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Des annexes en ligne sont disponibles à l'adresse suivante : https://sites.google.com/view/danial-lashkari/lbb

Technologies de l’information et rendements d’échelle

En nous appuyant sur des données encore peu exploitées sur l’investissement en équipements informatiques et en logiciels des entreprises françaises, nous documentons une corrélation robuste et positive entre la taille des entreprises et l’intensité de leur demande en TIC. Nous expliquons ce constat en défendant l’idée que le produit marginal des TIC augmente avec l’échelle de la production : les TIC aident en particulier les entreprises à dépasser les contraintes d’organisation liées à leur taille. Nous proposons un modèle d’équilibre général de dynamique sectorielle où la fonction de production des entreprises est compatible avec ce mécanisme. Nous estimons cette fonction de production et montrons que la demande en TIC est non-homothétique et que l’élasticité de substitution entre les TIC et les autres facteurs de production est inférieure à l’unité. Nous montrons que la relation positive observée entre la taille des entreprises et leur intensité en TIC et celle, négative, entre leur taille et la part du travail dans leur valeur ajoutée, correspondent aux prédictions du modèle calibré selon les valeurs estimées des paramètres. En outre, en réponse à la baisse du prix relatif des TIC après 1990 en France, le modèle explique environ la moitié de la hausse observée de la concentration et de la réallocation des parts de marché vers les entreprises à faible part du travail.

Mots-clés : technologie de l’information, part du travail, concurrence, fonction de production, non-homotheticité.

Information Technology and Returns to Scale

Relying on a novel dataset on hardware and software investments in the universe of French firms, we document a robust within-industry correlation between firm size and the intensity of IT demand. To explain this fact, we argue that the relative marginal product of IT inputs may rise with firm scale, since IT helps firms deal with organizational limits to scale. We propose a general equilibrium model of industry dynamics that features nonhomothetic production functions compatible with this mechanism. Estimating this production function, we identify the nonhomotheticity of IT demand and find an elasticity of substitution between IT and non- IT inputs that falls below unity. Under the estimated model parameters, the cross-sectional predictions of the model match the observed relationship of firm size with IT intensity (positive) and labor share (negative). In addition, in response to the fall in the relative price of IT inputs in post-1990 France, the model explains about half of both the observed rise in market concentration and the market reallocations toward low-labor-share firms.

Keywords: information technology, labor share, competition, production function, nonhomotheticity.

Classification JEL : E10 ; E23 ; E25

1 Introduction

Advances in Information Technology (IT) have drastically lowered the quality-adjusted prices of computing and information-intensive tools over the past few decades (Byrne and Corrado, 2017). In response, business investment in software and computing equipment has soared, fueling productivity growth at both firm and aggregate levels.[1] However, investment in IT may have some conceptually distinct features compared to investments in other forms of productive capital such as machinery, tools, and robots. Whereas machines typically enhance the productivity of firms in performing specific production tasks, IT tools can enhance the coordination and integration of firm processes across many distinct tasks. Consider for instance business management software such as Enterprise Resource Planning (ERP). The ERP systems are tools of organizational planning that standardize information flows across different business divisions such as project, supply chain, and inventory management, as well as procurement, accounting, and customer service.[2] Such IT tools enable firms to better cope with organizational complexities of production, both internally and also in relation with their sellers and buyers.[3] To the extent that such organizational complexities limit the scalability of production for firms, the rise of IT may have important implications for *returns to scale* in production.

In this paper, we provide empirical evidence in favor of the view that IT plays a distinctive role in shaping returns to scale at the firm and the aggregate levels. We further offer a simple theory that allows us to examine the consequences for industry concentration and factor income shares. We document a new fact using micro data from France: a robust correlation across and within firms between scale and IT intensity, defined as the ratios of IT to other or total inputs. We show that this fact can be rationalized by a firm-level production function that distinguishes IT from other types of capital, allowing for its marginal product (relative to that of other inputs) to systematically rise with firm size. If organizational efficiency declines with scale but rises with IT intensity, larger firms optimally choose to become more IT intensive. Two important consequences for the rise of IT immediately follow: it 1) raises the returns to scale at the firm level, and 2) disproportionately

[1] Between 1997 and 2015, the price of IT relative to machinery investment on average fell by over 65% across 12 richest OECD countries in the EU KLEMS dataset, while the ratio of IT to machinery stocks of capital rose over 100% (the corresponding numbers for the US are 82 and 337 percents, respectively). Empirical work has established that this rise in IT investments has led to strong productivity gains both at the micro (e.g., Brynjolfsson and Yang, 1996; Brynjolfsson and Hitt, 2003; Aral et al., 2006; Draca et al., 2009; Bloom et al., 2012) and macro levels (Oliner and Sichel, 2000; Jorgenson, 2001; Stiroh, 2002; Jorgenson et al., 2005; Stiroh, 2008).

[2] Since their appearance in the early 1990s, the ERP systems quickly spread across industries such that over 40% of US businesses with revenues over 1 billion dollars already had adopted them by 2001 (Stefanou, 2001). The global expenditure on ERPs has continued to grow to over 450 billion dollars per year by 2019 (source: www.statista.com). For a brief history of ERP systems, see Jacobs and Weston (2007).

[3] Productivity in each division of firm activities has in turn benefited from specialized software solutions, e.g., Human Resource Management (HRM), Supply Chain Management (SCM), or Consumer Relation Management (CRM). These tools are commonly integrated within ERP systems to support the decision making processes at the firm level.

benefits larger firms and reallocates market shares toward them.

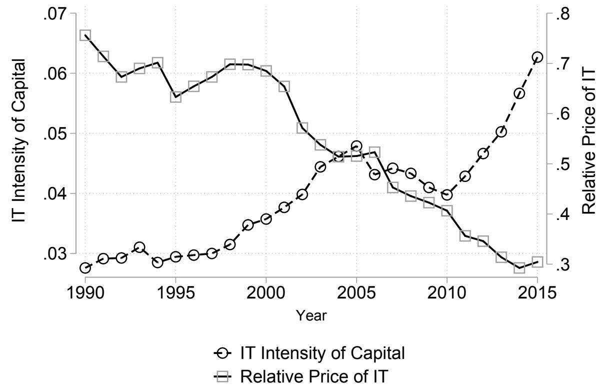
We further establish a tight theoretical connection between such nonhomotheticity in IT factor demand and *heterogeneity* in returns to scale across firms. We show that with nonhomothetic factor demand, the degree of returns to scale should vary with firm size. In particular, for the range of the production function parameters we estimate in our data, our model suggests that returns to scale falls in firm size. Since the degree of returns to scale and the income share of factor payments are positively related, the latter should also fall in firm size.[4] This is in line with the negative cross-sectional correlation between firm size and labor share in our data (see also Autor et al., 2020). In addition, this also implies a second channel through which the rise of IT affects the aggregate returns to scale: as it reallocates market shares toward large and IT intensive firms, it also lowers the aggregate returns to scale.

The dichotomy between within-firm and across-firm effects on returns to scale, and subsequently labor share, finds support in our data. We find divergent patterns between the two components of labor share in France, in line with recent results documented in the case of US (e.g., Autor et al., 2020; Kehrig and Vincent, 2018): whereas within-firm labor share rises, the reallocation toward low-labor-share firms contributes negatively in the aggregate. In a calibration of our model, we find that the fall in the relative IT prices observed in the data between 1990 and 2007 can quantitatively explain about half of the observed patterns in labor share and the observed rise in market concentration in the data. We show that nonhomotheticity plays a sizable role in explaining these patterns: aggregating from micro to macro, our model implies a *macro* elasticity of substitution between IT and other factor inputs of around unity, whereas a model with homothetic production functions leads to an elasticity of around 0.75.

Overview of the Paper Empirically, our point of departure is the introduction of novel datasets that detail micro-level software and hardware investments among French firms, covering a broad set of manufacturing and service industries between 1995 to 2007. We rely on the micro data to construct stocks of software and hardware capital for French firms, and document a positive within-industry relationship between size and IT intensity. This finding is robust to different measures of IT intensity, whether IT is proxied by software or hardware, whether by investment or capital, and whether intensity is measured relative to labor inputs or to non-IT capital. It is also robust to using different measures of firm scale, whether scale is measured by employment, value added, sales, or by more eclectic measures such as the number of plants, the depth of organizational

[4] In our model, markups are constant and variations in the shares of factor payments in income vis-á-vis profits do not stem from differences in market power. Instead, they correspond to differences in *Ricardian rents*, i.e., the returns to fixed, firm-specific, inimitable factors that distinguish firms from one another. We assume that all other factors receive their marginal products in perfectly competitive markets, leaving the residual value created to the owner of the firm.

Figure 1: Rise of IT



Note: This figure presents on the left axis the ratio of computing equipment capital services to non-IT capital services (excluding dwellings), and on the right axis the user cost of computing equipment capital relative to the user cost of non-IT capital, in France, Market Economy. Source: EU KLEMS.

structure, the number of exporting markets, or the number of exported products (the latter two measures only in the sample of exporting firms). We find this relationship to hold across a wide range of industries and classes of firm size, from small firms with just a few workers to large multinationals hiring thousands of workers. Focusing on the sample of exporting firms, we also use firm-level export demand shocks as instruments for output to estimate the within-firm elasticity of IT intensity to firm size. We find a positive and significant elasticity.

To structurally account for this fact and to study its macro implications, we construct a general equilibrium model that features monopolistically competitive firms endowed with a nested *Nonhomothetic CES* (nhCES) production function (Sato, 1974, 1977; Comin et al., 2015). Software and hardware constitute a bundle of IT inputs while labor and non-IT capital constitute a bundle of non-IT inputs. The two bundles are combined using a nhCES production function to produce firm-level output. Relative to the standard CES specification, the nhCES aggregator only adds a *nonhomotheticity parameter* that governs the elasticity of IT intensity with respect to output. We assume that firms are heterogeneous in terms of two productivity states, one factor-symmetric and one IT-biased, and the two evolve over time according to a simple Markovian process.

Nonhomothetic IT demand explains our first micro fact on the correlation between firm size and IT intensity. As mentioned earlier, the model also implies a connection between firm size and returns to scale. Importantly, the relationship between returns to scale and firm size in the model crucially hinges on the elasticity of substitution between IT and non-IT inputs. In particular, if the elasticity is below unity, the nonhomotheticity of IT demand implies that larger firms have both lower returns to scale and lower shares for factor payments in their income.[5] This result

[5] In Appendix C.2, we show that this result generalizes beyond the nhCES production function. In particular, subject to mild conditions, if the elasticity of substitution is locally constant and IT demand is locally nonhomothetic,

rationalizes a second micro fact that we document using our micro data from France: a negative correlation between firm size and labor share (in line with Autor et al., 2020).

We aggregate the model and derive the general equilibrium predictions of the model in response to an exogenous fall in the price of IT inputs. We show that the aggregate response can be summarized in terms of the response of the aggregate IT intensity to this shock. We decompose this response to within-firm and across-firm components, and examine the effect of nonhomothetic IT demand on each of the two components. The within-firm effect raises returns to scale (and factor income shares) for all firms, and the across-firm effect shifts market shares toward larger firms operating with lower returns to scale (and factor income shares).[6]

We bring the model to the data in two steps. First, we employ an identification strategy based on standard timing assumptions to estimate our production function using the panel structure of our micro data. We combine this method with a strategy that relies on shift-share instruments for the price of software relative to wages to estimate the full nhCES production function, including the elasticity of substitution between IT and non-IT inputs (similar to Oberfield and Raval, 2014). We find a nonhomotheticity parameter of around 0.4 and reject homotheticity of IT demand in the sample of all industries, the sample of all manufacturing industries, and in samples of more disaggregated industries. In line with the parametric restrictions required by our mechanism, we also find estimates for the elasticity of substitution between IT and non-IT inputs that are below unity: the estimated elasticity is 0.23 (0.17) in the sample of all (manufacturing) industries.[7] Finally, our estimated parameters imply values for the returns to scale that are very close to unity for the *average* firm, while still leading to sizable variations in the cross section depending on the firm's IT intensity.

Armed with these estimates, we study the ability of the model to quantitatively account for the observed macro trends in France over the period 1990-2015. This is a period that witnessed a substantial and widespread rise in the adoption of IT among French firms. Figure 1 shows the series for the user cost of IT equipment (relative to that of non-IT capital) and the ratio of IT equipment capital to non-IT capital services across the entire market economy in France. Between 1990 to 2015, we observe a fall of over 50% in the relative user cost of IT and a sizable shift in the composition of capital of firms toward IT equipment. We further use our data to revisit the evolution of market concentration and labor share, and the cross sectional relationship between labor share and firm size over this period. Similar to the patterns recently documented in the US and a number of

the returns to scale decreases (increases) in firm size if the elasticity of substitution is below (above) unity.

[6] Appendix C.5 provides a full characterization of the decomposition and compares it with a benchmark model with homothetic CES production functions. In doing so, we generalize the results of Oberfield and Raval (2014) and Baqaee and Farhi (2018) on the aggregate elasticity of substitution to a non-CRS case.

[7] These numbers are close to recent micro-level estimates of the elasticity of substitution between capital and labor (see, e.g., Oberfield and Raval, 2014; Doraszelski and Jaumandreu, 2018).

other advanced economies (eg., Andrews et al., 2016; Autor et al., 2017, 2020), we find a sizable rise in industry-level market concentration. In addition, we find that the implied market reallocations toward larger firms have contributed negatively to the evolution of the aggregate labor share (accumulating to a total of around 4 percentage points from 1990 to 2007). In contrast, we find that upward shifts in the distribution of labor share over the same period made a positive within-firm contribution of around the same magnitude to the evolution of the aggregate labor share (similar to patterns found by Kehrig and Vincent, 2018).

We assume that the fall in the price of IT observed in Figure 1 is driven by exogenous technological progress and study how it can help explain the documented macro trends through the lens of the model. Accordingly, we study the response of our model in moving between two stationary equilibria of the calibrated model, corresponding to the initial (in 1990) and final (in 2007) levels of the relative price of IT. The calibrated model predicts a rise in market concentration, proxied by the share of top 1% and 5% of firms in industry sales, about half of the rise observed in the data. The model also predicts positive within-firm and negative across-firm contributions to the aggregate labor share, both by around 2 percentage points, again accounting for about half of the two components observed in the data. An alternative model calibrated based on a homothetic CES production function generates quantitative responses with about half the magnitude of our model. We conclude that the nonhomotheticity of IT demand and the fall in IT prices together help explain a substantial part of the rise in industry concentration and the resulting reallocations toward low-labor-share firms in France.

Prior Literature Our paper contributes to a large literature that has studied the impacts of IT at both the micro and the macro levels.[8] While in this paper we focus on the aggregate consequences of the nonhomotheticity of IT demand, our results also have important implications for the micro side of this literature. In particular, the fact that the relative IT demand grows in firm size may in fact explain a part of the observed relationship between productivity and IT intensity.

Our paper further contributes to the literature that studies a number of recent secular macroeconomic trends across advanced economies. A number of papers have documented growing industry concentration and within-industry dispersion in firm outcomes (CEA, 2016; Andrews et al., 2016; Berlingieri et al., 2017). Indicators of business dynamism, such as the rate of startup formation, appear to be in decline across many advanced economies, particularly in the United

[8]Beyond the studies cited earlier, recent papers in this line of work rely on exogenous variations in the costs of IT adoption as a strategy for identifying the elasticity of output and productivity with respect to IT (e.g., DeStefano et al., 2014, 2016; Akerman et al., 2015). In two recent papers, Harrigan et al. (eg., 2016, 2018) have studied the rise of what they refer to as "techies," the specialized and technically oriented labor inputs that may constitute complementary inputs to IT, in the context of the French labor market. They argue that the shifts in the composition of labor hired by French firms toward techies has played an important role in labor market polarization and skill-biased productivity growth.

