized in Figure III: cells for which the *input-using* industry was promoted by the HCI drive are drawn with solid black circles, while the other cells are drawn in gray. The promoted heavy and chemical industries supply strongly to the non-targeted downstream industries, such as those producing textiles and consumer goods, and demand few inputs in return.

The upstreamness of the targeted heavy-chemical industries directly translates into their high distortion centrality in all specifications, as shown in Table III (with additional specifications in

[12] In an earlier version of this paper, I compute distortion centrality for Chinese industries using distortions estimated from firm-level production data, based on tools developed in the industrial organization literature. The distortion centrality from that exercise is also almost perfectly correlated with the benchmark distortion centrality.

Appendix Table B.1). All targeted industries have benchmark distortion centralities above unity, and the average is 1.21, thereby indicating that the social net return of spending in the promoted industries is over three times that of the private net return ($\frac{\xi_i \times PR_i - 1}{PR_i - 1} > 3$). In contrast, close to 45% of the non-targeted manufacturing industries have benchmark distortion centralities below one. The social net returns in these industries are below the private net returns and could even be negative, which suggests that resources would have been wasted if the state had promoted these industries. The results are nearly identical when the analysis is performed on the simulated distortion centralities, as shown in the table.

Intuitively, because the HCI industries are upstream, having higher distortion centrality in the non-targeted downstream industries than the targeted upstream ones would require a perverse distribution of market imperfections—that firms are highly constrained when purchasing textiles and shoes as production inputs but not too constrained in purchasing machineries and equipments. As Table IV shows, this could happen only when distortions on the purchase of non-targeted goods are implausibly higher (over 500% larger) than those on heavy-chemicals.

China State intervention in China has a long tradition and remains alive and well today. Two salient ways through which the government influences sectoral production in China are credit markets and state-owned enterprises (SOEs). Credit markets in China remain predominantly state-controlled, with the government holding direct ownership of the largest commercial banks. Both interest rates and loan sizes are heavily regulated, and banks often receive policy directives on lending priorities across industries (Aghion et al. 2015). Historically, East Asian governments have frequently utilized SOEs to directly expand sectoral production (Hernandez 2004). In China, it is well-documented that SOEs receive not only direct subsidies from the government, but also easy access to credit from Chinese banks.[13] Indeed, Song et al. (2011) explicitly model Chinese SOEs as financially-unconstrained market participants. Access to credit markets and the presence of SOEs are therefore plausible notions of government support.[14] I derive measures from the 2007 edition of China's firm-level Annual Industrial Survey to capture these notions of state intervention. For access to credit markets, I construct industry-level measures of debt-to-capital ratio and effective interest rates faced by privately-owned firms based on their reported liabilities and interest payments. For SOE presence, I compute their value-added shares in each industry.[15]

Which Chinese industries have high distortion centrality? Table V shows that, as in South Ko-

[13] See Boyreau-Debray and Wei (2005), Dollar and Wei (2007), and Riedel et al. (2007).

[14] I provide direct evidence in Appendix Table B.4 that SOEs receive more government subsidies and have significantly better access to external finance.

[15] I identify firms as SOEs using the procedure outlined in Hsieh and Song (2015).

rea, the Chinese industries with high benchmark distortion centrality tend to be upstream suppliers of intermediate inputs, particularly the heavy, chemical, and machinery-producing industries. On the other hand, the light industries that supply more heavily to consumers—those that produce textiles, household appliances, and processed food products—tend to have low distortion centrality. The table also reveals that linkages greatly magnify the effect of distortions: marginal spending in the metal industries has social net return ($= \xi_i^{Ref} \times 1.1 - 1$) that is over five times the 10% private net return; this stands in stark contrast to the light industries' negative social net return.

Table VI shows that the benchmark distortion centrality ξ_i^{Ref} predicts all three measures of government interventions. I standardize ξ_i^{Ref} to facilitate interpretation. The odd columns represent regressions of the respective outcome variables on the benchmark distortion centrality and a constant; the even columns control for industry characteristics, including the average capital intensity and profit shares of firms in the industry, as well as the industry's share of exporters. The specifications in columns (2) and (4) show that private firms in industries with high distortion centralities have significantly better access to credit: those with distortion centralities one standard deviation above the mean have on average 1.92 percentage points higher debt-to-capital ratios and pay 0.63 percentage points lower interest rates. These effects are economically significant and translate into 40% and 50% of standard deviation in the respective outcome variables. Column (6) shows that industries with distortion centralities one standard deviation above the mean have 5.7 percentage points higher share of value-added by state-owned enterprises.

One might be concerned that the network structure is endogenously affected by government interventions and that the demand matrix computed from the national input-output table does not represent cross-sector linkages in a *decentralized equilibrium.* However, this type of measurement error in $\hat{\Omega}$ is actually biased *against* finding a positive correlation between ξ_i^{Ref} and measures of interventions. This is because subsidies expand sectoral production and, consequently, increase the amount of intermediate inputs that flow into these sectors. As a result, subsidies cause sectors to appear more *downstream* than they would be in a decentralized equilibrium, pushing down the measured distortion centrality of these sectors and creating a negative bias in the estimated correlations between ξ_i^{Ref} and proxy measures of intervention.

Interpretation My results in this section show that the input-output demand matrices of historical South Korea and modern-day China are both approximately MH; as a result, the rank ordering of distortion centrality is insensitive to underlying market imperfections. Furthermore, I find that distortion centrality predicts the sectors promoted by government interventions in these economies. This result corresponds well with the claims in their own policy documents that "network linkages" is an important criterion for choosing sectors to support.

To be clear, my findings by no means suggest that polices adopted by these economies were optimal: my theory abstracts away from practical aspects of policy implementation, and there is also substantial qualitative evidence that various political economy factors affected policy choices in these economies (Krueger 1990; Robinson 2010). Nevertheless, my results indicate that there are aspects of Korean and Chinese industrial strategy that appear to be motivated by a desire to subsidize upstream sectors, and my theory shows that these interventions could create positive network effects and improve aggregate productive efficiency.

7 Conclusion

Although industrial policies have been widely adopted by developing countries, economists' formal understanding of these policies remains limited. In this paper, I revisit Hirschman's thesis on the importance of cross-sector linkages for economic development, and I formally characterize industrial policies in production networks. I find that sectoral market imperfections accumulate through backward demand linkages and generate aggregate sales distortions that are largest in the most upstream sectors. This aggregate sectoral distortion, which I term distortion centrality, is a sufficient statistic for the ratio between social and private marginal product of sectoral inputs; as a result, there is an incentive for a well-meaning government to subsidize the upstream sectors. My theoretical analysis therefore provides a counterpoint to the prevailing view that sector-based selective interventions must be a sign of inefficiency.

Furthermore, I find that the ranking of sectoral distortion centrality is insensitive to market imperfections if the production network exhibits monotone hierarchy property, and that the input-output structures of South Korea in the 1970s and modern-day China do approximately satisfy this property. I show that distortion centrality predicts the sectors targeted by government interventions in both of these economies, suggesting that certain aspects of their industrial strategy might have created positive network effects.

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Table I: Exhaustively testing the MH inequalities in Definition (8) shows that the input-output demand matrices of both South Korea and China are approximately MH

Truncation	Fraction of inequalities that hold true		Sum of truncated entries over sum of all entries in $\hat{\Omega}$	
threshold	South Korea	China	South Korea	China
no truncation	86%	72%	0	0
0.0001	91%	79%	0.001	0.001
0.0005	96%	86%	0.007	0.008
0.001	97%	92%	0.016	0.020

This table shows that the input-output demand matrices for South Korea and China are approximately MH. The first two columns report, for each country, the fraction of inequalities in Definition (8) that hold true, over all unique combinations of industries. The first row shows the results performed directly on the input-output demand matrices. The remaining rows conduct the same exercise but replace $\hat{\omega}_{ij} < w$ to zero, where w is the truncation threshold and takes the value of 0.0001, 0.0005, and 0.001, respectively for rows 2-4. These small entries represent weak input-output demand relationships and are unimportant in determining sectoral distortion centrality, c.f. Theorem 4. As the last two columns show, the sum of truncated entries is minuscule relative to the sum of all entries in the input-output demand matrices for both countries.