States (Decker and Haltiwanger, 2013; Haltiwanger, 2015; Decker et al., 2015; Andrews et al., 2016; Decker et al., 2016; Karahan and Pugsley, 2016; Gutiérrez and Philippon, 2017). In parallel, there is a large body of work on a global fall in the labor share across many industries (Elsby et al., 2013; Karabarbounis and Neiman, 2014; Koh et al., 2015; Barkai, 2020; Grossman et al., 2017).[9]

As discussed above, IT capital has been put forth as a potential explanation for the above trends,[10] and in particular for the fall in labor share through its potential substitution with labor (Karabarbounis and Neiman, 2014; Gaggl and Wright, 2017; Eden and Gaggl, 2018). Our paper reconciles this line of work with available evidence that the micro elasticities of capital-labor substitution fall below unity (Lawrence, 2015), and that market reallocations are responsible for the potential fall in the labor share (Kehrig and Vincent, 2018; Autor et al., 2020, 2017).[11] More recently, Aghion et al. (2019), Hsieh and Rossi-Hansberg (2019), Mariscal (2018), and De Ridder (2019) have provided theoretical models that link the rise of IT to the recent secular macroeconomic trends.[12] The mechanisms in these papers share a key feature with ours in connecting the rise of IT to changes in the span and scale of operation of firms. Our paper complements these contributions by providing direct empirical evidence on the micro-level relationship between size and scale. Furthermore, we are able to structurally identify our mechanism in the data, and use the resulting estimates to discipline a quantitative analysis of the connection between the observed fall in the price of IT and the aggregate trends.[13]

In this paper, we focus on identifying how the nonhomotheticity of IT demand at the level of firm production functions may shape the behavior of the aggregate economy. Prior work has identified potential forces that give rise to such nonhomotheticity patterns. For instance, the organizational theories of firm generates nonhomotheticity patterns similar to those uncovered here

[9]Since Karabarbounis and Neiman (2014), a sizable body of work has revisited the evidence on the fall of the labor share to examine the potential explanations, or whether this fact is robust to the relevant details in the construction of the labor share series (e.g., see Elsby et al., 2013; Koh et al., 2015). In this paper, we focus on the compositional aspects of the evolution of labor share across firms, i.e., the changes within and across firms, rather than the aggregate labor share. In fact, we do not find an aggregate fall in the labor share in France beginning in the 1990s.

[10]We note that IT is one among the several mechanisms offered in the literature as the potential drivers of the observed macroeconomic trends. For instance, Crouzet and Eberly (2017, 2018), Gouin-Bonenfant (2018), Martinez (2018), Akcigit and Ates (2019), Hopenhayn et al. (2018), and Liu et al. (2019) have proposed the rise of intangible capital, productivity dispersion, automation, and the decline in knowledge diffusion, population growth, and interest rates as potential channels for these trends, respectively.

[11]In addition, our framework further allows us to account for potential responses in the aggregate profit share to the rise in the price of IT (Autor et al., 2020; Barkai, 2020). Note that, in contrast to a number of recent other accounts of the fall of the labor share which focus on market power and markups (e.g., De Loecker et al., 2020; Baqaee and Farhi, 2020; Aghion et al., 2019), our model features efficient allocations and therefore our mechanism does not involve any changes in the level of allocative distortions.

[12]Relatedly, Autor et al. (2017, 2020) suggest that IT may have created network effects and facilitated more effective product comparisons for consumers, therefore helping superstar firms gain larger shares of the market.

[13]We also note that our model shares this core mechanism with the results of Basu and Fernald (1997), who study business cycle fluctuations in an environment where producers have heterogeneous returns to scale and where cyclical expansions of output are biased toward firms with higher returns to scale.

(Caliendo and Rossi-Hansberg, 2012; Caliendo et al., 2015a,b).[14] In addition, there is some evidence for the effects of IT on the integration and supply-chain management of firms (Fort, 2014; Basco and Mestieri, 2018), which may provide an alternative ground for the higher benefits of IT for larger firms. We discuss further evidence on the relationship between IT and firm in organization in Section C.1 below.

Outline of the Paper The remainder of this paper is organized as follows. Section 2 discusses the data sources and our key micro-level empirical facts. Section 3 presents the theory and Section 4 discusses our identification strategy for estimating the nhCES production function. Section 5 documents a number of macro trends in France and shows how a calibration of our models can help quantitatively account for them. Finally, Section 6 concludes the paper.

2 Data and Facts

2.1 Data

Our data covers active firms in the corporate sector in France from 1990 to 2007.[15] These firm-level data are collected from surveys and tax records by the French Institute of Statistics (INSEE). The Annual Survey of Firms (EAE) provides information on, among other things, software investment at the firm level. The BRN (normal tax regime) and RSI (simplified tax regime) data provide standard income and employment information for all French firms that have to report to the tax authorities, outside of agriculture. Firms in the BRN files also report their investments in several types of assets, including hardware. Additionally, we rely on the employee-level DADS data and the Customs data for the construction of proxies for the scale and scope of operation of firms. The unique firm identifier SIREN allows us to match these data sources. In addition to these firm-level data, we also rely on aggregate and sectoral series for France from INSEE National Accounts and the KLEMS dataset (Jäger, 2017).[16] Firms that exclusively report to the RSI tax regime are included in the analysis of the macro trends in France but because they do not report their investments in IT, they are not included in the IT data. Below, we discuss the features of the IT data (see Section A in the Appendix for further details).

[14] For a direct application of this theory to the impacts of IT, see Bloom et al. (2014).

[15] Firms are "legal units" with a unique SIREN identification number. We restrict our attention to the following sectors: manufacturing, mining, utility, construction, trade, transportation, accommodation and food services, information and communication, and professional services, excluding agriculture, real estate, finance, public administration, education, and health.

[16] The dataset is available online at http://www.euklems.net.

IT Data The EAE files contain information on software investment for all firms with more than 20 employees and a sample of smaller firms (Frouté, 2001). Surveyed firms report total investment in software, as the sum of expenditure on 1) software purchased from outside, 2) software created in-house, and 3) investment made in existing software.[17] Our measure of software investment includes all components, and we use the information on the disaggregated components of investment, when available, to ensure that they are compatible with the reported value of total investment in software.

The BRN files report the total investment of firms in office and computing equipment (Barbesol et al., 2008; Chevalier and Luciani, 2018). This component of investment in the BRN data provides, to our knowledge, the closest measure for hardware investments of firms in the universe of French firms, despite the fact that it includes non-investment components such as office furniture. We use this variable as our measure of investment in hardware and as our second indicator of IT investment, acknowledging the potential for measurement error due to the presence of non-IT components.

We construct measures of the stocks of hardware and other non-IT types of capital based on observed investments, starting from an initial stock in 1990, for all firms that appear at least once in the BRN data. For more than a third of these firms, which are also surveyed at least once by the EAE, we construct measures of their stock of software capital following the same procedure. For this procedure, we employ asset-specific price deflators, depreciation rates, and information on the total industry-level stocks in year 1990, for software, hardware, and the other components of capital, based on the KLEMS dataset and the series constructed by INSEE.[18] To ensure that our results are not driven by the initial values of stocks, we discard the first five years of the stock data and focus on the period 1995-2007.

The EAE and BRN files are exhaustive above certain thresholds of size, but still a fraction of firms are missing the values of their investment flows in some periods. Whenever we have no information on an investment flow, because the firm either is missing, reports to the simplified regime, or is not surveyed by EAE, we impute zero investment that year. We use the imputed investment measures only in the construction of our stock measures.[19]

[17] The survey further includes a disaggregation of software investment into these three components, for firms operating in some manufacturing, trade and services industries. Firms operating in the food sector also report the sources of funds (internal or external finance) for the investment.

[18] We use the EU KLEMS (September 2017 release, Jäger, 2017) to obtain depreciation rates by asset type for France. We rely on the INSEE Annual National Accounts (May 2018 release) for gross fixed capital stocks in current prices and gross fixed capital formation prices. We use these measures at the 38-industry level to construct software, hardware, and non-IT capital stocks depending on the firm's industry. Section A.3 in the Appendix provides the complete details of the procedure for construction of capital stock variables and presents the information on price deflators and depreciation rates used. Our procedure closely follows that used by Bloom et al. (2012), who construct capital stock measures based on various surveys of IT expenditure in the UK.

[19] See more details in the discussion of our treatment of the missing data in Appendix A.

Measures of IT Intensity We define a number of measures of IT intensity to document our core facts about the relationship between relative IT demand and firm size. Our first measure, the *IT intensity of labor* for a firm is defined as the ratio of a measure of IT inputs, e.g., investment or stock of software, to a measure of labor inputs, e.g., the firm's number of employees. Similarly, the *IT intensity of capital* for a firm is defined as the ratio of a measure of the firm's IT investment (or stock) to the total capital investment (or stock) of the firm.[20] Finally, we define two measures of *IT intensity of cost* corresponding to investment and stocks of IT as follows. We define the IT intensity of cost for *investment* as the ratio of investments in software or hardware, to the sum of the firm's wage bill and total investments. The latter corresponds to the accounting notion of total expenditures on production factors. We also use the more economically meaningful definition of IT intensity of cost for *stock* measures as the ratio of the payments to software or hardware divided by the total payments to all production factors, including labor, capital, and IT. Payments to capital factors are computed as the product of the user cost for each type of capital and the nominal value of the corresponding stock.[21]

Summary Statistics Table 1 presents the summary statistics of the main variables in our data. The table separately shows the summary statistics for all firms, on the left, and for manufacturing firms, on the right. We have around 15.2 million firm-year observations in the BRN + RSI files from 1990 to 2007, for which we provide standard income statistics. Of those, around 6.2 million observations refer to firms included once in the BRN files from 1995 to 2007, for which we provide statistics on hardware and other non-IT inputs, and around 2.4 million observations refer to firms surveyed at least once by the EAE from 1995 to 2007, for which we provide statistics on software inputs.

2.2 Facts

2.2.1 IT Intensity and Firm Scale

We examine the relationship between firm-level size and intensity of IT demand applying regressions with the following general form:

$$IT\,Intensity_{it} = \eta\, Size_{it} + FEs + \nu_{it}, \tag{1}$$

[20]We also compare our results with the total wage bill as an alternative definition of the labor inputs, and the investment or stock of tangibles as an alternative measure of capital inputs.

[21]The user cost is the sum of the long-term interest rate on government bonds, the depreciation rate specific to each type of capital, and the expected fall in the price of that type capital, computed as the 3-year moving average of the investment price.

Table 1: Summary Statistics

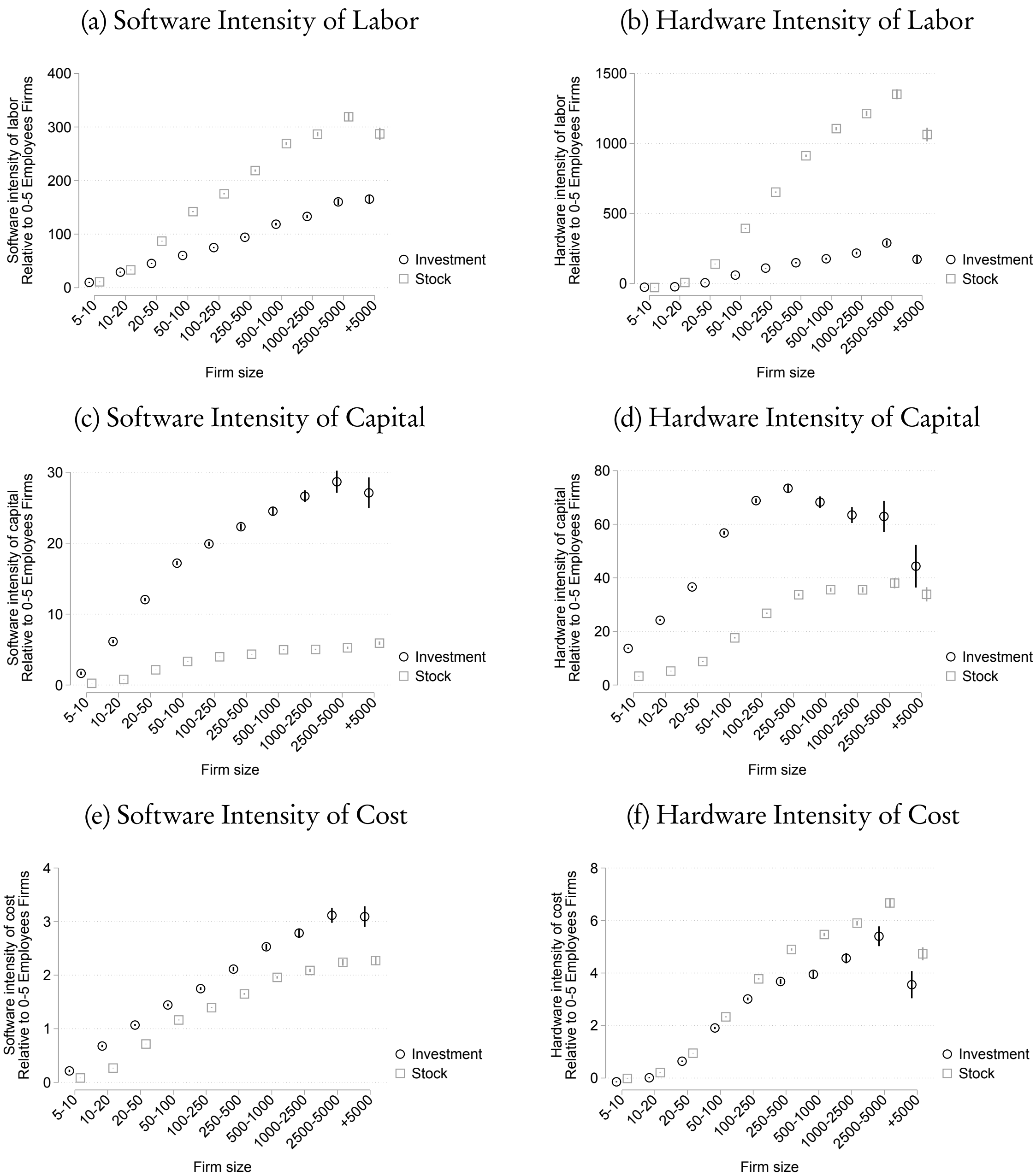
		All firms				Manufacturing firms			
	Source	Obs. (Nb)	Mean	Median	Sd	Obs. (Nb)	Mean	Median	Sd
Sales	BRN + RSI	15,202,967	2,498.8	265	85,056.8	2,422,381	4,171.2	316.9	60,560.2
Value-Added	BRN + RSI	15,202,967	708.3	106	33,071.4	2,422,381	1,271.9	147.1	25,846.5
Number of Employees	BRN + RSI	15,202,967	13.8	3	480.7	2,422,381	23.3	4	177.0
Wage Bill	BRN + RSI	15,202,967	472.4	74	18,404.5	2,422,381	815.2	109	8,105.5
Labor Share (%)	BRN + RSI	15,202,967	74.0	73.0	33.9	2,422,381	74.1	73.0	31.4
Total Investment	BRN	6,166,342	143.1	5	9,880.3	986,722	274.9	12	4,109.5
Total Capital Stock	BRN	6,166,342	1,202.2	88.0	92,297.9	986,722	2,599.2	217.9	30,598.2
Total Cost	BRN	6,166,341	898.1	181.0	33,623.7	986,722	1,578.2	305.9	12,659.3
IT Measures									
Software Investment	EAE	2,435,356	5.9	0	528.2	380,756	14.8	0	290.9
Software Stock	EAE	2,435,356	15.8	0	1,216.2	380,756	41.0	0.7	721.9
Hardware Investment	BRN	6,166,342	6.1	0	405.2	986,722	9.3	0	173.1
Hardware Stock	BRN	6,166,342	24.5	0	1,857.4	986,722	45.8	0	666.0
IT Intensity of Labor									
Software Investment	EAE	2,435,356	27.5	0	167.0	380,756	67.2	0	228.1
Software Stock	EAE	2,435,356	81.7	0	3,214.5	380,756	220.4	20.8	7,825.8
Hardware Investment	BRN	6,166,342	177.5	0	750.0	986,722	114.7	0	460.2
Hardware Stock	BRN	6,166,342	477.4	0	2,435.9	986,722	398.2	0	1,235.5
IT Intensity of Capital									
Software Investment	EAE	1,985,530	21.9	0	1,156.5	353,971	30.1	0	596.7
Software Stock	EAE	2,284,444	3.8	0	22.1	371,701	5.9	0.6	19.1
Hardware Investment	BRN	4,381,031	112.9	0	1,601.1	771,006	71.2	0	1,403.6
Hardware Stock	BRN	5,550,954	39.5	0	128.3	916,263	18.9	0.2	71.5
IT Intensity of Cost									
Software Investment	EAE	2,435,351	0.7	0	4.1	380,756	1.6	0	5.5
Software Stock	EAE	2,435,356	0.6	0	2.6	380,756	1.6	0.2	3.7
Hardware Investment	BRN	6,166,303	3.8	0	20.0	986,716	2.6	0	15.4
Hardware Stock	BRN	6,166,341	2.4	0	7.9	986,722	1.7	0	4.5

Note: The units for all variables are thousand euros except for those involving intensity, share, or numbers. The units for the IT intensity of labor, capital, and cost are euros per worker, euros per thousand euros of capital, and euros per thousand euros of cost, respectively. Labor share, in percentage points, is defined as the sum of wage bill and payroll taxes divided by values-added. Stock measures are built using the Perpetual Inventory Method (PIM), imputing zero investment for missing data. The table reports hardware and capital inputs for all firms included at least once in the BRN files, and software inputs for all firms surveyed at least once by EAE. Data Appendix A describes the sources for each variable. The period is 1990-2007 for BRN + RSI data, 1995-2007 for BRN and EAE data. For the IT intensity of capital, the number of non missing observations is lower because of the higher occurrence of zeros in the denominator.

where $IT\,Intensity_{it}$ denotes a measure of the relative demand for IT inputs for a firm i at time t, $Size_{it}$ denotes a measure of firm-i's size at time t, and FEs stands for a collection of various fixed effects, depending on whether we are interested in variations across or within firms.

Within-industry We first investigate the within-industry relationship between firm size and IT intensity across firms. We account for $Size_{it}$ in Equation (1) by dummies that account for the firm-i's size class in terms of its number of employees at time t. As for the fixed effects, we include a flexible set of industry-time (at the 3-digit level), age, and cohort fixed effects. Figure 2 shows the estimated coefficients for different size classes for each of our three proxies of IT intensity, sepa-

Figure 2: Cross-sectional Relationship Between IT and Firm Size



Note: This figure reports average IT intensity by firm size class. Averages are conditional on a set of flexible fixed effects constructed from the interaction of 3-digit industry codes and time dummies, and a full set of cohorts fixed effect (pre 1980, 1980-1993, 1993-1995 ... 2005-2007) and normalised age fixed effects. In the case of software, sample is all firms that were sampled in EAE (that year for investment, at least once for capital). In the case of hardware, sample is all firms that reported hardware investment lower than 0.99 times total investment. The units for the IT intensity of labor, capital, and cost are euros per worker, euros per thousand euros of capital, and euros per thousand euros of cost, respectively. Imputed values of the "investment" measures are dropped from the analysis. The bands around the estimates show the 90% confidence intervals.

rately for software and hardware.[22] In all cases, the estimates are reported relative to the estimated

[22]Figure 10 in the online appendix shows the fixed effects of cohorts. In some cases, there appears to be an upward trend in newer cohorts of firms (e.g., software or hardware capital intensity) but we do not find a robust pattern in

value for the dummy for the size class corresponding to 0-5 workers.

Starting with the software intensity measures (the left column), we find a strong relationship between different measures, both in terms of investment and stock, and the employment size of firms. For instance, a typical firm with more than 5,000 workers has a software investment (stock) intensity of labor close to 200 euros (300 euros) per worker higher than firms with 0-5 workers. The IT intensity *premium* of larger firms is fairly sizable considering that, as we saw with the statistics provided in Table 1, the average software investment (stock) intensity across all firms is around 27 euros (82 euros) per worker for labor. Large firms therefore have a software intensity gap relative to the smallest firms that is several times larger than the average software intensity in our data.[23] We find that the patterns above also broadly hold in the case of hardware. For instance, large firms have hardware investment (stock) intensities of labor that are 250 euros (1,000 euros) per worker higher than small firms, or 1 to 2 times the average hardware intensity.[24]

Next, we choose to measure firm scale in terms of its ouput (rather than employment). In this case, we account for firm size, $Size_{it}$ in Equation (1), by the logarithm of firm sales or value added, and use the same set of fixed effects as before. The first three rows of Figure 3 present the coefficients corresponding to firm size in regressions where $IT\,Intensity_{it}$ stands for the *logarithm* of our three proxies of IT intensity for the stocks of software and hardware (see Table 6 in the appendix for the full set of results). The coefficients are in the 0.2–0.4 range, suggesting that raising the scale of firm output by a factor of 2 raises its IT stock intensity by about 20% to 40%, with elasticities similar for software and hardware. Table 8 in the appendix shows that the relationship is also stable across different brackets of firm size.

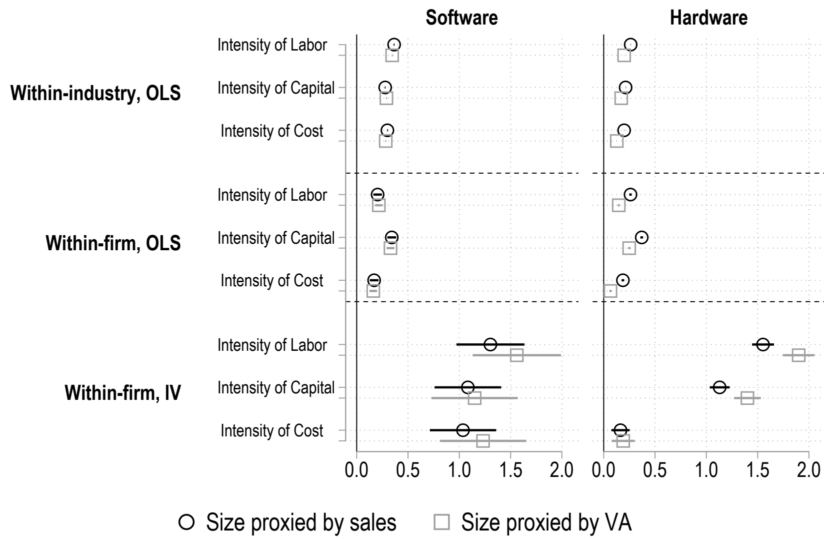
In addition to firm output and employment, we further investigate the relationship between a number of other proxies of firm scale and IT intensity. Firms can expand their scales along different margins: they can sell more of the same products to the same markets, they can sell the same products to more markets, or they can sell more products. The BRN data does not provide us with a decomposition of firm sales along these margins. Instead, we rely on customs data that allows

terms of IT intensity across firms. See Appendix B for a more detailed discussion of age and cohort fixed effects.

[23] Note that the results include the variations in IT intensity both along the intensive and the extensive margins. The differences in IT investment patterns as a function of firm size also emerge if we only consider the extensive margin. Figure 9 in the online appendix shows that the extensive margin of investment grows in firm size for both software and hardware. We also find similar results using the logarithm of the intensity measures, including in Section 4 when we turn to the estimation of our model, where by construction only the intensive margin is present.

[24] The main exception is the relative intensity of hardware investment that initially rises but then somewhat falls among the largest firms. We believe this pattern is likely to stem from the fact that our measure of hardware investment includes non-IT related office equipments. The mentioned pattern is largely driven by a group of mid-size firms that report 100% of their total investments in the "office and computing equipment" category, a likely indicator that their investment is in the office and furniture component, rather than IT. When we restrict our analysis to the sample of 38,410 observations for which we are able to distinguish between computing equipment and non-IT office furniture equipment (firms in the agrifood industry sampled in EAE), computing investment relative to total investment or to hardware investment (computing plus office furniture) is increasing in size (see Figure 8 in the online appendix).

Figure 3: Regressions of Measures of IT Intensity on Log Firm Size



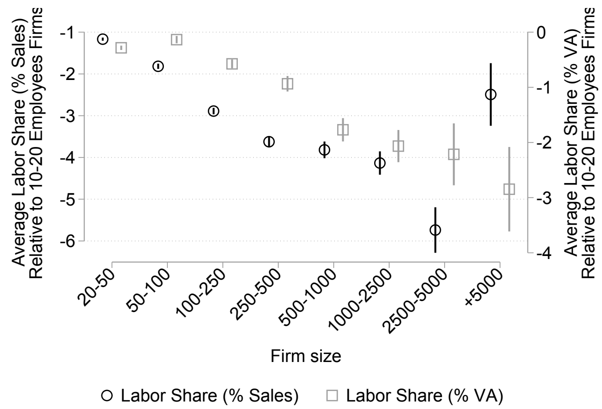
Note: This figure reports the relationship between IT intensity and size. Each coefficient is the result of a separate regresssion of the logarithm of IT stock intensity on the logarithm of firm size either proxied by sales or value added. The time period is 1995-2007. In the case of software, the sample is firms sampled by EAE, and in the case of hardware, the sample is BRN firms. Additionnally, in IV regressions, the sample restricted to exporting firms. Within-industry estimates include a full set of 3-digit industry classification fixed effects interacted with year fixed effects and a full set of cohorts fixed effect (pre 1980, 1980-1993, 1993-1995 ... 2005-2007) and normalised age fixed effects. Within-firm estimates include a full set of firm fixed effects. The units for the IT intensity of labor, capital, and cost are euros per worker, euros per thousand euros of capital, and euros per thousand euros of cost, respectively. See Tables 6, 9, and 10 An elasticity of 0.365 of sofware stock per worker to sales means that raising sales by a factor of 2 raises software stock per worker by 36.5%. The bands around the estimates show the 80% confidence intervals.

us to gain a partial picture of these different margins in the international markets in the sample of exporting firms. Table 7 in Appendix B presents the results of the same regressions as in Figure 3, where firm size $Size_{it}$ in Equation (1) is measured by: 1) the number of international markets (destination countries) and 2) the number of exported products. In both cases, there is a positive relationship between the IT intensity of the firm and these proxies of the scale of operations of the firm.

As we will see in the next section, we attribute the relationship between firm scale and IT intensity to the organizational demands that stem from more complex patterns of production as firms expand their scale. We rely on DADS data to find suggestive evidence that simple measures of organizational complexity of firms indeed appear to be correlated with IT intensity. In particular, Table 7 in Appendix B also shows a positive relationship between the IT intensity of the firm and 1) the firm's number of plants and 2) the number of occupational layers.

Within-firm Next, we examine the relationship between firm size and IT intensity within firm. The second set of three rows in Figure 3 present the coefficients corresponding to firm size in the same regressions as before, but controlling for additional firm-specific fixed effects (see Table 9

Figure 4: Labor Share and Firm Size



Note: The conditional average of labor share (measured as the ratio of wage bill to either sales or value added) by firm size. Averages are conditional on a set of flexible fixed effects constructed from the interaction of 3-digit industry codes and time dummies. The bands around the estimates show the 90% confidence intervals.

in Appendix B for the full results). We find positive and significant elasticities of IT intensity with respect to firm size similar to the cross-sectional estimates, in the 0.05-0.4 range.

The last set of three rows in Figure 3 shows the estimates for the sample of exporting firms, where firm size is instrumented by a firm-level, shift-share instrument for export demand shocks (see full table and details in Appendix B). This reduced-form identification strategy suggests that we can attribute the relationship between IT intensity and firm size to the effect of the latter on the former.[25] In Sections 3 and 4 below, we will provide a theoretical account of this effect and structurally identify it in the full sample of all firms in our data.

2.2.2 Labor Share and Firm Scale

Let us now examine the cross-sectional relationship between firm size and labor share in the French data, applying a similar strategy as that used above for the case of IT intensity. We run fixed effects regressions similar to those in Equation (1), where we replace the left-hand-side variable with labor share LS_{it}, denoting the ratio of the wage bill including payroll taxes to firm value added or sales. This allows us to revisit the patterns that Autor et al. (2020) have documented in the context of the US data.[26] Figure 4 presents the resulting fixed effects for different size classes for regressions

[25] Tables 9 and 10 in the appendix provide the full set of results. Note that the differences in the magnitudes of estimated coefficients under the OLS and IV settings is partly driven by the differences in the sample of firms. In particular, the IV estimates correspond to the much smaller sample of exporting firms. Table 11 in the appendix also provides results that are weighted by each firm's initial share of exports in total sales. The weighted results are typically smaller. Note that both the OLS and the IV estimates of the relationship between IT intensity and size are victims of omitted variable bias in a way that the structural approach laid out in Section 4 is not. We discuss the issues related with identifying this parameter in Section 4.8 of the online appendix.

[26] In the case of US data, data on firm-level value added is not available outside the manufacturing sector. Here, we are able to compare the patterns for the labor share measured both relative to sales and value added.

of labor share in value added and sales, relative to firms between 10-20 workers.[27] We find a strong negative relationship between labor share and firm size.

3 Theory

In this section, we provide a theory that rationalizes the empirical facts that we uncovered in the previous section. The core of the theory is an account of firm-level production that interprets the micro facts on the relation between IT intensity and size as evidence for the nonhomotheticity of IT factor demand. We set up the economic environment of the model in Section 3.1, introduce the production function in Section 3.2, and proceed to discuss the equilibrium of the model and the predictions regarding our micro and macro facts in Section 3.3.

3.1 Economic Environment

Consumers and Preferences The economy is populated by a unit mass of identical, infinitely-lived consumers, who in each period inelastically supply a unit of (homogenous) labor in the market and earn wage $W_{L,t}$. The consumers choose their consumption to maximize $\sum_t \varrho^t \log Y_t$, where ϱ is the discount factor and Y_t is a standard CES aggregator defined over a continuum of goods $i \in \mathcal{J}_t$ at time t:

$$Y_t = \left(\int_{i \in \mathcal{J}_t} Y_{it}^{\frac{\lambda-1}{\lambda}} di \right)^{\frac{\lambda}{\lambda-1}}. \tag{2}$$

Consumers own all production factors, and may additionally invest in an asset comprised of the portfolio of all firms in the economy.

Firms and Production We assume monopolistic competition. Each firm produces a unique good i using a production function that transforms four inputs: labor L_{it}, capital K_{it}, software S_{it}, and hardware H_{it} into output Y_{it}. We assume a nested structure in which the non-IT inputs, labor and capital, and the IT inputs, software and hardware, are first aggregated into bundles of non-IT and IT inputs, respectively. Accordingly, we consider the following relation between inputs and output:

$$Y_{it} = \mathcal{F}\left(e^{\theta_{it}} X_{N,it}, e^{\theta_{it}+\phi_{it}} X_{I,it}\right), \tag{3}$$

$$X_{N,it} = K_{it}^{\alpha} L_{it}^{1-\alpha}, \tag{4}$$

[27] We limit our analysis to firms with more than 10 employees because many firms with fewer employees in our data have unreasonably small values of labor share. We believe that our proxy for labor payments for these small firms is likely to be downwardly biased, due to the fact that it may not include the bulk of labor payments that goes to the firm's owner.

$$X_{I,it} = S_{it}^{\beta} H_{it}^{1-\beta}, \tag{5}$$

where θ_{it} and ϕ_{it} are factor-symmetric and IT-biased (log) productivity states, respectively, which are heterogeneous across firms. In addition, $X_{N,it}$ is a constant-returns-to-scale Cobb-Douglas bundle of non-IT inputs, capital and labor. Similarly, $X_{I,it}$ is a constant-returns-to-scale Cobb-Douglas bundle of the IT inputs, software and hardware.

The specification of the upper nest of the production function in Equation (3), i.e., function $Y = \mathcal{F}\left(e^{\theta} X_N, e^{\theta+\phi} X_I\right)$, lies at the heart of the model. We will present and discuss this specification in detail in Section 3.2 below. As we will see, our choice of production function $\mathcal{F}$ is compatible with nonhomothetic IT demand in the form of:

$$\frac{\partial \log(X_I/X_N)}{\partial \log Y} = \eta, \qquad \eta > 0, \tag{6}$$

which, in line with the empirical patterns we uncovered in the previous section, suggests a stable relationship between firm size and IT intensity.

Firm Exit, Entry, and Dynamics We assume that firms have to expend a fixed cost ψ in units of the bundle of non-IT inputs every period they operate. They can also temporarily shut down if they are not profitable. Therefore, endogenously exit is *reversible* and does not involve an option value.[28] In addition, we assume that firms may receive an exogenous death shock with probability δ every period, which makes them *irreversibly* exit the market.

Each period, potential entrants pay sunk entry costs χ in units of the bundle of non-IT inputs, draw productivity pair $\boldsymbol{\vartheta}_{it} \equiv (\theta_{it}, \phi_{it})$ from a distribution F, and enter the market. We assume a Markov structure on the evolution of firm-level productivity given by

$$\boldsymbol{\vartheta}_{it} = \boldsymbol{\mu}\left(\boldsymbol{\vartheta}_{it-1}\right) + \boldsymbol{u}_{it}, \tag{7}$$

where $\boldsymbol{\mu}(\cdot)$ is the conditional expectation function and $\boldsymbol{u}_{it} \equiv \left(u_{\theta,it}, u_{\phi,it}\right)'$ is a vector of zero-mean and normally distributed productivity innovations.

Factor Markets As with labor, the supply of all other factors are also inelastic and exogenous. In particular, let $\overline{K}$, $\overline{S}_t$, and $\overline{H}_t$ denote the aggregate stocks of non-IT capital, software, and hardware, respectively, where we allow the aggregate stocks of software and hardware to potentially

[28] We have made this assumption merely to maintain the simplicity of our model while 1) preserving an active role for selection and 2) generating a stationary distribution of firm sales with levels of concentration that are in line with the observed data. The option value of operation corresponding to potential irreversibility of endogenous exit would not play an important role in our setting.

vary over time. Correspondingly, we define the aggregate stocks of the bundle of non-IT inputs $\overline{X}_N = \overline{K}^\alpha$ and IT inputs $\overline{X}_{I,t} = \overline{S}_t^\beta \overline{H}_t^{1-\beta}$. In addition, we assume that all factors have perfect and national markets. Let $W_{L,t}$, $W_{K,t}$, $W_{S,t}$, and $W_{H,t}$ denote wages and the rental prices of non-IT capital, software, and hardware, respectively. We normalize the price of the bundle of non-IT inputs to unity and let W_t denote the prevailing price of the bundle of IT inputs at time t, that is, we assume:

$$1 \equiv \left(\frac{W_{K,t}}{\alpha}\right)^\alpha \left(\frac{W_{L,t}}{1-\alpha}\right)^{1-\alpha}, \qquad W_t \equiv \left(\frac{W_{S,t}}{\beta}\right)^\beta \left(\frac{W_{H,t}}{1-\beta}\right)^{1-\beta}. \tag{8}$$

3.2 Firm-Level Production Function

Consider a function $Y = \mathcal{F}\left(e^\theta X_N, e^{\theta+\phi} X_I\right)$ in Equation (3) that is implicitly defined through the constraint

$$\left(\frac{e^\theta X_N}{Y^\gamma}\right)^{\frac{\sigma-1}{\sigma}} + \left(\frac{e^{\theta+\phi} X_I}{Y^{\gamma+\epsilon}}\right)^{\frac{\sigma-1}{\sigma}} = 1. \tag{9}$$

We assume that parameters (γ, σ) are positive valued and ϵ satisfies $\epsilon > -\gamma$ to ensure the production function is globally monotonically increasing in both inputs. This production function belongs to the class of *nonhomothetic CES (nhCES) production functions* (Sato, 1974, 1977; Hanoch, 1975; Comin et al., 2015) for reasons that will become evident shortly.[29]

Since firms face perfect and frictionless factor markets, they solve the cost minimization problem corresponding to this production function to decide on the allocation of their inputs between IT and non-IT. The following lemma characterizes the cost minimizing solution for this production function.