Table II: Simulated distortion centralities are highly correlated

	Average correlation between the benchmark ξ_i^{Ref} and simulated distortion centrality			
	South Korea in 1970		China in 2007	
Distribution of χ_{ij}'s	Pearson	Spearman	Pearson	Spearman
Constant distortion				
$\chi_{ij} = 0.05$	1.00	1.00	1.00	1.00
$\chi_{ij} = 0.15$	1.00	1.00	1.00	1.00
$\chi_{ij} = 0.2$	1.00	1.00	1.00	1.00
Truncated Normal				
$\left(max\left\{0, \text{Norm}\left(\mu, \sigma^2\right)\right\}\right)$				
$\mu = 0.05,\ \sigma^2 = 0.05$	0.95	0.96	0.98	0.98
$\mu = 0.05,\ \sigma^2 = 0.1$	0.91	0.93	0.96	0.97
$\mu = 0.05,\ \sigma^2 = 0.2$	0.88	0.92	0.94	0.96
$\mu = 0.1,\ \sigma^2 = 0.05$	0.98	0.98	0.99	0.99
$\mu = 0.1,\ \sigma^2 = 0.1$	0.95	0.96	0.98	0.98
$\mu = 0.1,\ \sigma^2 = 0.2$	0.90	0.94	0.95	0.97
$\mu = 0.15,\ \sigma^2 = 0.05$	0.99	0.99	1.00	1.00
$\mu = 0.15,\ \sigma^2 = 0.1$	0.96	0.98	0.98	0.99
$\mu = 0.15,\ \sigma^2 = 0.2$	0.92	0.95	0.96	0.97
Uniform				
$U[0, 0.1]$	0.97	0.98	0.99	0.99
$U[0, 0.2]$	0.97	0.98	0.99	0.99
$U[0, 0.3]$	0.97	0.98	0.99	0.99
$U[0, 0.4]$	0.97	0.98	0.99	0.99
Exponential				
Scale = 0.05	0.92	0.95	0.96	0.97
Scale = 0.1	0.92	0.95	0.96	0.97
Scale = 0.15	0.90	0.94	0.94	0.95
Scale = 0.2	0.87	0.93	0.89	0.93

Note: This table reports the average Pearson and Spearman-rank correlation between ξ_i^{Ref} and simulated distortion centralities. ξ_i^{Ref} is the benchmark sectoral distortion centrality constructed by assuming $\chi_{ij} = 0.1$ for all i, j. The first three rows report correlations between ξ_i^{Ref} and distortion centralities computed under alternative constant distortions $\chi_{ij} = \chi$ for $\chi \in \{0.05, 0.15, 0.2\}$. The rest of the table reports specifications in which χ_{ij}'s are randomly and independently drawn from truncated normal, uniform, and exponential distributions with various parameters. Each specification is simulated 10,000 times, and the correlation between ξ_i^{Ref} and simulated distortion centrality, averaged over 10,000 draws, is reported.

Table III: Targeted HCI industries have higher distortion centrality than non-targeted industries in South Korea in 1970

	Average $\mathbb{E}[\xi_i]$		Share of industries with $\mathbb{E}[\xi_i] > 1$	
Distribution of χ_{ij}	HCI	non-HCI	HCI	non-HCI
$\chi_{ij} = 0.1$	1.21	1.03	100%	56.7%
Truncated Normal	1.21	1.03	100%	55.0%
Uniform	1.21	1.03	100%	55.0%
Exponential	1.21	1.03	100%	56.7%

This table shows that the targeted HCI industries have higher distortion centralities on average than the non-targeted industries, and a higher fraction of targeted industries have distortion centralities above unity. The first row is based on ξ_i^{Ref}, the benchmark distortion centrality under the assumption that $\chi_{ij} = 0.1$ in all sectors and for all inputs. The remaining rows report results using simulated distortion centrality, respectively computed by drawing χ_{ij}'s i.i.d. from truncated normal ($\max\{0, Norm(0.09, 0.1)\}$), uniform ($U[0, 0.2]$), and exponential (with scale 0.1) distributions. For each specification, $\mathbb{E}[\xi_i]$ is computed as the average distortion centrality of industry i over 10,000 simulations. The parameters used for simulating χ_{ij}'s are chosen such that $\mathbb{E}\left[\chi_{ij}\right] = 0.1$ under all three distributions; this makes the simulated distortion centrality comparable *in levels* to ξ_i^{Ref}. Additional specifications in Appendix Table B.1 show that results are quantitatively and qualitatively robust to alternative parametrizations: 1) all HCI industries have $\mathbb{E}[\xi_i] > 1$; 2) expected social net return to spending in the HCI sector is over three times of the private net return ($\frac{\mathbb{E}[\xi_i]\times\mathbb{E}\left[PR_{ij}\right]-1}{\mathbb{E}\left[PR_{ij}\right]-1}$); 3) around 45% of non-targeted industries have expected distortion centrality below one.

Table IV: Distortions on the purchase of non-targeted goods have to be enormous in order for targeted and non-targeted industries to have the same average distortion centralities

χ	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.1
$\bar{\alpha}$	520%	525%	530%	533%	534%	538%	540%	544%	547%	550%

This table shows that in order for the non-targeted industries to have higher distortion centrality on average than the HCI industries, the distortions on the purchases of non-targeted manufacturing goods have to be enormous relative to distortions on goods produced by the targeted industries. Specifically, for each (χ, α), I let $\chi_{ij} = \chi$ for all j's produced by the HCI industries and $\chi_{ij} = \alpha \cdot \chi$ for all j's produced by the non-targeted industries. I compute distortion centrality $\xi_i(\chi, \alpha)$ as functions of χ and α. The table reports, for a range of χ's, the smallest α under which the targeted and non-targeted manufacturing industries have the same average distortion centralities.

Table V: The top and bottom ten Chinese manufacturing industries by distortion centrality in 2007

Top 10	ξ_i^{Ref}	Bottom 10	ξ_i^{Ref}
Coke making	1.43	Misc. food products	0.77
Ferrous alloy	1.42	Meat processing	0.84
Iron smelting	1.41	Medicinal chemicals	0.84
Nonferrous metal smelting	1.40	Grain mill products	0.87
Metal cutting machinery	1.39	Textile, clothing and footwear	0.88
Steel smelting	1.39	Seafood processing	0.88
Railroad equipment	1.36	Household AV Equipment	0.89
Industrial furnace and boiler	1.35	Liquor and alcoholic drinks	0.90
Manufacturing of basic chemicals	1.33	Household Appliances	0.91
Refining and rolling of nonferrous metals	1.32	Vegetable oil products	0.91

Table VI: Chinese manufacturing industries with high distortion centrality receive more government support: 1) privately-owned firms in these industries have better access to credit markets, and 2) these industries have more state-owned enterprises

	Debt-To-Capital Ratio		Interest Rate		SOE Share of Value-Added	
	(1)	(2)	(3)	(4)	(5)	(6)
ξ_i^{Ref} (standardized)	1.842***	1.919***	−0.382**	−0.627***	9.537***	5.735***
	(0.533)	(0.483)	(0.142)	(0.117)	(2.167)	(1.963)
Capital Intensity		0.563		−1.810***		2.305
		(1.631)		(0.394)		(6.636)
Profit Share		−2.716***		0.443***		−0.778
		(0.499)		(0.121)		(2.032)
Share of Exporters		−4.999		−3.209***		−64.74***
		(3.062)		(0.740)		(12.46)
Outcome Mean & Standard Deviation	54.78 [4.88]		2.68 [1.26]		21.76 [20.79]	
Controls	No	Yes	No	Yes	No	Yes
Adjusted R^2	0.144	0.399	0.088	0.472	0.220	0.452
# Obs.	66	66	66	66	66	66

The table examines the correlation between standardized benchmark distortion centrality ξ_i^{Ref} and measures of government interventions extracted from the 2007 edition of China's Annual Industrial Survey. Columns (1) and (2) show that ξ_i^{Ref} predicts the average debt-to-capital ratio for privately-owned firms in the industry; columns (3) and (4) show that ξ_i^{Ref} predicts the average effective interest rate for privately-owned firms in the industry; columns (5) and (6) show that ξ_i^{Ref} predicts the share of industry value-added that is contributed by state-owned enterprises. Columns (1), (3), and (5) regress the respective outcome variables on ξ_i^{Ref} and a constant, while columns (2), (4), and (6) control for the average capital intensity and the average profit share of revenue for firms in the industry, as well as the share of exporters in the industry. Standard errors are shown in parenthesis. Industry averages of firm-level variables are computed after dropping outliers at 1%. Debt-to-capital is computed as the 100×the ratio between total outstanding debt at the end of the year and the total reported capital. Effective interest rate is computed as 100×total interest payment in 2007 divided by the total outstanding debt at the end of the year. Capital intensity is computed as the ratio between reported capital and firm revenue. Profit share is computed as 100×profits divided by revenue. A firm is identified as an exporter if it reported a positive amount of exports. SOEs are identified using the procedure outlined in Hsieh and Song (2015).