Lemma 1. *Consider the cost minimization corresponding to the production function in Equation (9) where W denotes the relative price of X_I to X_N. The relative factor demand is given by*[30]

$$\frac{W X_I}{X_N} = \left(e^{-\phi} W Y^\epsilon\right)^{1-\sigma}, \tag{10}$$

and the cost function (with the price of X_N as the numeraire) is given by

$$C = e^{-\theta} \mathcal{C}\left(Y; e^{-\phi} W\right) \equiv e^{-\theta} Y^\gamma \left[1 + \left(e^{-\phi} W Y^\epsilon\right)^{1-\sigma}\right]^{\frac{1}{1-\sigma}}. \tag{11}$$

[29] The general class of nonhomothetic CES preferences may be defined as $\left(X_N/\mathcal{F}_N(Y)\right)^{1-\frac{1}{\sigma}} + \left(X_I/\mathcal{F}_I(Y)\right)^{1-\frac{1}{\sigma}} = 1$ for two monotonically increasing functions $\mathcal{F}_N(\cdot)$ and $\mathcal{F}_I(\cdot)$ (see also Hanoch, 1975; Russell and Blackorby, 1981; Comin et al., 2015). To distinguish the more specific class defined by Equation (9), Sato (1977) refers to the class of preferences as *almost-homothetic* nonhomothetic CES preferences. Here, to simplify the exposition, we will follow Hanoch (1975) and Comin et al. (2015) and use the broad term nonhomothetic CES (nhCES) to refer to the particular class defined by Equation (9), which further imposes a constant elasticity of relative factor demand with respect to output.

[30] See proof in Section 1.2 of the online appendix.

The relative factor demand in Equation (10) systematically varies in output Y in line with Equation (6) with a constant elasticity $\eta \equiv (1-\sigma)\epsilon$. The nhCES production function above nests the standard homothetic CES production for the case of $\epsilon = 0$. As with the standard CES, a nhCES production function also features a globally constant elasticity of substitution σ between IT and non-IT inputs. For any given value of the elasticity of substitution $\sigma \neq 1$, changing the parameter ϵ allows us to vary the elasticity η of relative IT demand with respect to output. For this reason, we will refer to parameter ϵ as the *nonhomotheticity parameter*.

The specification in Equation (9) is a flexible generalization of the standard CES production function that allows for a systematic relationship between size and factor intensities. We next show that such nonhomotheticity has important implications for the returns to scale at the firm level. In Appendix C.1, we provide a simple motivation for our nhCES functional form to help build some intuition about the connection between IT, organization, and return to scale. Therein, we also discuss the connection between our framework and previous related models (e.g., Lucas, 1978).

Firm-Level Production Function and Returns to Scale

Define the *IT weight* of the firm as the term in Equation (9) involving the IT inputs:

$$\Omega \equiv \left(\frac{e^{\theta+\phi} X_I}{Y^{\gamma+\epsilon}} \right)^{\frac{\sigma-1}{\sigma}} \in [0,1]. \tag{12}$$

To simplify the exposition, throughout this section we consider the parametric restrictions $\sigma < 1$ and $\epsilon \geq 0$.[31] These restrictions correspond to the case where IT and non-IT inputs are gross complements and IT intensity rises with size. In this case, the IT weight is *decreasing* in the level of IT inputs X_I for a given level of output Y.

The main index of returns to scale is the *scale elasticity* of the production function, defined as the sum of the output elasticity of all inputs, which captures how the output scales as we proportionally scale all inputs. we can show that the scale elasticity of the full production function is given by

$$\frac{X_N \partial Y}{Y \partial X_N} + \frac{X_I \partial Y}{Y \partial X_I} = \frac{1}{\gamma + \epsilon \Omega}, \tag{13}$$

which is endogeous, decreasing in the IT weight, and strictly smaller than $1/\gamma$ if we deviate from the homothetic benchmark ($\epsilon > 0$). We can also show that the output elasticity of the bundle of non-IT inputs is given by

$$\frac{X_N \partial Y}{Y \partial X_N} = \frac{1-\Omega}{\gamma + \epsilon \Omega}, \tag{14}$$

[31] Our micro-level estimates of the two parameters σ and ϵ in Section 4.2 satisfy these restrictions.

which is also decreasing in the IT weight. Along an isoquant Y of a nhCES production function, as we substitute IT inputs X_I for non-IT inputs X_N, IT weight Ω falls and both scale elasticity and the output elasticity of the non-IT bundle rise. Thus, *adopting IT allows firms to raise their returns to scale.*

Examining the dual problem of cost minimization allows us to see the same forces from an alternative angle. The proof of Lemma 1 shows that, under cost minimization, the *cost share of IT*, i.e., WX_I/C, is equal to the IT weight defined in Equation (12). Since throughout this section we assume flexible inputs and perfectly competitive factor markets, cost minimization holds and we use the same notation Ω to also refer to the IT cost share to save on notation.[32] From Equation (10), we define a function that gives the cost share of IT as

$$\Omega\left(e^{-\phi} W Y^{\epsilon}\right) \equiv \frac{\left(e^{-\phi} W\, Y^{\epsilon}\right)^{1-\sigma}}{1+\left(e^{-\phi} W\, Y^{\epsilon}\right)^{1-\sigma}}. \tag{15}$$

We can show that the cost elasticity $\mathcal{E}$, defined as the ratio of the marginal to average costs for Equation (11), is a linear function of the IT cost share:[33]

$$\mathcal{E}\left(e^{-\phi} W Y^{\epsilon}\right) \equiv \frac{Y\, C'\left(Y; e^{-\phi} W\right)}{C\left(Y; e^{-\phi} W\right)} = \gamma + \epsilon\, \Omega\left(e^{-\phi} W Y^{\epsilon}\right). \tag{16}$$

As Equations (16) and (13) show, the cost elasticity is the reciprocal of the scale elasticity. Equation (15) shows that the differences in firm-level IT cost shares stem either from variations in the effective IT prices $e^{-\phi} W$ or in scales of operation Y. In particular, firms facing higher effective IT prices or firms that operate at larger scales have higher IT cost shares. Equation (16) then implies that, all else equal, *larger firms operate at higher levels of cost elasticity and therefore at lower levels of returns to scale*. Moreover, it shows that *the availability of IT lowers the cost elasticity and therefore raises the returns to scale for all firms.*

The above results have important implications for the connection between IT, labor share, and industry concentration. Under the assumption of perfect factor markets, factor prices equal marginal products and cost minimization holds. With CES demand and monopolistic competition, firms charge a constant markup of $\frac{\lambda}{\lambda-1}$. This implies that the ratio of firm revenues to variable

[32]Note, however, that in the empirical section we relax these assumptions to allow for inflexibility of capital and hardware inputs. In that case, the equality between the IT weight and the IT cost share does *not* hold.

[33]Note that, if $\gamma < 1$, Equation (16) implies a minimum efficient scale given by the level of output Y satisfying $\Omega = (1-\gamma)/\epsilon$.

factor payments is proportional to the firm's cost elasticity:

$$\frac{R}{C} = \frac{PY}{X_N + WX_I} = \frac{\frac{\lambda}{\lambda-1}\mathcal{C}'(Y)\times Y}{\mathcal{C}(Y)} = \frac{\lambda}{\lambda-1}\mathcal{E} = \frac{\lambda}{\lambda-1}(\gamma+\epsilon\Omega). \tag{17}$$

This simple equality allows us to translate the variations in cost elasticity to variations in the share of labor in the income of the firm. Despite the fact that all firms charge the same markups, Equation (17) implies that the share of all factors, including labor, in the income of firms falls with cost elasticity. First, as we saw above, firm-level cost elasticity is linear in the IT cost share, which in turn grows in firm scale due to nonhomotheticity. Second, a fall in IT prices reduces the cost elasticity, raising the share of all factors, including labor, in the income of firms. Lastly, it is straightforward to see that the fall in IT prices disproportionately reduces the costs of larger firms that are more IT intensive, leading to a rise in industry concentration.

Discussion The core theoretical mechanism in the paper is that the nonhomotheticity of factor demand implies the endogeneity of firm-level returns to scale and its heterogeneity across firms. In the context of our nhCES production function, Equations (13) and (16) show that the nonhomotheticity of the production function generates a dependence of scale and cost elasticities on firm size. However, this result is more general than the case of nhCES production functions. Importantly, we show in Appendix C.2 that the insight generalizes beyond the current specification, in the sense that it *locally holds for all production functions that satisfy nonhomothetic factor demand.* In other words, once we establish the nonhomotheticity of factor demand, it immediately follows that returns to scale should vary across firms as a function of firm size.

We should emphasize that the account of the relation between IT and returns to scale implied by production function in Equation (9) has a close conceptual connection to a model involving a fixed-cost of IT adoption. Appendix C.4 lays out a simple model in which adopting IT raises productivity subject to a fixed cost in units of the bundle of non-IT inputs. This model generates both the nonhomothetic IT demand and the negative relationship between size and scale elasticity. This result is in line with the generalized result mentioned above (Appendix C.2) that locally links nonhomothetic IT demand with the relationship between firm size and scale elasticity under any specification of the production function.

Despite the generality of the mechanism, our nhCES specification is particularly well suited, compared to alternatives such as the fixed-cost model, for a quantitative account of the patterns observed in the data. Consider the results of Table 8 in Appendix B that show a robust correlation between software intensity and firm size across different brackets of firm size. This finding suggests a specification of relative IT demand along the lines of Equation (6) with a value of η that is relatively constant as firm scale changes. The nhCES production function predicts exactly this pattern with $\eta = (1-\sigma)\epsilon$. In contrast, as the derivations in Section C.4 illustrate, the corresponding elasticity in the case of the fixed-cost model falls with the scale of firm output and converges to zero as firm size grows.

3.3 General Equilibrium

Having studied the properties of the nhCES production function, we now turn to the characterization of the general equilibrium of the model. For the purpose of this analysis, we study the stationary equilibria along which aggregate variables, including total output Y, price index P, mass of firms N, and the relative price of IT W are all constant. We henceforth drop the time indices to simplify the notation wherever it is clear from the context that the time dimension does not play a crucial role.

3.3.1 Stationary Equilibrium

Allocations Across Firms Let us first consider the problem of a firm with productivity state $\boldsymbol{\vartheta}_i \equiv (\theta_i, \phi_i)$ that decides to produce along a stationary equilibrium in which the relative price of IT is W. As usual, monopolistic competition and CES aggregation imply that the firm faces the demand $Y_i = Y(P_i/P)^{-\lambda}$ where the aggregate CES price index for consumers is given by $P = \left(\int_{i\in\mathcal{I}} P_i^{1-\lambda} di\right)^{\frac{1}{1-\lambda}}$. Therefore, as mentioned in the derivation of Equation (17), the firm prices its output at constant markup $\frac{\lambda}{\lambda-1}$ over its marginal cost. From Lemma 1, we know that the variable cost of the firm satisfies $C_i = e^{-\theta_i}\mathcal{C}\left(Y_i; e^{-\phi_i}W\right)$ and Equation (16) allows us to write the marginal cost of the firm.

The following lemma characterizes the firm's choice of output and price.

Lemma 2. *Assume that the elasticity of IT demand with respect to output is positive, i.e., $\eta = \epsilon(1-\sigma) > 0$, that model parameters $(\gamma, \epsilon, \sigma, \lambda)$ satisfy $\gamma > 1 - 1/\lambda$, and that, if $1 < \sigma$, the additional constraint $\sigma < 1 + \frac{4}{\epsilon}\left(\gamma + \epsilon - 1 + \frac{1}{\lambda}\right)\left(1 + \frac{\gamma}{\epsilon}\right)$ holds. The optimal output $\widetilde{Y}(\boldsymbol{\vartheta}_i)$ of a firm with productivity pair $\boldsymbol{\vartheta}_i \equiv (\theta_i, \phi_i)$ is the unique solution to the following equation*

$$Y_i^{\frac{1}{\zeta}} = \frac{\lambda - 1}{\lambda} P Y^{\frac{1}{\lambda}} \Psi\left(e^{-\phi_i} W Y_i^{\epsilon}\right) e^{\theta_i}, \tag{18}$$

where we have defined the composite parameter $\zeta \equiv \frac{\lambda}{1+\lambda(\gamma-1)}$ and the function:

$$\Psi\left(e^{-\phi_i} W Y_i^{\epsilon}\right) \equiv \frac{\left[1 - \Omega\left(e^{-\phi_i} W Y_i^{\epsilon}\right)\right]^{\frac{1}{1-\sigma}}}{\mathcal{E}\left(e^{-\phi_i} W Y_i^{\epsilon}\right)}, \tag{19}$$

with $\Omega(\cdot)$ and $\mathcal{E}(\cdot)$ following Equations (15) and (16). The optimal output Y_i and the corresponding optimal price $\widetilde{P}(\boldsymbol{\vartheta}_i) = P\left(\widetilde{Y}(\boldsymbol{\vartheta}_i)/Y\right)^{-1/\lambda}$ defined by Equation (18) are monotonically increasing and decreasing, respectively, in each of the two firm productivity states θ_i and ϕ_i.[34]

Under the conditions stated in the lemma, the solution to the firm problem is unique and has the same intuitive characteristics as those of the standard models of monopolistic competition (Melitz, 2003).[35] More productive firms charge lower prices and produce larger quantities of output, earn higher revenues, and hire more workers. Equation (18) further shows how the presence of nonhomotheticity impacts the optimal firm sizes across firms through function $\Psi(\cdot)$. The expression in the numerator of function $\Psi(\cdot)$ captures differences in average cost across firms showing that, for given level of factor-symmetric productivity θ_i, output declines with the IT cost share.[36] The term in the denominator of function $\Psi(\cdot)$ captures the effect of variations in cost elasticity: as the IT cost share rises, marginal cost grows relative to average cost, leading to a further decline in output.

Given a tuple of aggregate variables (P, Y, W, N), Equation (18) determines the allocations of output $\widetilde{Y}(\boldsymbol{\vartheta})$ and price $\widetilde{P}(\boldsymbol{\vartheta})$. We can then define functions that characterize the cost share and cost elasticity of a firm with productivity pair $\boldsymbol{\vartheta}_i$ as $\Omega_i = \widetilde{\Omega}(\boldsymbol{\vartheta}_i) \equiv \Omega\left(e^{-\phi_i} W \widetilde{Y}(\boldsymbol{\vartheta}_i)^{\epsilon}\right)$ and $\mathcal{E}_i = \widetilde{\mathcal{E}}(\boldsymbol{\vartheta}_i) \equiv \mathcal{E}\left(e^{-\phi_i} W \widetilde{Y}(\boldsymbol{\vartheta}_i)^{\epsilon}\right)$. Similarly, we can define a function $\widetilde{\Psi}(\boldsymbol{\vartheta})$ from Equation (19) as well as revenue $\widetilde{R}(\boldsymbol{\vartheta}) \equiv \widetilde{P}(\boldsymbol{\vartheta})\widetilde{Y}(\boldsymbol{\vartheta})$ and variable cost function $\widetilde{C}(\boldsymbol{\vartheta})$ from Equation (11). With these allocations at hand, it is straightforward to characterize the value function of firms, the set $\mathcal{J}$ of productivity states of active firms $\mathcal{J} \equiv \left\{\boldsymbol{\vartheta} \,|\, \widetilde{R}(\boldsymbol{\vartheta}) - \widetilde{C}(\boldsymbol{\vartheta}) \geq \psi\right\}$, and the pdf $g(\boldsymbol{\vartheta})$ of the stationary distribution of productivities among active firms. To close the model, we need to clear all markets and apply a free entry condition to pin down the aggregate variables (P, Y, W, N). The steps involved are standard and we relegate the discussion to the online appendix.[37]

The following corollary of Lemma 2 characterizes the distribution of revenues and (variable) factor payments across firms.