Figure I: Illustration of the vertical production economy

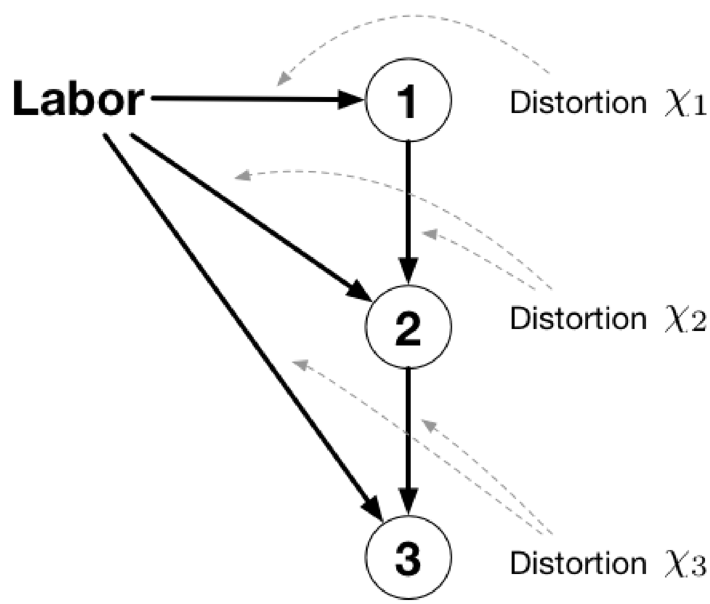
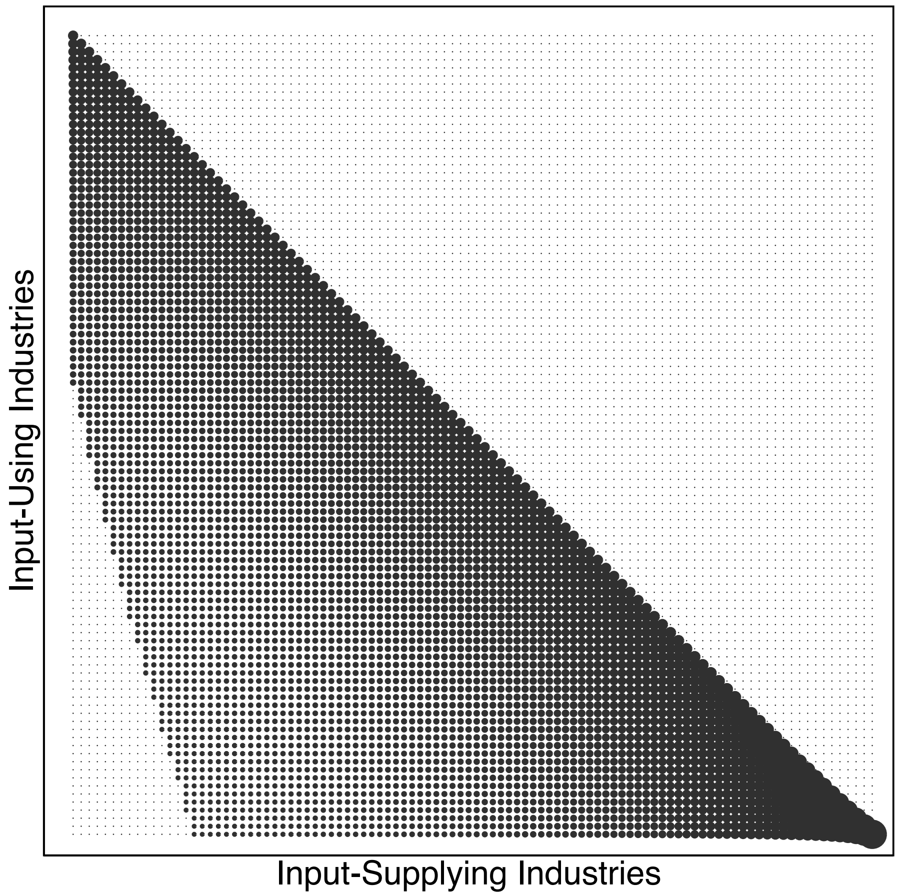
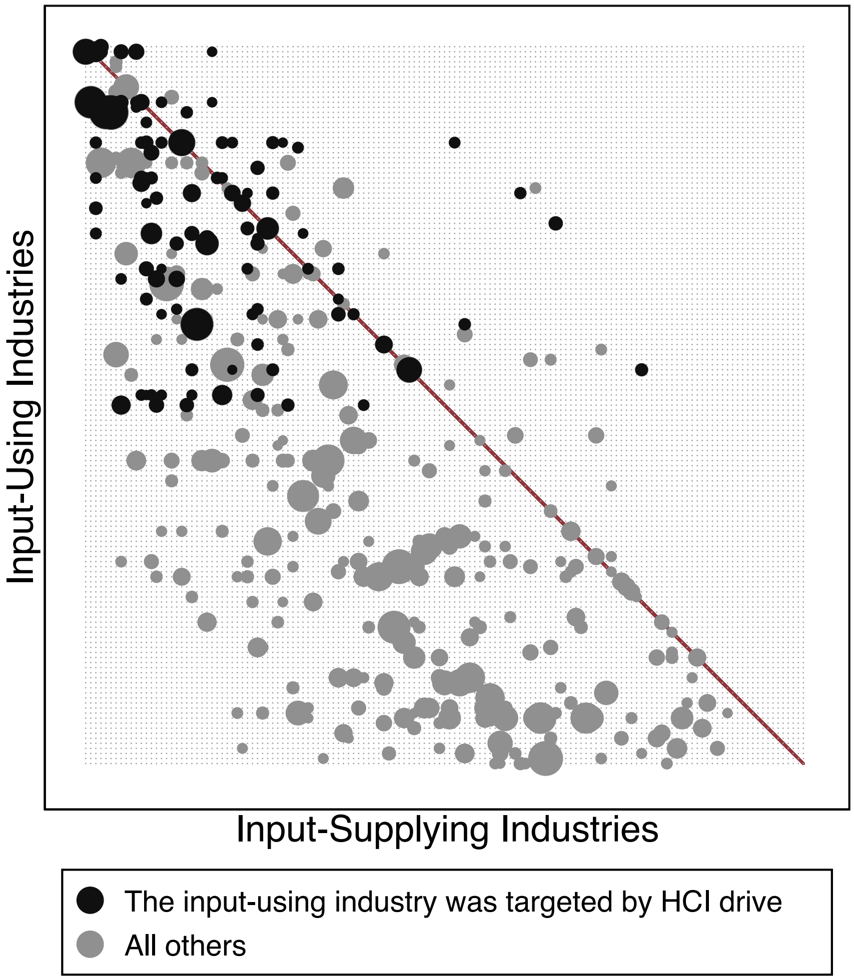


Figure II: An illustrative input-output matrix of a monotone-hierarchical network



The figure visualizes a hypothetical lower-triangular $\hat{\Omega}$ matrix that satisfies the **MH** property. Rows represent *input-using* industries and columns represent *input-supplying* industries. The ij-th entry in the figure corresponds to $\hat{\omega}_{ij}$, the faction of (column) good j that is supplied to (row) industry i. The size of each entry is drawn proportionally to $\hat{\omega}_{ij}$.

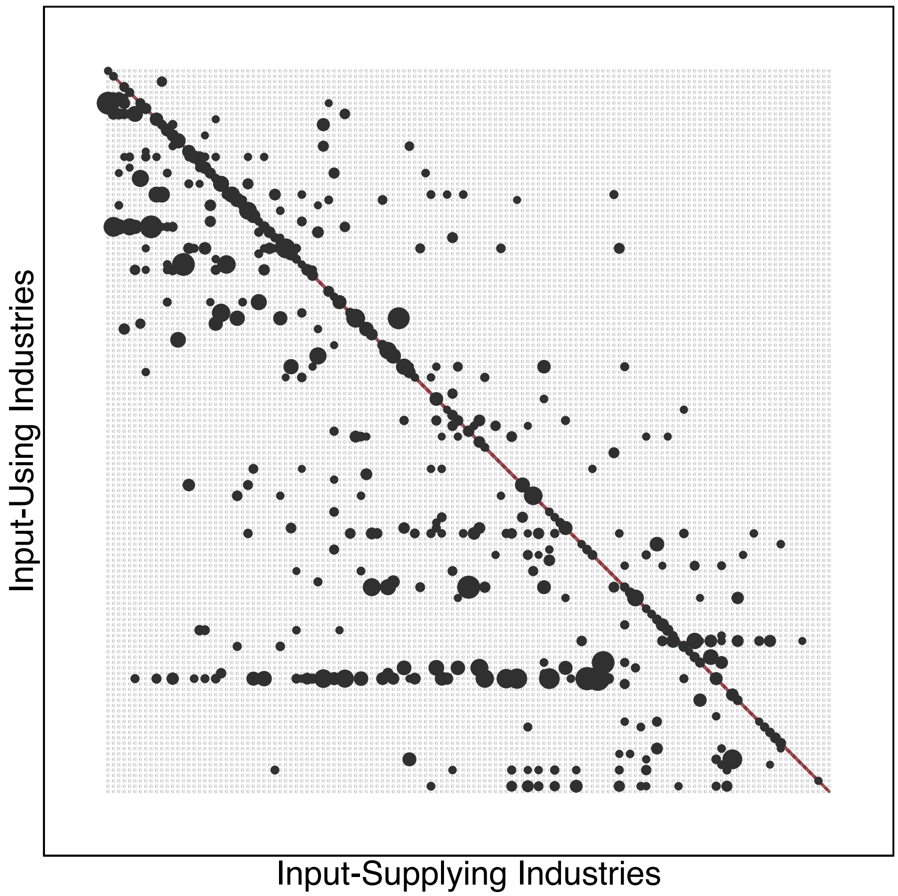
Figure III: Input-output demand matrix of South Korea in 1970



The figure visualizes the input-output demand matrix $\hat{\Omega}$ of South Korea in 1970. Rows represent *input-using* industries and columns represent *input-supplying* industries. The ij-th entry in the figure corresponds to $\hat{\omega}_{ij}$, the faction of (column) good j that is supplied to (row) industry i. Cells for which the *input-using* industry was promoted by the HCI drive are highlighted with solid black circles. The size of each entry is drawn proportionally to $\hat{\omega}_{ij}$ and is truncated below at 5%, so that only important input-output demand relationships are represented in the figure. A line is drawn across the diagonal entries.

The figure reveals that the relationship of input-flows is highly asymmetric across the targeted and non-targeted groups of industries. The targeted ones are upstream: they supply *to* the non-targeted downstream industries while purchasing few intermediate inputs in return, resulting in an approximately lower-triangular input-output demand matrix. This pattern only emerges after industries are ordered by their distortion centrality—in this case, industries are arranged in decreasing order of ξ_i^{Ref}, the sectoral distortion centrality under the assumption that distortions are uniform across all sectors and all inputs with $\chi_{ij} = 0.1$.

Figure IV: Input-output demand matrix of China in 2007



The figure visualizes the input-output demand matrix $\hat{\Omega}$ of China in 2007. Rows represent *input-using* industries and columns represent *input-supplying* industries. The ij-th entry in the figure corresponds to $\hat{\omega}_{ij}$, the faction of (column) good j that is supplied to (row) industry i. The size of each entry is drawn proportionally to $\hat{\omega}_{ij}$ and is truncated below at 5%, so that only important input-output demand relationships are represented in the figure. A line is drawn across the diagonal entries. Industries are arranged in decreasing order of ξ_i^{Ref}, the sectoral distortion centrality under the assumption that distortions are uniform across all sectors and all inputs with $\chi_{ij} = 0.1$.

Appendix

A Proofs

A.1 Proof of Lemma 1

The market clearing condition for good j is

$$Q_j = Y_j + \sum_{i \in S} M_{ij}.$$

Multiplying both sides by P_j/WL and using the fact that $\gamma_j \equiv \frac{P_j Q_j}{WL}$ and $\beta_j \equiv \frac{P_j Y_j}{Y}$, we obtain

$$\gamma_j = \frac{Y}{WL}\beta_j + \sum_{i \in S} \omega_{ij}\gamma_i$$

or in matrix notation,

$$\gamma' = \frac{Y}{WL} \cdot \beta' (I - \Omega)^{-1}.$$

The labor share in the economy sums to one, which implies that $\sum_{i \in S} \omega_i^L \gamma_i = 1$. Therefore it must be the case that $\frac{WL}{Y} = \beta' (I - \Omega)^{-1} \omega^L$, as desired.

A.2 Proof of Proposition 1

The equilibrium prices $\{P_i\}$ and W form the fixed point to the system of equations

$$P_i = \mathscr{C}_i \left(W, \left\{P_j\right\}; z_i\right) \quad \text{for } i \in S;$$

$$1 = \mathscr{C}^F \left(\left\{P_j\right\}\right).$$

Totally differentiating, we obtain

$$d \ln P_i = -d \ln z_i + \sigma_i^L d \ln W + \sum_{j \in S} \sigma_{ij} d \ln P_j$$

$$0 = \sum_{j \in S} \beta_j d \ln P_j$$

or in matrix form,

$$\begin{aligned} d\ln\mathbf{P} &= -d\ln\mathbf{z} + \sigma^L d\ln W + \Sigma d\ln\mathbf{P} \\ &= (I-\Sigma)^{-1}\left(-d\ln\mathbf{z} + \sigma^L d\ln W\right) \end{aligned}$$

$$0 = \beta' d\ln\mathbf{P}.$$

Combining the two equations, we get that

$$\frac{d\ln\mathbf{P}}{d\ln z_i} = (I-\Sigma)^{-1}\left(\sigma^L \cdot \frac{d\ln W}{d\ln z_i} - \mathbf{e}_i\right)$$

and

$$\frac{d\ln W}{d\ln z_i} = \frac{\beta' (I-\Sigma)^{-1} \cdot \mathbf{e}_i}{\beta' (I-\Sigma)^{-1} \sigma^L} = \mu_i$$

where the last equality follows because $\beta' (I-\Sigma)^{-1} \sigma^L = 1$ under the assumption that all production functions have constant-returns-to-scale.

A.3 Proof of Lemma 3

Following the proof for Proposition 1, we can write the equilibrium prices $\{P_i\}$ and W as the fixed point to the system of equations

$$P_i = \mathscr{C}_i\left(W, \{P_j\}; \{\chi_{ij}\}\right) \quad \text{for } i, j \in S;$$

$$1 = \mathscr{C}^F\left(\{P_j\}\right). \tag{A.1}$$

Differentiating the first equation with respect to $1+\chi_{ij}$ and stacking into a vector, we get

$$\frac{d\ln\mathbf{P}}{d\ln\left(1+\chi_{ij}\right)} = (I-\Sigma)^{-1}\left(-\sigma_{ij} \cdot \mathbf{e}_i + \sigma^L \frac{d\ln W}{d\ln\left(1+\chi_{ij}\right)}\right), \tag{A.2}$$

which proves part 1 of the lemma. Differentiating (A.1) gets us

$$0 = \beta' \frac{d\ln\mathbf{P}}{d\ln\left(1+\chi_{ij}\right)}. \tag{A.3}$$

Plugging equation (A.2) into (A.3), we get

$$\frac{d\ln W}{d\ln\left(1+\chi_{ij}\right)} = -\mu_i \cdot \sigma_{ij}.$$

In absence of public consumption, $C = WL$ and we have $\frac{d\ln C}{d\ln\left(1+\chi_{ij}\right)} = -\mu_i \cdot \sigma_{ij}$ as desired.

A.4 Proof of Theorem 1

First, note that the marginal cost of implementing subsidy τ_{ik} is

$$\left.\frac{d\left(\frac{\tau_{ik}}{1+\tau_{ik}} P_k M_{ik}\right)}{d\tau_{ik}}\right|_{\tau_{ik}=0} = P_k M_{ik}.$$

That is, for Δ units (a small amount) of additional resources available to the economy, the level of subsidy that can be implemented is $\tau_{ik} = \frac{\Delta}{P_k M_{ik}}$.

The marginal gain in aggregate consumption that results from the subsidy τ_{ik}, starting from the decentralized equilibrium, is captured by

$$\left.\frac{d\ln C}{d\ln\left(1+\tau_{ik}\right)}\right|_{\tau_{ik}=0} = \mu_i \cdot \sigma_{ik}.$$

The expression is a direct corollary of Lemma 3, because the effect of $d\ln\left(1+\tau_{ik}\right)$ on aggregate consumption is similar to that of a marginal decrease in distortion χ_{ik}. The expression is also intuitive in light of Lemma 2 and Proposition 1: σ_{ik} captures the partial equilibrium effect of τ_{ik} on the sectoral unit cost of production while holding all input prices constant, and μ_i captures the general equilibrium effect on aggregate consumption resulting from a proportional shift in $\mathscr{C}_i(\cdot)$, the mapping from input prices to the unit cost of production. The total effect of τ_{ik} on aggregate consumption C is the product of the partial and general equilibrium effects.