Corollary 1. *Let $\overline{R} \equiv PY/N$ and $\overline{C}$ stand for mean revenue and mean variable factor payment across*

[34]See the proof of this lemma and the next corollary in Section 1.2 of the online appendix.

[35]Imposing the upper bound on the elasticity of substitution between IT and non-IT inputs ensures the convexity of the cost function. Lemma 1.1 in the online appendix characterizes the the elasticity of the marginal cost function with respect to the size of output Y. It shows that the convexity of the cost function rises (falls) with the variance of the IT share Ω if $\sigma < 1$ $(1 < \sigma)$. When $\sigma < 1$, the conditions $\gamma > 1$ and $\epsilon > 0$ are sufficient to ensure that the marginal cost always exceeds average costs and the cost function is globally convex. When $\sigma > 1$, the cost function may not in general remain globally convex, even if the scale elasticity parameter satisfies $\gamma > 1$.

[36]Note that from Equations (11) and (15), we have $\mathcal{C}\left(Y; e^{-\phi} W\right) = Y^{\gamma}\left[1 - \Omega\left(e^{-\phi} W Y^{\epsilon}\right)\right]^{\frac{1}{\sigma-1}}$.

[37]Section 1.1 of the online appendix sets up the two fixed point problems that determine the distribution g and the value function $V(\boldsymbol{\vartheta})$ of the firms, given the functions above and the Markov process for productivity states. Definition 1.1 in Section 1.1 of the appendix lays out the conditions characterizing the stationary general equilibrium.

firms, and define the aggregate productivity $\overline{Z}$ *as*

$$\overline{Z} \equiv \left[\int\int_{\mathcal{J}} \left(\widetilde{\Psi}(\boldsymbol{\vartheta}) e^{\theta}\right)^{\gamma\zeta-1} g(\boldsymbol{\vartheta})\, d^2\boldsymbol{\vartheta}\right]^{\frac{1}{\gamma\zeta-1}}. \tag{20}$$

Then, the distribution densities of revenue and (variable) factor payments $\Lambda_R(\boldsymbol{\vartheta}) \equiv \widetilde{R}(\boldsymbol{\vartheta})\, g(\boldsymbol{\vartheta}) / \overline{R}$ *and* $\Lambda_C(\boldsymbol{\vartheta}) \equiv \widetilde{C}(\boldsymbol{\vartheta})\, g(\boldsymbol{\vartheta}) / \overline{C}$ *across firms satisfy*

$$\Lambda_R(\boldsymbol{\vartheta}) = \left(\frac{\widetilde{\Psi}(\boldsymbol{\vartheta}) e^{\theta}}{\overline{Z}}\right)^{\gamma\zeta-1} g(\boldsymbol{\vartheta}), \qquad \Lambda_C(\boldsymbol{\vartheta}) = \frac{\overline{\mathcal{E}}}{\widetilde{\mathcal{E}}(\boldsymbol{\vartheta})} \Lambda_R(\boldsymbol{\vartheta}), \tag{21}$$

where the aggregate cost elasticity $\overline{\mathcal{E}}$ *is defined as*

$$\overline{\mathcal{E}} \equiv \int\int_{\mathcal{J}} \widetilde{\mathcal{E}}(\boldsymbol{\vartheta}) \Lambda_C(\boldsymbol{\vartheta})\, d^2\boldsymbol{\vartheta} = \left[\int\int_{\mathcal{J}} \widetilde{\mathcal{E}}(\boldsymbol{\vartheta})^{-1} \Lambda_R(\boldsymbol{\vartheta})\, d^2\boldsymbol{\vartheta}\right]^{-1}. \tag{22}$$

Moreover, the ratio of revenues to (variable) factor payments satisfies $\frac{\overline{R}}{\overline{C}} = \frac{\lambda}{\lambda-1}\overline{\mathcal{E}}$.

The corollary shows that the elasticity of market shares with respect to factor symmetric productivity e^{θ}, for a constant level of IT cost share $\widetilde{\Omega}(\boldsymbol{\vartheta})$, is given by $\gamma\zeta - 1 \equiv \frac{\lambda-1}{1+\lambda(\gamma-1)}$. More importantly, in line with Equation (17), we find that the micro wedge between the share of a firm in aggregate revenues and its share in aggregate (variable) factor payments is proportional to the cost elasticity $\widetilde{\mathcal{E}}(\boldsymbol{\vartheta})$. We also find that the macro wedge between aggregate revenues PY and aggregate variable factor payments $N\overline{C}$ is the *aggregate cost elasticity*, i.e., the factor-payment-weighted mean of cost elasticities across firms. Finally, Equation (16) implies that the aggregate cost elasticity is linear *aggregate IT cost share* $\overline{\Omega}$*, i.e.*, the factor-payment-weighted mean IT cost share $\overline{\Omega}$:

$$\overline{\mathcal{E}} = \gamma + \epsilon\overline{\Omega} \equiv \gamma + \epsilon \int\int_{\mathcal{J}} \widetilde{\Omega}(\boldsymbol{\vartheta}) \Lambda_C(\boldsymbol{\vartheta})\, d^2\boldsymbol{\vartheta}. \tag{23}$$

Micro Predictions: Cross Sectional Relationships Let us examine the cross-sectional relationships between firm size, IT intensity, and labor share under the stationary distribution g. First, consider the regression coefficient of log ratio of IT to (variable) non-IT inputs on log firm size (Figure 3):

$$\frac{Cov\left(\log\left(\frac{\widetilde{\Omega}(\boldsymbol{\vartheta})}{1-\widetilde{\Omega}(\boldsymbol{\vartheta})}\right), \log\widetilde{Y}(\boldsymbol{\vartheta})\right)}{Var\left(\log\widetilde{Y}(\boldsymbol{\vartheta})\right)} = (1-\sigma)\epsilon - (1-\sigma)\frac{Cov\left(\phi, \log\widetilde{Y}(\boldsymbol{\vartheta})\right)}{Var\left(\log\widetilde{Y}(\boldsymbol{\vartheta})\right)}, \tag{24}$$

where the covariances and the variance are defined under the distribution g. This expression shows that the positive correlation between IT intensity and firm size that we documented in Section 2 can be driven by two potential mechanisms: 1) the nonhomotheticity in IT factor demand, $\eta = (1-\sigma)\epsilon > 0$, or 2) a negative correlation between IT biased productivity ϕ_i and size $\log Y_i$. In Section 4, we develop a micro-level estimation strategy to separate these two potential channels and identify the parameters ϵ and σ.

Next, consider the relationship between labor share and firm size in Figure 4. The labor share of the firm satisfies

$$LS_i \equiv \frac{W_{L,i}L_i}{P_i Y_i} = (1-\alpha)\frac{\lambda-1}{\lambda}\frac{1-\Omega_i+\frac{\psi}{\Omega_i}}{\gamma+\epsilon\Omega_i}, \tag{25}$$

in which, just like Equation (14), the cost elasticity $\mathcal{E}_i = \gamma+\epsilon\Omega_i$ appears in the denominator. Then, a regression of labor share on log size yields the coefficient

$$Cov\left(\widetilde{LS}(\vartheta), \log\widetilde{Y}(\vartheta)\right) \approx -\frac{1-\alpha}{\gamma}\frac{1-\lambda}{\lambda}\left(1+\frac{\epsilon}{\gamma}\right) Cov\left(\widetilde{\Omega}(\vartheta), \log\widetilde{Y}(\vartheta)\right),$$

where we have again abstracted away from the fixed costs ψ and have additionally used the approximation $\widetilde{\Omega}(\vartheta) \ll 1$. Given the positive correlation between IT share and size in Equation (24), the expression above predicts a negative relationship between labor share and firm size in the cross section. A larger share of IT in income implies a factor substitution away from labor and a lower labor share of income. In addition, nonhomotheticity of factor demand in the case of $\epsilon > 0$ implies that the relationship between labor share and firm size is going to be stronger compared to the homothetic case by a factor of ϵ/γ.

3.3.2 Aggregation

The stationary general equilibrium of the model defines the aggregate output Y of the economy as a function of the aggregate stocks $\overline{X}_I$ of IT and $\overline{X}_N$ of non-IT inputs. We can show that the aggregate output Y and price P satisfy

$$Y^\gamma = N^{\frac{1}{\gamma\xi-1}}\left(\frac{\gamma+\epsilon\overline{\Omega}}{1-\overline{\Omega}+\psi/\overline{C}}\right)\overline{Z}\,\overline{X}_N^{prod}, \qquad P = \frac{\lambda}{\lambda-1}Y^{\gamma-1}N^{-\frac{1}{\gamma\zeta-1}}\overline{Z}^{-1}, \tag{26}$$

where $\overline{X}_N^{prod}$ denotes the total non-IT inputs deployed in the production sector, and aggregate productivity $\overline{Z}$, aggregate IT cost share $\overline{\Omega}$, and mean variable factor payment $\overline{C}$ are defined as in

Corollary 1.[38]

We can show that the aggregate profit to cost ratio in the production sector is given by $\frac{1}{1+\psi/\overline{C}}\frac{\lambda}{\lambda-1}\overline{\mathcal{E}}-1$, and that the labor share in the production sector satisfies:[39]

$$LS^{prod} = (1-\alpha)\frac{\lambda-1}{\lambda}\frac{1-\overline{\Omega}+\frac{\psi}{\overline{C}}}{\gamma+\epsilon\overline{\Omega}}. \tag{27}$$

Equation (27) is the aggregate parallel to Equation (25), and allows us to draw intuitions about the drivers of aggregate profit and labor shares. As we saw in Corollary 1, the profit share depends on the aggregate cost elasticity $\overline{\mathcal{E}} = \gamma + \epsilon\overline{\Omega}$. When the IT cost share and the aggregate cost elasticity rise, the returns to scale and the share of factor payments in aggregate income fall. As we can see in Equation (27), this further leads to a fall in the aggregate labor share. This channel is in addition to the standard substitution channel due to the shift of income from non-IT to IT inputs.[40]

Response to the Fall in IT Prices and the Aggregate Elasticity of Substitution Next, we examine the comparative statics of factor income shares with respect to a change in the relative IT price W. Let $dw \equiv d\log W$ and consider the comparative statics of the aggregate IT cost share $d\overline{\Omega}/dw$. From Equation (27), we can write the response of the labor share of income in the production sector to a small IT shock as

$$\frac{1}{1-\alpha}\frac{\lambda}{\lambda-1}\frac{d\log LS^{prod}}{dw} \approx -\frac{\gamma+\epsilon}{\left(\gamma+\epsilon\overline{\Omega}\right)^2}\frac{d\overline{\Omega}}{dw} \approx -\frac{1}{\gamma}\left(1+\frac{\epsilon}{\gamma}\right)\frac{d\overline{\Omega}}{dw}, \tag{28}$$

where the first and second approximations follow the assumptions that fixed costs are small relative to the average variable costs ($\psi/\overline{C} \ll 1$), and that the aggregate IT cost share is small ($\overline{\Omega} \ll 1$), respectively. As with the benchmark model with homothetic CES production functions ($\epsilon = 0$), the substitution between IT and non-IT inputs implies that the labor share moves in the opposite direction of the response of aggregate IT cost share $d\overline{\Omega}/dw$. As we saw above, the presence of nonhomotheticity ($\epsilon > 0$) introduces the additional *endogenous response of returns to scale*, which

[38] See the derivations of these results, as well as the Equation (27) below and an expression for the mass of active firms N, in Section 1.3.1 of the online appendix.

[39] We focus on the labor share in the production sector since it is the natural parallel to what we observe in the data. Alternatively, we can assume that the costs of entry are paid in units of a final good, which is produced by competitive firms according to the aggregator in Equation (2) and is used both for final good consumption and for the costs of entry. In this case, the labor share in the production sector corresponds to the aggregate labor share in the model.

[40] Since we assumed fixed operation costs are paid in labor and capital, the expressions above also depend on the ratio of fixed to average variable costs $\psi/\overline{C}$, which we expect to be negligible in typical calibrations of the model. We can make the alternative assumption that the aggregator in Equation (2) corresponds to a final good producer, the output of which used both for final good consumption and for the fixed operation costs. Under such a model, the term $\psi/\overline{C}$ drops out of Equation (27).

creates an additional shift in the share of all factor payments in aggregate income. This channel is captured through the response in the aggregate cost elasticity $\overline{\mathcal{E}} \equiv \gamma + \epsilon \overline{\Omega}$ in the denominator of Equation (27) and the additional term ϵ/γ in Equation (28). For a given response in the IT cost share $d\overline{\Omega}/dw$, our model predicts a larger fall in the aggregate labor share in the production sector.

We note that the response of the aggregate IT cost share, $d\overline{\Omega}/dw$ is tied to the *aggregate elasticity of substitution* between IT and variable non-IT factors in production. Defining the aggregate elasticity as $\overline{\sigma} \equiv d \log\left(\frac{1-\overline{\Omega}}{\overline{\Omega}}\right)/dw$, we find that:

$$\frac{d\overline{\Omega}}{dw} = \overline{\Omega}\left(1-\overline{\Omega}\right)\left(1-\overline{\sigma}\right). \tag{29}$$

Equations (29) and (28) together show that if the aggregate elasticity of substiuttion $\overline{\sigma}$ exceeds unity, a fall in the price of IT lowers the share of labor in factor payments (e.g., Karabarbounis and Neiman, 2014; Eden and Gaggl, 2018).

In addition to the relation between aggregate labor and aggregate IT cost shares in Equation (28), the presence of nonhomotheticity also affects the aggregate elasticity of substitution $\overline{\sigma}$ and the response $d\overline{\Omega}/dw$. As is well-known, and also emphasized by several recent papers (e.g., Oberfield and Raval, 2014; Baqaee and Farhi, 2018), the heterogeneity in factor intensities across firms creates a gap between the micro (σ) and macro ($\overline{\sigma}$) elasticities of substitution. A change in factor prices not only induces each firm to adjust its factor intensity, but also reallocates factors toward firms that are more or less intensive in that factor. We can decompose the response of the IT cost share into within-firm and across-firm effects as

$$\frac{d\overline{\Omega}}{dw} = \underbrace{\int\int \frac{d\widetilde{\Omega}(\boldsymbol{\vartheta})}{dw}\Lambda_C(\boldsymbol{\vartheta})\, d^2\boldsymbol{\vartheta}}_{\text{Within-firm Effect}} + \underbrace{\int\int \widetilde{\Omega}(\boldsymbol{\vartheta})\frac{d\Lambda_C(\boldsymbol{\vartheta})}{dw} d^2\boldsymbol{\vartheta}}_{\text{Across-firm Effect}}, \tag{30}$$

where $\Lambda_C(\boldsymbol{\vartheta})$ is the density of factor payment shares defined by Equation (21). Appendix C.5 characterizes the within and across firms components of the response of the IT cost share in Equation (30), and compares the components against a benchmark model with homothetic CES production functions.[41] Unlike the benchmark CES model, in presence of nonhomotheticity computing $d\overline{\Omega}/dw$ requires solving the full general equilibrium model. For this reason, Section 5 below studies the effect of nonhomotheticity on the decomposition of Equation (30) for a calibration of the model to the French economy. We find that nonhomotheticity substantially strengthens the across-firm effect, raising the macro elasticity of substitution $\overline{\sigma}$ to around unity. This number is compatible with the stability of the aggregate labor share in France (Figure 5b) and much larger

[41] In the appendix, we also present a simplified partial equilibrium analysis that illustrates the main effects of nonhomotheticity on the response of the aggregate IT cost share $d\overline{\Omega}/dw$.

than our estimated micro elasticity σ.

4 Estimation

In this section, we identify the parameters of the production function of Section 3.2 in the micro data, and provide structural evidence for the nonhomotheticity of the IT demand.

4.1 Estimation Strategy

To construct our estimation strategy, we first revisit the environment that a panel of firms faces in our model. We then proceed to derive specifications that characterize the relationship between observables, the production function parameters, and unobserved productivity states, *independently of all other model parameters*. Finally, we discuss the identification assumptions that allow us to estimate the parameters and present the estimation equations implied by them.

Our approach to identification builds on the literature on production function estimation and particularly relies on dynamic panel methods (see, e.g., Blundell and Bond, 2000; Ackerberg et al., 2015; Ackerberg, 2016). The strategy involves imposing a Markov assumption on the productivity shocks, and using lagged inputs decisions as instruments for current decisions while controlling for the persistence in productivity shocks. Since we have two dimensions of unobserved productivity, we derive corresponding equations for each based on our model. We additionally include shift-share instruments for local wages to help identify the elasticity of substitution between IT and non-IT inputs. Our main estimating equations are equations (37) and (38) below, which state the orthogonality of productivity innovations with lagged firm decisions and the shift-share instruments.