The social marginal return is obtained by dividing the marginal change in consumption and the required expenditure,

$$SR_{ik} = \left.\frac{dC/d\tau_{ik}}{d\left(P_k M_{ik} \cdot \frac{\tau_{ik}}{1+\tau_{ik}}\right)/d\tau_{ik}}\right|_{\tau_{ik}=0}.$$

The numerator can be written as $dC/d\tau_{ik} = C \cdot d\ln C/d\ln\left(1+\tau_{ik}\right)$ whereas the denominator simplifies to

$$\left.\frac{d\left(P_kM_{ik}\cdot\frac{\tau_{ik}}{1+\tau_{ik}}\right)}{d\tau_{ik}}\right|_{\tau_{ik=0}}=\left.\left(P_kM_{ik}+\frac{d\left(P_kM_{ik}\right)}{d\tau_{ik}}\cdot\frac{\tau_{ik}}{1+\tau_{ik}}\right)\right|_{\tau_{ik=0}}=P_kM_{ik}.$$

Therefore we have

$$\begin{aligned}SR_{ik} &= \frac{C}{P_kM_{ik}}\cdot\frac{d\ln C}{d\ln\left(1+\tau_{ik}\right)}\\ &= \frac{\mu_i\cdot\sigma_{ik}}{\frac{P_kM_{ik}}{P_iQ_i}\cdot\frac{P_iQ_i}{C}}\\ &= PR_{ik}\cdot\xi_i,\end{aligned}$$

as desired.

A.5 Proof of Theorem 2

In the presence of public consumption E, it is no longer the case that $C=WL$. Nevertheless, a direct corollary from Lemma 3 is that $\frac{d\ln WL}{d\ln(1+\tau_{ik})}=\mu_i\cdot\sigma_{ik}$. Now consider a marginal change in τ_{ik} financed by cutting back E while holding the lump-sum tax T constant. From the budget constraint of the representative consumer ($WL=C+T$), we derive

$$\frac{dWL}{d\ln\left(1+\tau_{ik}\right)}=\frac{dC}{d\ln\left(1+\tau_{ik}\right)}=WL\cdot\mu_i\cdot\sigma_{ik}.$$

From the planner's fiscal constraint ($E+\frac{\tau_{ik}}{1+\tau_{ik}}P_kM_{ik}=T$), we derive

$$\frac{dE}{d\ln\left(1+\tau_{ik}\right)}=-\frac{d\left(\frac{\tau_{ik}}{1+\tau_{ik}}P_kM_{ik}\right)}{d\ln\left(1+\tau_{ik}\right)}.$$

Therefore the social return of expenditure on τ_{ik} is

$$\begin{aligned}
SR_{ik} &\equiv -\frac{dC/d\tau_{ik}}{dE/d\tau_{ik}}\bigg|_{\tau_{ik}=0,T\text{ constant}} \\
&= \frac{WL\cdot\mu_i\cdot\sigma_{ik\cdot}}{\frac{d\left(\frac{\tau_{ik}}{1+\tau_{ik}}P_kM_{ik}\right)}{d\ln(1+\tau_{ik})}\bigg|_{\tau_{ik}=0,T\text{ constant}}} \\
&= \frac{\mu_i\cdot\sigma_{ik\cdot}}{\frac{P_kM_{ik}}{P_iQ_i}\cdot\frac{P_iQ_i}{WL}} \\
&= PR_{ik}\cdot\xi_i,
\end{aligned}$$

as desired.

A.6 Proof of Proposition 2

The transfer η_i induces sectoral allocations that are equivalent to a subsidy on the purchase of the constrained inputs, with

$$\left(1+\tau_i^K\right)\equiv\frac{\Gamma_i+\eta_i}{\Gamma_i}.$$

Also note that the Lagrange multiplier χ_i is equal to

$$1+\chi_i=\frac{\sum_{j\in D_i}\sigma_{ij}}{\sum_{j\in D_i}\omega_{ij}},$$

and therefore it captures the private return to a subsidy τ_i^K that applies to inputs in the constrained set D_i.

The social return on the grant of working capital is

$$\begin{aligned}
SR_i^K &\equiv \frac{dC/d\eta_i}{dE/d\eta_i}\bigg|_{\eta_i=0,T\text{ constant}} \\
&= \frac{dC/d\tau_i^K}{dE/d\tau_i^K}\bigg|_{\eta_i=0,T\text{ constant}} \\
&= (1+\chi_i)\times\xi_i
\end{aligned}$$

where the last equality follows from Corollary 1.

A.7 Proof of Proposition 3

Note that sales subsidy can be interpreted as a subsidy, applied to all sectoral inputs, that shifts the sectoral cost function in a Hicks-neutral way. Sectoral constant-returns-to-scale implies

$$\sum_{j=1}^{S}\left(1+\chi_{ij}\right)\omega_{ij}=\sum_{j=1}^{S}\sigma_{ij}=1 \text{ for all } i.$$

The result is therefore a direct application of Corollary 1, recognizing that the private return to sales subsidy is equal to one.

A.8 Proof of Theorem 3

To prove Theorem 3, consider a Cobb-Douglas economy with subsidies $\left(1+\tau^L\right)$. The sectoral allocations satisfy

$$P_jM_{ij}=\omega_{ij}P_iQ_i,\;\; WL_i=\left(1+\tau_i^L\right)\omega_i^LP_iQ_i$$

where

$$\omega_{ij}=\frac{\sigma_{ij}}{1+\chi_{ij}},\;\; \omega_i^L=\frac{\sigma_i^L}{1+\chi_i^L}.$$

Note that under Cobb-Douglas assumptions, $\left\{\sigma_{ij},\omega_{ij}\right\}_{i,j=1}^{S}$, $\left\{\sigma_i^L,\omega_i^L\right\}_{i=1}^{S}$, and consequently $\{\mu_i,\gamma_i\}_i^S$ are all stable and do not change in response to value-added subsidies.

We can solve for the quantity of inputs as

$$M_{ij}=\omega_{ij}\frac{\gamma_i}{\gamma_j}Q_j,\;\; L_i=\left(1+\tau_i^L\right)\omega_i^L\gamma_iL.$$

Labor market clearing yields

$$\sum_i\left(1+\tau_i^L\right)\omega_i^L\gamma_i=1.$$

Sectoral output can be written as

$$\begin{aligned}\ln Q_i &= \ln z_i+\sigma_i^L\ln L_i+\sum_j\sigma_{ij}\ln M_{ij}\\ &= \zeta_i+\sigma_i^L\left(\ln\left(1+\tau_i^L\right)+\ln\gamma_i\right)+\sum_j\sigma_{ij}\left(\ln\gamma_i+\ln Q_j-\ln\gamma_j\right)\end{aligned}$$

where

$$\zeta_i \equiv \ln z_i + \sigma_i^L \ln \omega_i^L + \sigma_i^L \ln L + \sum_j \sigma_{ij} \ln \omega_{ij}.$$

Constant-returns-to-scale implies $\sigma_i^L + \sum_j \sigma_{ij} = 1$ hence

$$\ln Q_i - \ln \gamma_i \quad = \quad \zeta_i + \sigma_i^L \ln\left(1+\tau_i^L\right) + \sum_j \sigma_{ij}\left(\ln Q_j - \ln \gamma_j\right).$$

Since $\gamma_i \equiv \frac{P_i Q_i}{WL}$, we have $\ln Q_i - \ln \gamma_i = \ln WL - \ln P_i$ and we can stack the equation above into a vector equation as

$$\ln WL - \ln \mathbf{P} = (I-\Sigma)^{-1}\left(\zeta + \sigma^L \circ \ln\left(1+\tau^L\right)\right)$$

By normalizing the price of the final good to be one, we know

$$\beta'\left(\ln \mathbf{P} - \ln \beta\right) = 1$$

where $\sum_{i=1}^S \beta_i = 1$. Thus

$$\ln WL \quad = \quad \text{constant} + \beta'(I-\Sigma)^{-1}\left(\sigma^L \circ \ln\left(1+\tau^L\right)\right).$$

Now to find the constrained-optimal value-added subsidies, we solve

$$\max_{\{\tau_i^L\}} \ln W\left(\left\{\tau_i^L\right\}\right) \text{ s.t. } \sum_{i=1}^S \tau_i^L W L_i = T.$$

Let λ be the Lagrange multiplier on the planner's budget constraint. The first-order condition with respect to τ_i^L is

$$\begin{aligned}
\frac{d\ln W}{d\ln\left(1+\tau_i^L\right)} \cdot \frac{1}{1+\tau_i^L} \quad &= \quad \lambda\left[WL_i + \left(\sum_{i=1}^S \tau_i^L WL_i\right)\frac{d\ln W}{d\ln\left(1+\tau_i^L\right)} \cdot \frac{1}{1+\tau_i^L}\right] \\
&= \quad \frac{\lambda}{1-\lambda T} WL_i
\end{aligned}$$

or equivalently

$$\frac{\mu_i \sigma_i^L}{1+\tau_i^L} \propto \left(\omega_i^L \gamma_i\right).$$

We therefore have

$$\left(1+\tau_i^L\right) \propto \xi_i\left(1+\chi_i^L\right),$$

as desired. Note that the result is stated in terms of proportionality because the level of taxes depends on the lump-sum tax T to which the planner has access.

A.9 Proof of Theorem 4

Let $\delta \equiv \frac{WL}{Y}$. Sectoral influence is

$$\mu_j = \beta_j + \sum_{i \in S} \mu_i \sigma_{ij}$$

Dividing influence by sales, we get

$$\begin{aligned} \xi_j &= \frac{\beta_j}{\gamma_j} + \sum_{i \in S} \frac{\mu_i \sigma_{ij}}{\gamma_j} \\ &= \frac{Y_j/Y}{P_j Q_j/WL} + \sum_{i \in S} \frac{\mu_i}{\gamma_i} \frac{\gamma_i}{\gamma_j} \frac{\sigma_{ij}}{\omega_{ij}} \omega_{ij} \\ &= \hat{\omega}_j^F \cdot \delta + \sum_{i \in S} \xi_i \left(1 + \chi_{ij}\right) \hat{\omega}_{ij}, \end{aligned}$$

or in matrix form,

$$\xi' = \delta \cdot \left(\hat{\omega}^F\right)' \left(I - \mathbf{D} \circ \hat{\Omega}\right)^{-1},$$

where $\mathbf{D} \equiv \left[1 + \chi_{ij}\right]$ is the matrix of underlying sectoral distortions.

A.10 Proof of Proposition 4

Lemma 4. *Let $X \equiv \{\underline{x}, \underline{x}+1, \cdots, \bar{x}\}$ and Y be ordered sets. Suppose $a_{mi} \in \mathbb{R}_{\geq 0}$ is log-supermodular in $(m,i) \in X \times Y$ and $\sum_{m \in X} a_{mi} = \sum_{m \in X} a_{mj} < \infty$ for all $i, j \in Y$. Then we have*

1. *$\sum_{m=\underline{x}}^{K} a_{mi} \geq \sum_{m=\underline{x}}^{K} a_{mj}$ for all $K \in X$ and $i < j \in Y$;*
2. *If $\{b_m\}_{m \in X}$ is a non-increasing and non-negative sequence, then*

$$\sum_{m \in X} a_{mi} b_m \geq \sum_{m \in X} a_{mj} b_m \text{ for } i < j \in Y.$$

Proof. Consider $i < j \in Y$. Log-supermodularity implies that for $m < n \in X$,

$$a_{mi} a_{nj} \geq a_{mj} a_{ni}.$$

Now consider the sum $\sum_{m=\underline{x}}^{K} a_{mi}$. Log-supermodularity again implies that for all $n > K \in X$,

$$\left(\sum_{m=\underline{x}}^{K} a_{mi}\right) a_{nj} \geq \left(\sum_{m=\underline{x}}^{K} a_{mj}\right) a_{ni}.$$

Summing over $n = K+1, \cdots, \bar{x}$, we have

$$\left(\sum_{m=\underline{x}}^{K} a_{mi}\right)\left(\sum_{n=K+1}^{\bar{x}} a_{nj}\right) \geq \left(\sum_{m=\underline{x}}^{K} a_{mj}\right)\left(\sum_{n=K+1}^{\bar{x}} a_{ni}\right).$$

Let $c \equiv \sum_{m \in X} a_{mi} \geq 0$. Then the inequality can be re-written as

$$\left(\sum_{m=\underline{x}}^{K} a_{mi}\right)\left(c - \left(\sum_{m=\underline{x}}^{K} a_{mj}\right)\right) \geq \left(\sum_{m=\underline{x}}^{K} a_{mj}\right)\left(c - \left(\sum_{m=\underline{x}}^{K} a_{mi}\right)\right)$$

which implies

$$\left(\sum_{m=\underline{x}}^{K} a_{mi}\right) \geq \left(\sum_{m=\underline{x}}^{K} a_{mj}\right),$$

proving the first part of the lemma. Note that this result also implies that

$$\left(\sum_{m=K}^{\bar{x}} a_{mi}\right) \leq \left(\sum_{m=K}^{\bar{x}} a_{mj}\right) \text{ for all } K \in X \text{ and } i < j \in Y.$$

To show the second part, note that

$$\begin{aligned}
\sum_{m=\underline{x}}^{\bar{x}} a_{mi} b_m &= \sum_{m=\underline{x}}^{\bar{x}} a_{mi} b_{\bar{x}} + \sum_{m=\underline{x}}^{\bar{x}-1} a_{mi}\left(b_m - b_{\bar{x}}\right) \\
&= \sum_{m=\underline{x}}^{\bar{x}} a_{mi} b_{\bar{x}} + \sum_{m=\underline{x}}^{\bar{x}-1} a_{mi}\left(b_{\bar{x}-1} - b_{\bar{x}}\right) + \sum_{m=\underline{x}}^{\bar{x}-2} a_{mi}\left(b_m - b_{\bar{x}-1}\right) \\
&\vdots \\
&= b_{\bar{x}} \sum_{m=\underline{x}}^{\bar{x}} a_{mi} + \sum_{k=1}^{\bar{x}-\underline{x}}\left(\left(b_{\bar{x}-k} - b_{\bar{x}-(k-1)}\right) \sum_{m=\underline{x}}^{\bar{x}-k} a_{mi}\right) \\
&\geq b_{\bar{x}} \sum_{m=\underline{x}}^{\bar{x}} a_{mj} + \sum_{k=1}^{\bar{x}-\underline{x}}\left(\left(b_{\bar{x}-k} - b_{\bar{x}-(k-1)}\right) \sum_{m=\underline{x}}^{\bar{x}-k} a_{mj}\right) \\
&= \sum_{m=\underline{x}}^{\bar{x}} a_{mj} b_m,
\end{aligned}$$

where the inequality follows from part 1 of the lemma and the fact that $\left(b_{\bar{x}-k} - b_{\bar{x}-(k-1)}\right) \geq 0$ since

b_m is non-increasing. □

Lemma 5. *The product of two MH matrices is MH.*

Proof. Let A and B be two $S \times S$ matrices that are MH. Let ε^A be the $S \times 1$ vector with entries $\varepsilon_i^A \equiv 1 - \sum_{m=1}^{S} A_{mi}$, and define the vector $\varepsilon^B \equiv \left[1 - \sum_{m=1}^{S} B_{mi}\right]_{i=1}^{S}$ accordingly. Define $(S+1) \times (S+1)$ matrices Γ^A and Γ^B as follows:

$$\Gamma^A \equiv \begin{bmatrix} A & \mathbf{0} \\ \left(\varepsilon^A\right)' & 1 \end{bmatrix}, \; \Gamma^B \equiv \begin{bmatrix} B & \mathbf{0} \\ \left(\varepsilon^B\right)' & 1 \end{bmatrix}.$$

Both Γ^A and Γ^B are stochastic matrices with columns summing to one, and both are log-supermodular in their entries given that A and B are MH. Multiplying Γ^A and Γ^B, we get

$$\left(\Gamma^A \Gamma^B\right)_{mi} = \sum_{k=1}^{S} \Gamma^A_{mk} \Gamma^B_{ki},$$

and because log-supermodularity is preserved under multiplication and integration, we have that $\left(\Gamma^A \Gamma^B\right)$ is log-supermodular in its entries. Furthermore, it is also a stochastic matrix with column sums equal to one. Lastly, note that the ij-th entry of $(A \times B)$ is precisely the ij-th entry of $\Gamma^A \Gamma^B$ for all $i, j \leq S$, thus establishing that $(A \times B)$ is MH. □

Lemma 6. *If A is an $S \times S$ MH matrix, its column sum is non-increasing:*

$$\sum_{m=1}^{S} A_{mi} \geq \sum_{m=1}^{S} A_{mj} \;\; \textit{for } i < j.$$

Proof. Define Γ^A as in the proof of Lemma 5 and apply the first result of Lemma 4. □