Environment As in Section 3, the relationship between labor, capital, software, and hardware of the firm to its output is given by $Y_{it} = \mathcal{F}\left(e^{\theta_{it}} K_{it}^{\alpha} L_{it}^{1-\alpha}, e^{\theta_{it}+\phi_{it}} S_{it}^{\beta} H_{it}^{1-\beta}\right)$, where function $\mathcal{F}(\cdot,\cdot)$ is the nhCES function defined in Equation (9). The production function is fully characterized by the tuple of parameters $\varsigma \equiv (\epsilon, \sigma, \gamma, \alpha, \beta)$, which we aim to estimate, and the pair of unobserved productivity states $\boldsymbol{\vartheta}_{it} \equiv (\theta_{it}, \phi_{it})$.

In order to bring the model to the micro data, we relax and modify a few assumptions made in the aggregative model of Section 3. First, we modify our frictionless account of the factor markets to allow for potential frictions in some of the factors.

Assumption 1. *The factor markets satisfy the following conditions:*

1. *Hardware and non-IT capital may involve adjustment costs and other firm-level distortions.*

2. *Labor is a flexible input with perfect local markets.*

3. *Software is a flexible input with a perfect national market.*

The first part allows firms to face adjustment costs and other potential firm-level distortions, e.g., those stemming from financial constraints, when investing in hardware and non-IT capital. The second part assumes that firms operate in perfectly competitive, local labor markets, which allows for variations in firm-level wages in the cross-section of locations. In practice, depending on the location n of the headquarter of a given firm i, we use a measure of average wage at the corresponding local employment area to construct a location-specific wage $W_{L,nt}$.[42] Software remains the only factor with a frictionless and national market with a price $W_{S,t}$.[43]

In addition, we allow for a potential time-trend in the evolution of the productivity states in Equation (7). More specifically, we assume the AR(1) structure $\boldsymbol{\vartheta}_{it} = \boldsymbol{\mu}_t\left(\boldsymbol{\vartheta}_{it-1}; \boldsymbol{\rho}\right) + \boldsymbol{u}_{it}$, where productivity innovations $\boldsymbol{u}_{it} \equiv \left(u_{\theta,it}, u_{\phi,it}\right)'$ are zero-mean and the conditional expectation of the productivity states are given by:

$$\boldsymbol{\mu}_t\left(\boldsymbol{\vartheta}_{it-1}; \boldsymbol{\rho}\right) \equiv \begin{pmatrix} \rho_{\theta\theta} & \rho_{\theta\phi} \\ \rho_{\phi\theta} & \rho_{\phi\phi} \end{pmatrix} \boldsymbol{\vartheta}_{it-1} + \begin{pmatrix} \eta_\theta + \mu_\theta t \\ \eta_\phi + \mu_\phi t \end{pmatrix}. \tag{31}$$

The vector $\left(\mu_\theta, \mu_\phi\right)'$ captures the trend in mean industry productivity over time, and the tuple $\boldsymbol{\rho} \equiv \left(\rho_{\theta\theta}, \rho_{\theta\phi}, \rho_{\phi\theta}, \rho_{\phi\phi}, \eta_\theta, \eta_\phi, \mu_\theta, \mu_\phi\right)$ includes all parameters of the Markov process.

Model Specification Let us now derive equations that relate the parameters of the production function and the productivity states to the observables, namely, the input choices and the output of each firm, in our panel of firms. Of course, the production function provides us with exactly one such relationship. Rewriting Equation (9) in terms of the logarithms of firm inputs and outputs, we find

$$\gamma y_{it} = \frac{\sigma}{\sigma - 1} \log\left[e^{\frac{\sigma-1}{\sigma}(\alpha k_{it} + (1-\alpha) l_{it})} + e^{\frac{\sigma-1}{\sigma}(\beta s_{it} + (1-\beta) h_{it} + \phi_{it} - \epsilon y_{it})} \right] + \theta_{it}, \tag{32}$$

[42] As discussed below, we rely on the observed regional variations in wages as part of our strategy for the identification of the elasticity of substitution parameter σ. See Appendix A.4 for further details on the construction of our measures of local wages.

[43] This assumption creates the question of how firms may disinvest in software to lower their stocks of software capital. First, note that software faces a high depreciation rate (the number is 31% in our analysis based on the data from the series provided by the French National Statistical Institute). Therefore, lack of investment activity makes substantial downward adjustments in the stock of software. In addition, we observe a strong negative trend in the user cost of software during the period under out study, implying that firms generally tend to raise their stocks of software capital in the absence of strong IT-biased productivity shocks.

where we have introduced lower case letters to denote the logarithm of each corresponding variable, e.g., $y_{it} \equiv \log Y_{it}$.

The expression (32) provides a nonlinear parallel to the linear or quadratic specifications that appear under standard production functions such as Cobb-Douglas or Translog (see, e.g., Ackerberg et al., 2015). The factor symmetric productivity state θ_{it} is linearly additive in the same fashion as the standard Hicks-neutral unobserved productivity under the standard production functions.[44] The key difference with the standard case is that here we have an additional source of unobserved heterogeneity in the IT -biased productivity ϕ_{it} that nonlinearly interacts both with output and observed input choices of the firm on the right hand side of Equation (32).

We next derive an additional relationship between the IT-biased productivity ϕ_{it}, the observed data, and the parameters of the production function. This allows us to substitute for the term involving ϕ_{it} in Equation (32) and arrive at an expression relating factor-symmetric productivity state θ_{it} to data and other parameters.[45] The following lemma leverages Assumption 1 to set up the dynamic problem of the firm, and establishes the desired relationship based on within-period cost minimization.

Lemma 3. *Under Assumption 1 and under general forms of adjustment costs and other frictions for non-IT capital and hardware, the firm's choices of inputs in each period satisfy*

$$s_{it} - l_{it} = -\sigma\left(w_{S,t} - w_{L,nt}\right) + (1-\sigma)\epsilon y_{it} + (1-\sigma)[\alpha(k_{it} - l_{it}) - (1-\beta)(h_{it} - s_{it})] + (\sigma - 1)\phi_{it}, \tag{33}$$

where $w_{S,t} - w_{L,nt}$ is the (location-specific) price of software relative to wages.[46]

The idea behind this lemma is simple. Since Assumption 1 maintains two flexible inputs, labor in the non-IT and software in the IT bundle, the relative prices of the two inputs and their respective marginal products are equalized. This allows us to write the variations in the software intensity of labor across firms as a function of four potential sources. First, firms may face different (log) prices of software relative to wages $w_{S,t} - w_{L,nt}$, e.g., since they locate in regions with different wages. Depending on relative prices, they may substitute toward or away from software with elasticity σ. Second, firms of different sizes vary in their software intensity due to nonhomotheticity with elasticity $\eta = (1-\sigma)\epsilon$. Third, firms with different (log) capital-to-labor ratios $k_{it} - l_{it}$ and hardware-to-software ratios $h_{it} - s_{it}$ have different intensities.[47] Fourth, firms with different levels

[44]Note that in the definition of the production function in Equation (9) e^{θ} is a factor-symmetric but *not* a Hicks-Neutral productivity. The production function satisfies the *almost-homogeneous* property in the terminology of Sato (1977), in the sense that it satisfies $\mathcal{F}(Z^{\gamma}X_N, Z^{\gamma+\epsilon}X_I) = Z\,\mathcal{F}(X_N, X_I)$, everywhere. This equality shows that a Hicks-Neutral productivity term is *not* symmetric with respect to IT and non-IT inputs, unless if $\epsilon = 0$.

[45]For another recent example of this approach applied to the estimation of a CES production function, see Doraszelski and Jaumandreu (2013).

[46]See the proof in Section 1.2 of the online appendix.

[47]Note that this result also poses a challenge for potential alternative reduced-form identification strategies relying

of IT-biased productivity have varying degrees of software intensities. This last relationship allows us to infer IT-biased productivity ϕ_{it} from observed data and model parameters.

The lemma generalizes the static cost minimization results of the previous section (Equation 10) to accommodate potential firm-level distortions in hardware and non-IT capital input choices. When all factors are frictionless, capital-to-labor and hardware-to-software ratios are equalized across firms within a given location.[48] In the presence of distortions to the firms' choices of hardware and non-IT capital, the two ratios vary across firms even within a given location. The variations in these ratios correspond to the differences that distortions generate across firms in the *shadow* relative capital-to-labor and hardware-to-software prices, respectively. This is why the effect of these ratios in Equation (8) on the (log) ratio labor intensity of software $s_{it}-l_{it}$ also depends on the elasticity of substitution σ.[49]

Crucially, Equation (33) allows us to write the IT-biased productivity ϕ_{it} in terms of the observables and model parameters. Substituting this expression for ϕ_{it} in Equation (32) then allows us to write output in terms of observables, model parameters, and the factor symmetric productivity θ_{it}. Let $\boldsymbol{d}_{it} \equiv \left(w_{S,t}, w_{L,nt}, l_{it}, k_{it}, s_{it}, h_{it}, y_{it}\right)$ denote the vector of all relevant data observations for firm $i \in \mathcal{J}_{nt}$ in location n at time t. Now, Equations (32) and (33) together yield expressions for log output y_{it} and log software stock s_{it} as functions of observables and model parameters $(\boldsymbol{d}_{it};\varsigma)$ with linearly additive factor-symmetric θ_{it} and IT-biased productivity ϕ_{it} states, respectively. Defining the vector of log output and software stock of the firm $\boldsymbol{y}_{it} \equiv (y_{it}, s_{it})'$, we can therefore combine the two equations in vector form as:

$$\boldsymbol{y}_{it} = \boldsymbol{f}(\boldsymbol{d}_{it};\varsigma) + \tilde{\boldsymbol{\vartheta}}_{it}, \tag{34}$$

where the vector of two functions $\boldsymbol{f}(\boldsymbol{d}_{it};\varsigma) \equiv \left(f_y(\boldsymbol{d}_{it};\varsigma), f_s(\boldsymbol{d}_{it};\varsigma)\right)'$ follow from Equations (32) and (33) and the additive term is a vector of scaled productivity states $\tilde{\boldsymbol{\vartheta}}_{it} \equiv (\theta_{it}/\gamma, (\sigma-1)\phi_{it})'$. It is straightforward to see that the evolution of the vector of scaled productivity states also follows an AR(1) model satisfying $\tilde{\boldsymbol{\vartheta}}_{it} = \tilde{\boldsymbol{\mu}}_t\left(\tilde{\boldsymbol{\vartheta}}_{it-1};\boldsymbol{\rho},\varsigma\right) + \tilde{\boldsymbol{u}}_{it}$ where $\tilde{\boldsymbol{u}}_{it} \equiv \left(u_{\theta,it}/\gamma, (\sigma-1)u_{\phi,it}\right)'$ is the corresponding vector of scaled productivity innovations.[50]

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solely on demand shocks as potential instruments for output y_{it} in Equation (33). Since output y_{it} may have an impact on capital-to-labor and hardware-to-software ratios, due potentially to adjustment costs or financial constraints, Equation (33) shows that we additionally need instruments for the latter two ratios to identify ϵ. See Section 4.8 of the online appendix for more details.

[48] Cobb Douglas aggregators of the two bundles of non-IT and IT inputs imply that the optimal relative capital-to-labor and hardware-to-software ratios satisfy $K_{it}/L_{it} = \alpha/(1-\alpha) \times W_{L,nt}/W_{K,t}$ and $H_{it}/S_{it} = (1-\beta)/\beta \times W_{S,t}/W_{H,t}$, and are constant across firms within a given location. Combining these expressions with the cost minimization Equation (10) and the definition of relative factor prices in Equation (8) yields the Equation (33).

[49] One key consequence of this point is that the variations in capital-to-labor and hardware-to-software ratios help in the identification of the elasticity of substitution σ based on Equation (33). As we will see below, the variations in these ratios are instrumented by their corresponding lagged values in a model-consistent way.

[50] Section 1.3.2 of the online appendix provides the explicit expressions defining functions $f_y(\cdot;\varsigma)$, $f_s(\cdot;\varsigma)$, and

Identification Problem Equation (34) expresses log output and log software stock in terms of data $\boldsymbol{d}_{it}$, model parameters $\boldsymbol{\varsigma}$, and scaled unobserved productivity states $\tilde{\boldsymbol{\vartheta}}_{it}$. To identify the model parameters, we need instruments for the data $\boldsymbol{d}_{it}$ that are uncorrelated with the productivity states $\boldsymbol{\vartheta}_{it}$ and their scaled transformation $\tilde{\boldsymbol{\vartheta}}_{it}$. More specifically, we need instruments for the four factor inputs $(l_{it}, k_{it}, s_{it}, h_{it})$ and the relative price of software $w_{S,t} - w_{L,nt}$.[51]

To best leverage the comprehensiveness of our data, we ideally seek instruments that can be constructed for a broad set of firms in our sample. The literature on production function estimation provides us with a natural framework to derive instruments for factor inputs within our model with few additional assumptions or constraints on data. We follow this literature and rely on a number of assumptions on the dynamics and timing of firm decision making that allow us to employ the lagged input choices of the firms as instruments (see, e.g., Blundell and Bond, 2000; Ackerberg et al., 2015; Ackerberg, 2016).

Before presenting our approach, let us first emphasize that lagged firm input choices do not readily provide valid instruments for data $\boldsymbol{d}_{it}$ in Equation (34), as they may correlate with the scaled productivity states $\tilde{\boldsymbol{\vartheta}}_{it}$. Optimal firm behavior implies that lagged input choices of the firm are functions of lagged productivity states, which in turn influence current productivity states due to persistence. To see this, we can substitute for the evolution of the scaled productivity states in Equation (34) to find:

$$\boldsymbol{y}_{it} = \boldsymbol{f}(\boldsymbol{d}_{it}; \boldsymbol{\varsigma}) + \tilde{\boldsymbol{\mu}}_t\left(\boldsymbol{y}_{it-1} - \boldsymbol{f}\left(\boldsymbol{d}_{it-1}; \boldsymbol{\varsigma}\right); \boldsymbol{\rho}, \boldsymbol{\varsigma}\right) + \tilde{\boldsymbol{u}}_{it}, \tag{35}$$

where, as before, $\tilde{\boldsymbol{\mu}}_t$ is the conditional expectation function for $\tilde{\boldsymbol{\vartheta}}_{it}$ and where we have additionally used the lagged version of Equation (34) to substitute $\tilde{\boldsymbol{\vartheta}}_{it-1} = \boldsymbol{y}_{it-1} - \boldsymbol{f}\left(\boldsymbol{d}_{it-1}; \boldsymbol{\varsigma}\right)$. The term involving $\tilde{\boldsymbol{\mu}}_t$ constitutes a part of the residual in Equation (34) and is likely to be correlated with lagged input choices.

Nevertheless, Equation (35) resolves the main concern with using lagged firm inputs as instruments since it explicitly controls for their potential correlation with the current productivity states. All we need is to ensure that lagged input choices are uncorrelated with current productivity inno-

$\tilde{\boldsymbol{\mu}}_t(\cdot; \boldsymbol{\rho}, \boldsymbol{\varsigma})$.

[51] As a naive approach, for instance, one can use current vector of input choices and the current price of software relative to wages as instruments for the observables $\boldsymbol{d}_{it}$. However, it is well-known that under most models of optimal firm behavior, the current input choices are correlated with unobserved productivity states. In particular, the proof of Lemma 3 shows that each of the firm input choices can be written as a function of the current productivity states $\boldsymbol{\vartheta}_{it}$, the lags of the inflexible inputs, i.e., non-IT capital k_{it-1} and hardware h_{it-1}, as well as a state variable τ_{it} that characterizes the potential distortions to the choices of the firm with respect to these two inputs, e.g., $l_{it} = \tilde{l}\left(\boldsymbol{\vartheta}_{it}; k_{it-1}, h_{it-1}, \tau_{it}\right)$.

On the other hand, using the current price of software relative to wages as an instrument for itself raises an empirical concern. Recall that Assumption 1 implies that the cross-regional variations in the price of software relative to wages are driven by the cross-sectional variations in wages. We may worry that the variations in wages may systematically be correlated with the variations in the IT-biased productivity across regions.

vations $\tilde{\boldsymbol{u}}_{it}$. Therefore, it provides an alternative estimation equation consistent with our model. The following assumption formally introduces the conditions that allow us to use lagged input choices of the firm, as well as the vector of lagged productivity states $\tilde{\boldsymbol{\vartheta}}_{it-1} = \boldsymbol{y}_{it-1} - \boldsymbol{f}\left(\boldsymbol{d}_{it-1};\varsigma\right)$, as valid instruments for data $\boldsymbol{d}_{it}$ in Equation (35).[52]

Assumption 2. *Let $\mathcal{I}_{it}$ denote the information set of the firm i at time t, which includes the paths of all observables up to time t.*

1. *We have $\boldsymbol{\vartheta}_{it} \in \mathcal{I}_{it}$ and all choices of the firm at time t only depend on its information set $\mathcal{I}_{it}$.*[53]
2. *The evolution of the productivity states satisfies the Markov structure in Equations (7) and (31) with the additional condition that $\mathbb{E}\left[\boldsymbol{u}_{it}|\mathcal{I}_{it-1}\right] = \mathbf{0}$.*

The key part of Assumption 2 is the condition $\mathbb{E}\left[\boldsymbol{u}_{it}|\mathcal{I}_{it-1}\right] = \mathbf{0}$, which implies that the productivity innovations are mean zero conditional on the lagged information set of the firm, which includes all its lagged input choices. This condition holds for the dynamic problem of the firm that we have considered in Lemma 3. It also holds more generally for any dynamic settings in which the firm does not have any information about future productivity innovations above and beyond that revealed by current productivity states.