A.10.1 Proof of Case 1

First note that

$$\mu' = \beta' \left(I - \Sigma\right)^{-1}, \;\; \gamma' \propto \beta' \left(I - \Omega\right)^{-1}$$

implies that there exist a constant c such that

$$c\mu' \left(I - \Sigma\right) = \gamma' \left(I - \Omega\right)$$

or

$$c\mu' - \gamma' = c\mu'\Sigma - \gamma'\Omega.$$

We write out the j-th entry of the equation above and divide both sides by γ_j,

$$\begin{aligned}\frac{c\mu_j-\gamma_j}{\gamma_j} &= \sum_i \frac{c\mu_i\sigma_{ij}-\gamma_i\omega_{ij}}{\gamma_i}\frac{\gamma_i}{\gamma_j}\\ &= \sum_i \frac{(c\mu_i-\gamma_i)\,\sigma_{ij}+\gamma_i\left(\sigma_{ij}-\omega_{ij}\right)}{\gamma_i}\frac{\gamma_i}{\gamma_j}\\ &= \sum_i \frac{(c\mu_i-\gamma_i)\,\omega_{ij}\left(1+\chi_{ij}\right)+\gamma_i\omega_{ij}\chi_{ij}}{\gamma_i}\frac{\gamma_i}{\gamma_j}\\ &= \sum_i \left(\frac{c\mu_i-\gamma_i}{\gamma_i}\hat{\omega}_{ij}\left(1+\chi_{ij}\right)+\hat{\omega}_{ij}\chi_{ij}\right).\end{aligned}$$

In vector form,

$$c\xi'-\mathbf{1}'=\left(c\xi'-\mathbf{1}'\right)\left(\mathbf{D}\circ\hat{\Omega}\right)+\mathbf{1}'\mathbf{D}\circ\hat{\Omega}-\mathbf{1}'\hat{\Omega}$$

implying

$$\begin{aligned}c\xi'-\mathbf{1}' &= \mathbf{1}'\left(\mathbf{D}\circ\hat{\Omega}-\hat{\Omega}\right)\left(I-\mathbf{D}\circ\hat{\Omega}\right)^{-1}\\ &= \sum_{k=0}^{\infty}\mathbf{1}'\left(\mathbf{D}\circ\hat{\Omega}-\hat{\Omega}\right)\left(\mathbf{D}\circ\hat{\Omega}\right)^k.\end{aligned}$$

Since $\left(\mathbf{D}\circ\hat{\Omega}-\hat{\Omega}\right)$ and $\left(\mathbf{D}\circ\hat{\Omega}\right)$ are both MH, we know that for all k, $\left(\mathbf{D}\circ\hat{\Omega}-\hat{\Omega}\right)\left(\mathbf{D}\circ\hat{\Omega}\right)^k$ is MH according to Lemma 5 and therefore has non-increasing column sums according to Lemma 6. As a result, ξ must be non-increasing, as desired.

A.10.2 Proof of Case 2

Suppose $\hat{\Omega}$ is MH and lower-triangular. Let $d_i \equiv \frac{1}{\delta}\xi_i$, and $\hat{\omega}_{S+1,S}\equiv\hat{\omega}_S^F$ to simplify notation. From Theorem (4) and the fact that $\hat{\Omega}$ is lower-triangular, we have

$$\begin{aligned}d_S &= \hat{\omega}_{S+1,S}+\hat{\omega}_{S,S}\left(1+\chi_{S,S}\right)d_S\\ &= \frac{\hat{\omega}_{S+1,S}}{1-\hat{\omega}_{S,S}\left(1+\chi_{S,S}\right)}.\end{aligned}$$

Because of sectoral constant-returns-to-scale and the fact that $\sigma_i^L>0$ in any equilibrium under Assumption 1, the denominator has to be positive since $\hat{\omega}_{S,S}\left(1+\chi_{S,S}\right)=\omega_{S,S}\left(1+\chi_{S,S}\right)=\sigma_{S,S}<1$. We therefore have $d_S\geq\frac{\hat{\omega}_{S+1,S}}{1-\hat{\omega}_{S,S}}=1$ where the equality comes from the market clearing condition of good S $\left(\hat{\omega}_{S,S}+\hat{\omega}_{S+1,S}=1\right)$. Further,

$$\begin{aligned}
d_{S-1} &= \frac{\hat{\omega}_{S+1,S-1}+\hat{\omega}_{S,S-1}d_S\left(1+\chi_{S,S-1}\right)}{1-\hat{\omega}_{S-1,S-1}\left(1+\chi_{S-1,S-1}\right)} \\
&\geq \frac{\hat{\omega}_{S+1,S-1}+\hat{\omega}_{S,S-1}d_S\left(1+\chi_{S,S-1}\right)}{1-\hat{\omega}_{S-1,S-1}}.
\end{aligned}$$

By MH, we have

$$\hat{\omega}_{S,S-1}\hat{\omega}_{S+1,S}\geq\hat{\omega}_{S,S}\hat{\omega}_{S+1,S-1}.$$

We now use Lemma 4 to show $\mathbb{E}\left[d_{S-1}\middle|\{\chi_{kk}\}_{k=1}^S\right]\geq\mathbb{E}\left[d_S\middle|\{\chi_{kk}\}_{k=1}^S\right]$. Let $a_{s,S}\equiv\hat{\omega}_{s,S}$ and $a_{s,S-1}\equiv\frac{\hat{\omega}_{s,S-1}}{1-\hat{\omega}_{S-1,S-1}}$ for $s\in\{S,S+1\}$. By construction, $a_{s,s'}$ is log-supermodular in $(s,s')\in\{S,S+1\}\times\{S-1,S\}$ and $\sum_{s\in\{S,S+1\}}a_{s,S-1}=\sum_{s\in\{S,S+1\}}a_{s,S}=1$. Furthermore, let

$$b_{S+1}=1,\ \ b_S=\mathbb{E}\left[d_S\left(1+\chi_{S,S-1}\right)\middle|\{\chi_{kk}\}_{k=1}^S\right];$$

thus b_s is a non-increasing sequence for $s\in\{S,S+1\}$. Applying Lemma 4, we have

$$\begin{aligned}
\mathbb{E}\left[d_{S-1}\middle|\{\chi_{kk}\}_{k=1}^S\right] &\geq \frac{\hat{\omega}_{S+1,S-1}+\hat{\omega}_{S,S-1}\mathbb{E}\left[d_S\left(1+\chi_{S,S-1}\right)\middle|\{\chi_{kk}\}_{k=1}^S\right]}{1-\hat{\omega}_{S-1,S-1}} \\
&\geq \hat{\omega}_{S+1,S}+\hat{\omega}_{S,S}\mathbb{E}\left[d_S\left(1+\chi_{S,S-1}\right)\middle|\{\chi_{kk}\}_{k=1}^S\right] \\
&\geq \hat{\omega}_{S+1,S}+\hat{\omega}_{S,S}\mathbb{E}\left[d_S\left(1+\chi_{S,S}\right)\middle|\{\chi_{kk}\}_{k=1}^S\right] \\
&= \mathbb{E}\left[d_S\middle|\{\chi_{kk}\}_{k=1}^S\right]
\end{aligned}$$

where the second inequality follows from the second part of the Lemma 4 and the third inequality follows from the assumption that $\chi_{S,S}\leq\chi_{S,S-1}$ almost surely.

We now apply induction. Suppose $\mathbb{E}\left[d_s\middle|\{\chi_{kk}\}_{k=1}^S\right]\geq\mathbb{E}\left[d_{s+1}\middle|\{\chi_{kk}\}_{k=1}^S\right]$ for $s=m+1,m+2,\cdots,S$. We have that for all $s\geq m+1$,

$$\begin{aligned}
\mathbb{E}\left[d_s\left(1+\chi_{s,m+1}\right)\middle|\{\chi_{kk}\}_{k=1}^S\right] &= \mathbb{E}\left[d_s\middle|\{\chi_{kk}\}_{k=1}^S\right]\mathbb{E}\left[\left(1+\chi_{s,m+1}\right)\middle|\{\chi_{kk}\}_{k=1}^S\right] \\
&\geq \mathbb{E}\left[d_{s+1}\middle|\{\chi_{kk}\}_{k=1}^S\right]\mathbb{E}\left[\left(1+\chi_{s+1,m+1}\right)\middle|\{\chi_{kk}\}_{k=1}^S\right] \\
&= \mathbb{E}\left[d_{s+1}\left(1+\chi_{s+1,m+1}\right)\middle|\{\chi_{kk}\}_{k=1}^S\right].
\end{aligned}$$