Finally, to construct a valid instrument for the price of software relative to wages, we borrow from Oberfield and Raval (2014) and construct shift-share instruments z_{it} for local wages faced by each firm. This instrument is constructed by interacting the *initial* industrial composition of each location with the time evolution of each industry's wage bill at the national level. We expect wages to rise relatively more in locations in which employment was initially concentrated in those industries that witness higher demand shocks at the national level.[54] The following assumption formally introduces the identification assumption behind our shift-share instrument.[55]

[52]Section 4.1 of the online appendix illustrates the logic of the identification strategy using a 2SLS analogy. We note a key simplification of our approach relative to the benchmark approach to production function estimation (e.g., Olley and Pakes, 1996; Levinsohn and Petrin, 2003) that requires an additional proxy variable to estimate lagged productivity. In the current context, the benchmark method would assume that log output is measured with additive error e_{it} such that $y_{it} = f_y\left(\boldsymbol{d}_{it};\varsigma\right) + \tilde{\theta}_{it} + e_{it}$. Under this assumption, $y_{it-1} - f_y\left(\boldsymbol{d}_{it-1};\varsigma\right)$ does not constitute a valid instrument in Equation (35) since it includes the additive error. In out setting, we abstract away from such additive error. Empirically, for the special case of a Cobb-Douglas production function we observed that applying the benchmark proxy variable methods yield estimates in our data similar to those of our method, which abstracts from such measurement error.

[53]Note that based on the accumulation equation that we have used to construct the stocks of capital (Equation 40 in the appendix), the firm's choices at time t include its investment choices within that period, which is in turn within the information set of the firm at time t.

[54]Following Bartik (1991), a vast empirical literature has relied on shift-share instruments such as that used here to construct exogenous variations in wages at the regional level. For recent contributions to the analysis and design of these instruments in settings involving micro data, see Adao et al. (2019); Borusyak et al. (2018); Goldsmith-pinkham et al. (2018).

[55]See more details about the construction of the instrument in Section 2 of the online appendix.

Assumption 3. *Let ν_{nj0} denote the share of employment of region n in industry j in 1990, and let $\overline{L}_{jt}$ denote the share of the industry in the national wage bill. Define the instrument z_{nt} for region n at time t as*

$$z_{nt} \equiv \sum_{j} \nu_{nj0} \times \log \overline{L}_{jt}. \tag{36}$$

Then for each firm $i \in \mathcal{J}_{nt}$, we assume that the innovation to the IT-biased productivity at time t is mean zero conditional on the value of instrument z_{nt}, that is, $\mathbb{E}\left[u_{\phi,it}|z_{nt}\right] = 0$.

Note that Assumption 3 is weaker than those required in the standard applications of the shift-share instruments. In particular, we require the instrument to be uncorrelated with the innovations to the IT-biased productivity state, rather than with the unobserved productivity itself.

Estimation Equations Combining the identification Assumptions 2 and 3, we can now construct the moment conditions that allow us to estimate the parameters of the production function and the Markov process. As before, let f_y and f_s stand for the components of the vector function $\boldsymbol{f} \equiv \left(f_y, f_s\right)'$, defined as in Equation (34), and $\tilde{\mu}_{\theta,t}$ and $\tilde{\mu}_{\phi,t}$ for the components of the conditional expectation of the scaled productivity $\tilde{\boldsymbol{\mu}}_t \equiv \left(\tilde{\mu}_{\theta,t}, \tilde{\mu}_{\phi,t}\right)'$. We consider the following moment conditions:

$$\mathbb{E}\left[\left(y_{it} - f_y(\boldsymbol{d}_{it};\varsigma) - \tilde{\mu}_{\theta,t}\left(\boldsymbol{y}_{it-1} - \boldsymbol{f}\left(\boldsymbol{d}_{it-1};\varsigma\right);\boldsymbol{\rho},\varsigma\right)\right) \times z_{it}^{y}\right] = 0, \tag{37}$$

$$\mathbb{E}\left[\left(s_{it} - f_s(\boldsymbol{d}_{it};\varsigma) - \tilde{\mu}_{\phi,t}\left(\boldsymbol{y}_{it-1} - \boldsymbol{f}\left(\boldsymbol{d}_{it-1};\varsigma\right);\boldsymbol{\rho},\varsigma\right)\right) \times z_{it}^{s}\right] = 0, \tag{38}$$

where we have 8 instruments z_{it}^{y} for the log output and 8 instruments z_{it}^{s} for the log software stock:

$$z_{it}^{y} \in \left\{l_{it-1}, k_{it-1}, s_{it-1}, h_{it-1}, y_{it-1} - f_y\left(\boldsymbol{d}_{it-1};\varsigma\right), s_{it-1} - f_s\left(\boldsymbol{d}_{it-1};\varsigma\right), 1, t\right\},$$
$$z_{it}^{s} \in \left\{z_{nt}, k_{it-1} - l_{it-1}, s_{it-1} - h_{it-1}, y_{it-1} - f_y\left(\boldsymbol{d}_{it-1};\varsigma\right), s_{it-1} - f_s\left(\boldsymbol{d}_{it-1};\varsigma\right), 1, t\right\},$$

where z_{nt} is the shift-share instrument defined in Equation (36) for location n that hosts firm i. We use the system of moment conditions (37) and (38) to estimate the production function in a nonlinear GMM framework.

4.2 Estimation Results

Table 2 presents the estimated parameters of the production function for the pooled sample of all industries (the first three columns from left) and for the sample of all manufacturing firms (the three columns from right).[56] For each sample, the table compares the estimated values of parameters under nhCES (the first column) with two standard production functions nested in our model: a homothetic CES production function (second column), when we restrict the nonhomotheticity parameter to $\epsilon = 0$, and a Cobb-Douglas production function (third column), when we additionally assume $\sigma = 1$. In the Cobb-Douglas case, the cost minimization equation does not deliver any information for the estimation and we drop it from the framework, which leads us to a standard dynamic-panel production function estimation with four inputs: non-IT capital, labor, software, and hardware.[57]

Table 2: Estimation Results

		All Industries			Manufacturing		
		Nonhomothetic CES	CES	Cobb-Douglas	Nonhomothetic CES	CES	Cobb-Douglas
IT Nonhomotheticity	ϵ	0.389			0.477		
		(0.011)			(0.019)		
Elasticity of substitution	σ	0.225	0.125		0.171	0.165	
		(0.012)	(0.016)		(0.009)	(0.013)	
Cost elasticity	γ	0.947	0.978	1.001	0.954	1.014	1.022
		(0.004)	(0.004)	(0.004)	(0.006)	(0.005)	(0.006)
Capital elasticity	α	0.074	0.068	0.070	0.182	0.166	0.167
		(0.005)	(0.005)	(0.005)	(0.009)	(0.008)	(0.008)
Software elasticity	β	0.113	0.185	0.015	0.120	0.148	0.303
		(0.029)	(0.023)	(0.038)	(0.034)	(0.028)	(0.042)
Observations	N	302318	302318	307227	145966	145966	147471

Note: Results of the estimation procedure for the pooled sample of all firms in (columns 1-3), and for the pooled sample of manufacturing firms (columns 4-6). Standard errors are reported in brackets. Columns 2 and 5 present the estimated model parameters for a CES production function (where ϵ is constrained to be 0). Columns 3 and 6 present the estimated model parameters for a Cobb-Douglas production function (where σ is additionally constrained to be 1).

Let us begin with our core parameter of interest ϵ, presented in the first row of Table 2. We find precise, significant, and sizable positive estimates for this parameter in the two samples of firms ($\epsilon = 0.39$ for all industries and $\epsilon = 0.48$ in manufacturing). We can reject the homotheticity of the production function. The second row of the table presents the estimated elasticities of substitution. In both samples, we find values for the elasticity of substitution that are below unity ($\sigma = 0.23$ for all industries and $\sigma = 0.17$ in manufacturing), implying gross complementar-

[56] Table 3 in the online appendix also reports the parameters of the Markov process.

[57] See Section 4 in the online appendix for further details on the algorithm used for the estimation and for the schemes used for the estimation of the Cobb-Douglas and CES production functions.

ity between IT and non-IT inputs.[58] Even in the case of the homothetic CES, under the constraint $\epsilon = 0$, we still find that the estimated elasticity of substitution is below unity. The estimated values appear smaller relative to the nhCES specification in both samples of firms, which suggests that ignoring nonhomotheticity may result in a downward bias in our estimated values of the elasticities of substitution.

In all cases, the combination of the two estimated parameters ϵ and σ result in positive values for $\eta = (1-\sigma)\epsilon$, the elasticity of relative IT demand with respect to output in Equation (6). Recall also that Equation (24) shows how a positive correlation between IT intensity and firm size can be explained either through a positive elasticity $\eta = (1-\sigma)\epsilon$, or through a nonzero covariance between IT-biased productivity states ϕ_{it} and log firm size y_{it}. Therefore, our estimation results confirm that the nonhomotheticity of IT factor demand at least partially explains the positive correlations between IT intensity and size uncovered in Section 2.

The third row of Table 2 presents our estimated values for the cost elasticity parameter γ.[59] We find similar estimates for this parameter in both samples of firms ($\gamma \approx 0.95$). Recall from Equation (16) that the (variable) cost elasticity $\mathcal{E}_i$ for firm i satisfies $\mathcal{E}_i = \gamma + \epsilon\Omega_i$, where Ω_i corresponds to the IT cost share of the firm. Recall also that the elasticity $\mathcal{E}_i$ has an inverse relationship with the scale elasticity of the firm. Our estimated parameters for ϵ and σ already suggest a positive relationship between firm size and the IT cost share Ω_i. Therefore, an estimated value for γ below unity implies increasing returns to scale for the very small firms, for whom the IT cost share is negligible, i.e., $\Omega_i \approx 0$. Moreover, the combination of point estimates for γ and ϵ implies a positive (negative) relationship between firm size and cost elasticity (scale elasticity). In the sample of all industries, we find scale elasticities that range from 1.06 to 0.75 as we move from the smallest to the largest firms (the corresponding values are 1.05 to 0.70 for the sample of manufacturing firms). The smallest firms in the sample operate under increasing returns to scale, whereas the largest operate under decreasing returns to scale.

In contrast to the case of the nhCES production function, the scale elasticity is constant in the cross section of firms under both CES and Cobb-Douglas production functions. As we would expect, the estimated values of the cost elasticity parameter γ under these restricted models imply scale elasticities that fall between the two limits implied by the nhCES production function. In particular, we find numbers fairly close to constant return to scale (e.g., in the sample of all in-

[58] Oberfield and Raval (2014) and Doraszelski and Jaumandreu (2018) estimate the micro-level elasticity of substitution between capital and labor using identification strategies that account for potential factor-augmenting productivity shocks, and find values between 0.4 and 0.7. An earlier set of macroeconomic estimates find values slightly higher but still below unity (e.g., Antràs, 2004; Klump et al., 2007; Chirinko, 2008). We also note that Karabarbounis and Neiman (2014) use an estimation strategy that relies on the cross-sectional variations in the industry-level data and finds a value above 1.

[59] In the case of the Cobb-Douglas production function, this parameter corresponds to the reciprocal of the scale elasticity, which is found as the sum of all output elasticities of all four inputs.

dustries, 1.01 under CES and 1.00 under Cobb-Douglas), which is in line with most prior micro estimates of the returns to scale. Crucially, these constant estimates mask substantial heterogeneity in returns to scale across firms, as implied by the nhCES production function. As we will see in the next section, this heterogeneity generates rich implications for the response of the aggregate economy to shocks such as a fall in the price of IT factors.

Table 2 shows that the values of the elasticities of non-IT capital α and software β, in their respective aggregators for the bundles of non-IT and IT inputs, are precisely estimated. These values imply lower output elasticities for non-IT capital and software compared to labor and hardware, respectively. The estimates for the elasticity α is similar across the three production functions, and therefore appear fairly robust to misspecification. In contrast, the estimates for the elasticity β appear more sensitive to the specification. For instance, estimates for Cobb-Douglas are much larger (smaller) than those under the two CES specifications in the sample of all industries (manufacturing).[60]

Finally, we estimate parameters ϵ, σ and γ across 17 industries at the A38 level of the aggregated NAF classification. The estimated values of the parameter ϵ are positive and significant for most of the industries, estimated values of the parameter σ are never above 1, and estimated values of the cost elasticity parameter γ are generally close to 1 across industries. The results are reported in Figure 6 of the online appendix.

5 Implications for Macro Trends in France

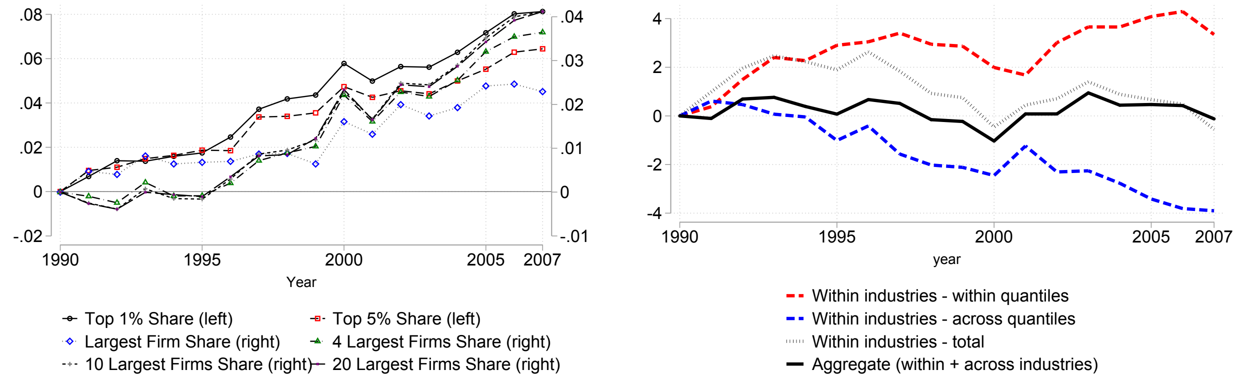
In this section, we study the implications of our model for explaining a number of recent macroeconomic trends in France in response to the fall in the relative price of IT presented in Figure 1. We begin by using our data to revisit a number of trends that have been recently uncovered about the evolution of industry concentration and labor share in the US and across other OECD countries (Andrews et al., 2016; Autor et al., 2020; Kehrig and Vincent, 2018; Berlingieri et al., 2017), in the context of the French economy. We then present the results of a calibration of the general equilibrium model of Section 3.3 to investigate its quantitative implications for 1) the micro facts in Section 2.2 and 2) the macroeconomic trends documented here in response to fall in relative IT prices.

[60] Note that the parameters α and β are distinct from the output elasticities of non-IT capital and software in the overall production function. Table 23 in the online appendix reports the output elasticities of each of the four factors in the case of the Cobb-Douglas production function.

Figure 5: Macro Trends in France

(a) Rise in Concentration

(b) Labor Share



Note: Panel (a) presents the evolution of the sales-weighted averages (across 3-digits industries) of the cumulative change in concentration, measured as the share in total industry sales of the largest 1%, 5% , 1, 4, 10 or 20 firms. Panel (b) presents the cumulative change in the total labor share, as well as the decomposition of this change to within and across-firm components (at the level of 2-digit industries).

5.1 Macro Trends in France

We first examine the trends in a number of indices of market concentration in France from 1990 to 2007 on the BRN + RSI sample that includes all tax paying firms. We compute for each 3-digit industry the share of total industry sales accounted for by the top 1%, top 5%, the largest, the top 4 largest, the top 10 largest, and the top 20 largest firms within the industry. We then average these measures across all industries, weighting industries by their share in total sales. Figure 5a shows that the top 1% and 5% shares increased by around 8.1 and 6.4 percentage points on average across industries, while the shares of the top 1, 4, 10, and 20 largest firms increased by 2.3 to 4.1 percentage points.[61]

Second, we look at the evolution of the labor share in France within the same period.[62] Figure 5b shows the cumulative change in the aggregate wage bill (including payroll taxes) as a share of

[61]The initial value of the weighted averages of the top 1% and 5% share measures across industries in 1990 are 43.4% and 65.0%, respectively. The corresponding numbers for the shares of the top 1, 4, 10, and 20 largest firms range from 14.0% to 41.3% in that year.