In other words, $\mathbb{E}\left[d_s\left(1+\chi_{s,m+1}\right)\middle|\{\chi_{kk}\}_{k=1}^S\right]$ form a non-increasing sequence in $s\geq m+1$. We also have

$$d_{m+1} = \hat{\omega}_{S+1,m+1} + \sum_{n=m+1}^{S} \hat{\omega}_{n,m+1} d_n \left(1+\chi_{n,m+1}\right)$$

$$\begin{aligned} d_m &= \frac{\hat{\omega}_{S+1,m} + \sum_{n=m+1}^{S} \hat{\omega}_{n,m} d_n \left(1+\chi_{n,m}\right)}{1-\left(1+\chi_{m,m}\right)\hat{\omega}_{m,m}} \\ &\geq \frac{\hat{\omega}_{S+1,m} + \sum_{n=m+1}^{S} \hat{\omega}_{n,m} d_n \left(1+\chi_{n,m}\right)}{1-\hat{\omega}_{m,m}}. \end{aligned}$$

Now let $a_{s,m+1} = \hat{\omega}_{s,m+1}$ and $a_{s,m} = \frac{\hat{\omega}_{s,m}}{1-\hat{\omega}_{m,m}}$ for $s \in \{m+1, m+2, \cdots, S+1\}$. $a_{s,s'}$ is log-supermodular and $\sum_{s=m+1}^{S+1} a_{s,m} = \sum_{s=m+1}^{S+1} a_{s,m+1} = 1$. We therefore have

$$\begin{aligned} \mathbb{E}\left[d_{m+1} \middle| \{\chi_{kk}\}_{k=1}^{S}\right] &= \hat{\omega}_{S+1,m+1} + \sum_{n=m+1}^{S} \hat{\omega}_{n,m+1} \mathbb{E}\left[d_n\left(1+\chi_{n,m+1}\right) \middle| \{\chi_{kk}\}_{k=1}^{S}\right] \\ &\leq \frac{\hat{\omega}_{S+1,m} + \sum_{n=m+1}^{S} \hat{\omega}_{n,m} \mathbb{E}\left[d_n\left(1+\chi_{n,m+1}\right) \middle| \{\chi_{kk}\}_{k=1}^{S}\right]}{1-\hat{\omega}_{m,m}} \\ &\leq \frac{\hat{\omega}_{S+1,m} + \sum_{n=m+1}^{S} \hat{\omega}_{n,m} \mathbb{E}\left[d_n\left(1+\chi_{n,m}\right) \middle| \{\chi_{kk}\}_{k=1}^{S}\right]}{1-\hat{\omega}_{m,m}} \\ &\leq \mathbb{E}\left[d_m \middle| \{\chi_{kk}\}_{k=1}^{S}\right]. \end{aligned}$$

The second line follows from Lemma 4 and the fact that $\mathbb{E}\left[d_s\left(1+\chi_{s,m+1}\right) \middle| \{\chi_{kk}\}_{k=1}^{S}\right]$ is non-increasing in s; the third line follows by the conditional independence of χ_{ij}'s. By induction, we have that $\mathbb{E}\left[d_i \middle| \{\chi_{kk}\}_{k=1}^{S}\right] \geq \mathbb{E}\left[d_j \middle| \{\chi_{kk}\}_{k=1}^{S}\right]$ for all $i < j$. Applying the law of iterated expectations, we have $\mathbb{E}[d_i] \geq \mathbb{E}\left[d_j\right]$ for all $i < j$, as desired.

B Additional Tables

Table B.1: Targeted HCI industries have higher distortion centrality than non-targeted industries in South Korea in 1970

	Average $\mathbb{E}[\xi_i]$		Share of industries with $\mathbb{E}[\xi_i] > 1$	
Distribution of χ_{ij}'s	HCI	non-HCI	HCI	non-HCI
$\mathbb{E}[\chi_{ij}] = 0.05$				
$\chi_{ij} = 0.05$ constant $\forall i, j$	1.10	1.02	100%	56.7%
$\max\{0, Norm(0.045, 0.05)\}$	1.10	1.02	100%	56.7%
$\max\{0, Norm(0.019, 0.1)\}$	1.10	1.02	100%	56.7%
$U[0, 0.1]$	1.10	1.02	100%	56.7%
$\exp(0.05)$	1.10	1.02	100%	58.3%
$\mathbb{E}[\chi_{ij}] = 0.15$			100%	55.0%
$\chi_{ij} = 0.15$ constant$\forall i, j$	1.32	1.05	100%	55.0%
$\max\{0, Norm(0.15, 0.05)\}$	1.33	1.05	100%	55.0%
$\max\{0, Norm(0.147, 0.1)\}$	1.33	1.05	100%	55.0%
$\max\{0, Norm(0.115, 0.2)\}$	1.35	1.05	100%	55.0%
$U[0, 0.3]$	1.33	1.05	100%	55.0%
$\exp(0.15)$	1.33	1.05	100%	56.7%
$\mathbb{E}[\chi_{ij}] = 0.2$				
$\chi_{ij} = 0.2$ constant$\forall i, j$	1.46	1.06	100%	55.0%
$\max\{0, Norm(0.2, 0.05)\}$	1.46	1.06	100%	53.3%
$\max\{0, Norm(0.2, 0.1)\}$	1.47	1.06	100%	53.3%
$\max\{0, Norm(0.18, 0.2)\}$	1.50	1.06	100%	51.7%
$U[0, 0.4]$	1.47	1.06	100%	53.3%
$\exp(0.2)$	1.49	1.06	100%	56.7%

This table is a continuation of Table III and it shows that the targeted HCI industries have higher distortion centrality on average than the non-targeted industries, and a higher fraction of targeted industries have distortion centrality above unity. For each specification, $\mathbb{E}[\xi_i]$ is computed as the average distortion centrality of industry i over 10,000 simulations. The results show that for all specifications, 1) all HCI industries have $\mathbb{E}[\xi_i] > 1$; 2) expected social net return to spending in the HCI sector is over three times of the private net return ($\frac{\xi_i \times PR_{ij} - 1}{PR_{ij} - 1} > 3$) around 45% of non-targeted industries have expected distortion centrality below one.

Table B.2: Industries targeted by the Heavy-Chemical Industry drive

Industry Name	(K)SIC	Industry Name	(K)SIC
Sulfuric acid and hydrochloric acid	66	Steel rolling	98
Carbide	67	Pipe and plated steel	99
Caustic soda products	68	Steel casting	100
Industrial compressed gases	69	Non-ferrous metals	101
Other inorganic basic chemicals	70	Primary non-ferrous metal products	102
Petrochemical based products	71	Construction metal products	104
Acyclic intermediate	72	Other metal products	105
Cyclic intermediate	73	Prime movers, boilers	106
Other organic basic chemicals	74	Machine tool	107
Chemical fertilizer	75	Special industry machinery	108
Pesticides	78	Office machines	109
Synthetic resin	79	General purpose machinery and equipment	110
Explosives	82	General machinery parts	112
Paints	83	Industrial electrical machinery and apparatus	113
Other chemical products	85	Electronics and telecommunications equipment	114
Petroleum products	86	Other electrical equipment	116
Pig iron	95	Shipbuilding and ship repair	117
Crude iron	96	Railroad transportation equipments	118
Ferroalloys	97	Cars and parts	119

Table B.4: Chinese SOEs receive direct government subsidies and have significantly better access to credit

	$\mathbf{1}_{\text{Subsidies}>0}$		Log(subsidies)		Debt-to-Capital Ratio		Effective Interest Rate	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\mathbf{1}_{SOE}$	0.113	0.101	1.623	1.326	9.119	9.373	-1.203	-1.251
	(0.003)	(0.003)	(0.038)	(0.036)	(0.227)	(0.228)	(0.052)	(0.0516)
Constant	0.106	-	5.001	-	54.386	-	2.638	-
	(0.001)	-	(0.012)	-	(0.051)	-	(0.0.011)	-
Industry Fixed Effects	No	Yes	No	Yes	No	Yes	No	Yes
Obs.	298,368	298,368	33,211	33,211	296785	296785	276,598	276,598
adj. R^2	0.01	0.02	0.05	0.19	0.005	0.027	0.002	0.040

The table shows that Chinese SOEs receive significantly more subsidies from the government than private firms, and that they have significantly better access to credit markets. Each unit of observation is a firm. The four outcome variables are, respectively, 1) dummy variable that the firm receives a positive amount of subsidy in year 2007; 2) log of total subsidies received in year 2007, conditioning on having received any subsidy; 3) debt-to-capital ratio, computed as 100×total liability over total assets; 4) effective interest rate, computed as 100×total interest payments over total liability. The odd columns regress respective outcome variables on a constant and the dummy variable that the firm is state-owned; the even columns include industry fixed effects. Standard errors are shown in parenthesis.