[62]Table 1 reports the unweighted average value of labor share (across firms). It is fairly high and around 74%, similar between manufacturing and non-manufacturing, and does not show strong skewness (since mean and median values are fairly close). Still, the data also suggests substantial heterogeneity in labor share across firms, with a standard deviation of around 34 percentage points in the entire sample. In the next section, we will explore the extent to which the variations in labor share (within industry) are driven by variations in firm size. Figure 7 in the online appendix reports the aggregate labor share in our data, defined as the value-added-weighted average labor share, compared to the aggregate labor share in the corporate sector in France reported by INSEE. We find an average aggregate labor share that is stable around 66% in our data, close to the macroeconomic data value of 64%. Differences are attributable to sectoral composition effects, as the macroeconomic data includes the real estate, finance, and agriculture sectors that our data does not cover. Sectoral data for the corporate sector only (excluding sole proprietorship firms) is not made public by INSEE.

Table 3: Calibrated Parameters

Model Component	Parameter		Value	
Production Function	IT nonhomotheticity	ϵ	0.39	Estimated
	Cost Elasticity Parameter	γ	0.95	Estimated
	Elasticity of substitution	σ	0.22	Estimated
	Fixed Costs	ψ	0.08	Search
Productivity Process	Persistence of Shocks	$(\rho_{\theta\theta}, \rho_{\phi\phi})$	(0.83, 0.90)	Estimated
	Long-run Mean Productivities	(η_θ, η_ϕ)	(0.59, 0.68)	Estimated
	Variances of Innovations	$(\varkappa_\theta^2, \varkappa_\phi^2)$	(0.09, 0.48)	Estimation
Entry & Exit	Distribution of Entry	$(\xi_o, \overline{\theta}_o)$	(2.82, 8.12)	Estimation
		$\varkappa_o^2$	2.10	Estimation
		$\underline{\theta}_o$	2.17	Search
		$\overline{\phi}_o$	6.13	Search
	Costs of Entry	χ	0.08	Calibrated
	Exogenous Probability of Exit	δ	0.03	Calibrated
Demand	Elasticity of Substitution	λ	5.00	Calibrated
	Discount Factor	ϱ	0.95	Calibrated

Note: The calibrated and estimated parameters of the model and the source of information used for each parameter. For details, see Appendix D.

aggregate value added for our sample of all BRN and RSI firms. In addition, it shows the contribution to this change of a within-industry (as opposed to cross-industry) component, when we keep industry shares of total value added constant from one period to the next. Over the course of the entire period, the aggregate labor share and the within-industry component have not substantially fallen in our data, with the former remaining around 66% of value added.

Following the strategy used recently by Kehrig and Vincent (2018) for the US data, we further decompose the average within-industry changes in labor share into that stemming from, first, the shifts in the industry's distribution of firm-level labor shares (keeping shares of firm-level value added constant), and second, the within-industry reallocations in value-added shares of different quantiles of labor share.[63] Figure 5b presents the results of this decomposition and shows that, while for the typical firm the labor share increased by around 3.4 percentage points over the entire period (by 4.3 percentage points until 2006), the reallocations of market shares had a negative contribution of around -3.9 percentage points to the aggregate labor share.[64]

Our goal is to explain the above trends as the consequences of fall in IT prices. We construct

[63] Section 3.2 in the online appendix provides the full details of this decomposition exercise.

[64] Section 3 of the online appendix presents three additional facts on the evolution of the French economy within this period: 1) stability of the share of capital in aggregate income, 2) a gradual fall in the number of firms (per worker), and 3) a positive correlation between the fall in labor shares and the rise in concentration. We will return to these facts in Section 5.3 where we compare the predictions of our model with these additional trends.

the series for the relative price of IT as the ratio of the price of the bundle of IT inputs to the price of the bundle of non-IT inputs. To aggregate the price of each bundle, we rely on the macro data on average wages and the user costs of software, hardware, and non-IT capital, and use the estimated values of parameters (α, β) from Table 2.[65] The resulting series suggests a fall in the relative price of the bundle of IT inputs from an initial level of $W = 0.0203$ in the beginning of the 1990s to around $W' = 0.0075$ by 2007. As already discussed, our estimation uncovers negligible trends in IT-biased productivity over this period, and therefore we take our *IT shock* to be completely captured by the fall in the relative IT price. Correspondingly, we first calibrate the model at the initial level of relative IT price W, and subsequently examine the equilibrium at the new level of the relative price of IT corresponding to W'.

5.2 Model Calibration

The estimation results of Section 4 allow us to determine the values of most model parameters that characterize the production function or the heterogeneity in the productivity states within and across firms. Furthermore, they suggest the following functional form for the joint distribution of the productivity states of entrants:[66]

$$F(\theta, \phi) \equiv TrunPareto\left(e^{\theta}; \xi_o, \underline{\theta}_o, \overline{\theta}_o\right) \times \mathcal{N}\left(\phi; \overline{\phi}_o, \varkappa_o^2\right), \tag{39}$$

where the cumulative distribution function of the truncated Pareto distribution is given by $F(\theta) = \left(e^{-\xi_o \underline{\theta}_o} - e^{-\xi_o \theta}\right) / \left(e^{-\xi_o \underline{\theta}_o} - e^{-\xi_o \overline{\theta}_o}\right)$, and IT-biased productivity state ϕ has a normal distribution with mean $\overline{\phi}_o$ and variance $\varkappa_o^2$. Appendix D provides the details of our calibration strategy, which leads to the model parameters reported in Table 3. The table indicates the parameters directly estimated in Section 4 as "Estimated," those that are indirectly implied by the estimation results as "Estimation," and those calibrated based on the values common in the prior work as "Calibrated." We determine the values of the remaining parameters using a simple parameter search targeting the aggregate IT intensity and two measures of industry concentration observed in the data.

Table 4 presents the data moments used in the calibration and their model counterparts. For each moment, the table also indicates the corresponding model parameters that have been cali-

[65] See Section 2.5 of the online appendix for a discussion of the construction of the relative price of IT based on the series reported in the French national accounts. We note that the size of the fall in the IT prices that we used here is substantially lower than the values reported in recent work that attempts to improve IT price indices by on properly adjusting for quality improvements (see, e.g., Byrne and Corrado, 2017). Since we partially rely on other macro values reported by INSEE, we choose to also rely on their series for the prices of IT inputs for consistency.

[66] Figures 18-21 in the online appendix display the distributions of θ and ϕ for entrants implied by the results of our estimation in the previous section. In particular, we provide evidence that the distribution of the factor-symmetric productivity θ among entrants has a Pareto tail. In contrast, the distribution for ϕ appears best described by a normal distribution.

Table 4: Calibrated Moments

	Moments	Source	Data	Model	Relevant Parameters
Targeted	Entrant Top %1 θ	EAE (Estimation)	3.46	3.80	ξ_o
	Entrant Top %0.1 θ	EAE (Estimation)	4.28	4.62	ξ_o
	Entrant Highest θ	EAE (Estimation)	8.12	8.12	$\overline{\theta}_o$
	Share of Top 1% of Firms in Sales	BRN+RSI	59.3%	59.9%	$(\psi, \underline{\theta}_o, \overline{\phi}_o)$
	Share of Top 5% of Firms in Sales	BRN+RSI	77.4%	77.0%	$(\psi, \underline{\theta}_o, \overline{\phi}_o)$
	Aggregate IT Intensity	INSEE	3.8%	3.8%	$(\psi, \underline{\theta}_o, \overline{\phi}_o)$
	Mass of Firms (N)	BRN+RSI	0.073	0.073	χ
	Rate of Exit of Large Firms	BRN+RSI	0.031	0.031	δ
Untargeted	Aggregate Labor Share	BRN+RSI	66.2%	65.8%	—
	Unweighted Mean of Labor Share	BRN+RSI	73.5%	73.4%	—
	Unweighted Mean of IT Intensity	EAE	0.2%	0.3%	—
	S.D. of Log Sales	BRN+RSI	1.4	1.3	—
	S.D. of Log Employment	BRN+RSI	1.2	1.3	—

Note: The targeted moments based on the data and the model. EAE source dataset refers to the sample of EAE firms, while EAE (Estimation) refers to the sample of EAE firms used in our estimation, *i.e.* with positive stocks of hardware and non-IT capital, value added, employment, and stocks of software larger than 10€. The three moments used for the calibration of $(\psi, \underline{\theta}_o, \overline{\phi}_o)$ are taken from BRN+RSI or INSEE data in 1995. All remaining moments use data from 1995 to 2007.

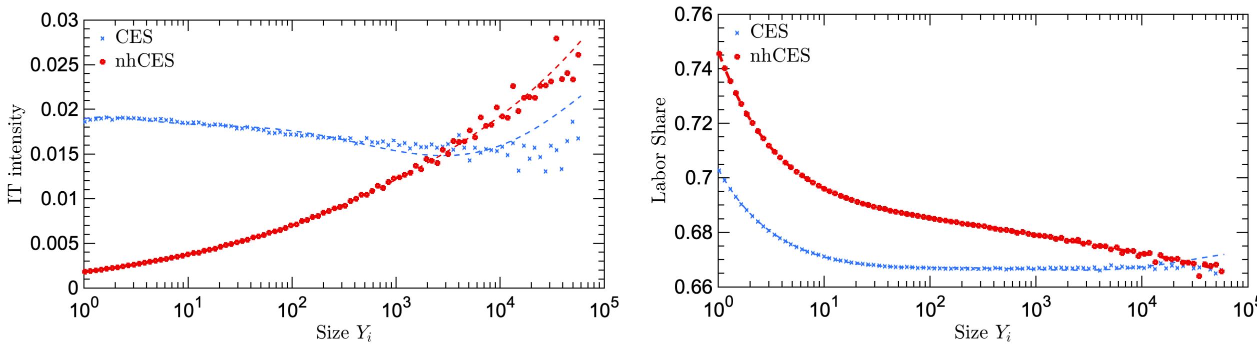
brated based on that moment. The model closely fits the values of all the moments based on the data. The table further provides a number of untargeted moments, including the aggregate labor share, the unweighted means of the distribution of labor share and IT intensity, and alternative measures of concentration, specifically, the standard deviations of the distributions of log sales and employment. The model further provides a reasonable fit for these untargeted moments.[67]

We follow the same procedure to calibrate an alternative model with a homothetic CES production function starting from the estimated parameters reported in the second column of Table 2 and setting $\epsilon = 0$.[68] Throughout, we compare the results of our model with the nhCES produc-

[67]To compute the value of labor share in Table 4 and throughout the rest of this section, we use the value $\alpha = 0.182$ for the capital intensity of the bundle of non-IT inputs estimated in the sample of manufacturing firms and reported in Table 2. As shown in Table 4, this value provides a close fit between the predictions of the model and the micro and macro data. If we instead use the reported estimate for the sample of all industries, i.e., the value $\alpha = 0.074$, the predicted labor share in the model uniformly shifts up by 13.2%, e.g., from the aggregate labor share of 65.8% reported in Table 4 to 74.49%. Note that the parameter α is not used in the calibration of the model and only becomes relevant for computing the predictions regarding labor share. Moreover, changing this value only changes a uniform multiplicative factor $(1-\alpha)$ in the predictions of labor share and otherwise does not bear on the within versus cross-firm predictions of the model.

[68]Tables 27 and 28 in the online appendix provide the calibrated parameters and the targeted and untargeted moments for the model with a CES production function.

Figure 6: Cross-sectional Relationship between Size and IT Intensity/Labor Share



(a) IT Intensity (b) Labor Share

Note: Binscatter plots of the relationship between firm size and (a) IT intensity and (b) labor share, in the cross-section of 10 million samples from the stationary distribution of the calibrated models with CES and nhCES production functions. Figures also present best 9-degree polynomial fits corresponding to each scatter plot.

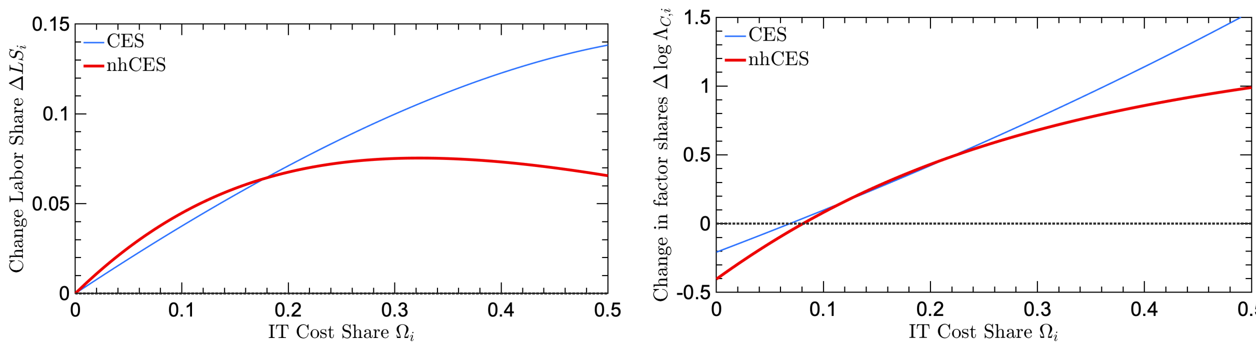
tion function against this benchmark to illustrate the consequences of nonhomotheticity in the production function for the model predictions.

5.3 Calibration Results

Cross-sectional Patterns Figure 6 shows how firm size varies with IT intensity of cost and labor share across firms in the model. In line with the facts we documented in Section 2.2.1, our model predicts a strong positive relationship between firm size and IT intensity. A regression of log IT intensity on log size in the model gives a coefficient of 0.330, which is closely in line with the corresponding estimates reported in panels 1 and 3 of Table 6 based on our micro data. In contrast, the benchmark model with homothetic CES production functions produces a small relationship between size and IT intensity.[69] Regarding the relationship between size and labor share, Figure 6b shows that the benchmark model does indeed predict a negative relationship between size and labor share across firms. This is driven by the fact that our model attributes all fixed costs to non-IT factors, and this fixed cost is relatively larger for smaller firms. However, the figure shows that this negative relationship is stronger in our model, due to the relationship between IT intensity and firm size already shown in Figure 6a. As we discussed at length in Section 3, higher IT intensity among larger firms implies both a higher profit share and a higher income share for IT inputs among these firms.

[69] Even if not discernible in Figure 6a, a regression of log IT intensity on log size in the benchmark model still produces a small positive coefficient. This positive relationship is driven by the selection channel: firms with higher factor-symmetric productivity θ can remain active with lower levels of ϕ. Since the elasticity of substitution is smaller than unity, this implies that large firms may on average have higher levels of IT cost share.

Figure 7: Heterogeneity in Responses to the IT Price Shock



(a) Response of Labor Share

(b) Response of Share in Factor Payments

Note: The change in the labor share LS_i and the share density of factor payments $\Lambda_{C,i}$ across firms with different initial levels of IT cost share Ω_i in response to the observed fall in the relative price of IT inputs.

Heterogeneity in Firm-Level Response to the IT Shock Figure 7 shows the responses of labor share and the shares of firms in factor payments to the IT shock as a function of the IT cost share Ω_i. As we saw before, the IT cost share summarizes all the relevant information for the response of the firm. Figure 7a compares the response of labor share among different firms between the model with nhCES production functions and the calibrated benchmark model with CES production functions. For firms with small IT cost shares, which constitute the vast majority of the firms in the calibrated model and in the data, the same IT shock generates a larger rise for labor share in our model. As we discussed in Section 3.3.2, this is due to the returns to scale channel introduced by nonhomotheticity: lower IT prices allow firms to adopt IT to raise their returns to scale, shifting income from profits to factor payments, and raising the labor share. However, the figure shows that this pattern reverses for firms with large IT cost shares. For these firms, the direct effect of nonhomotheticity highlighted in Equation (58) kicks in: since they gain market share and their outputs rise, they also choose to raise their IT intensity, shifting their income from labor to IT. Figure 7b compares the reallocations between the two models. As predicted by Equation (60), for firms with IT cost shares up to around 25%, which again constitute the vast majority of firms, the nhCES model predicts greater reallocations from firms with low IT cost shares to those with high IT cost shares.[70]

Aggregate Response Table 5 presents the response of aggregate variables to the IT shock in the calibrated model. For each aggregate variable, we compare the change observed in the data in the 1990-2007 period with the predicted change caused by the IT shock in our "nhCES" model. The table also presents the change predicted by a benchmark homothetic "CES" model to the same

[70]Figure 22 in the online appendix presents the responses of the IT cost share Ω_i, the cost elasticity $\mathcal{E}_i$, lot output $y_i \equiv \log Y_i$, and log revenues $\log(P_i Y_i)$.

Table 5: Calibration Results

Aggregate Variable		CES	nhCES	Data
Change in Price of IT	W	-63.1%	-63.1%	-63.1%
Change in Aggregate Output	Y	+3.7%	+5.8%	—
Change in Price Index	P	-5.4%	-6.9%	—
Change in Mass of Active Firms	N	+3.7%	-3.4%	-14.1%
Change in Share of Top 1% of Firms in Sales		+3.0 p.p.	+5.4 p.p.	+8.1 p.p.
Change in Share of Top 5% of Firms in Sales		+1.4 p.p.	+2.7 p.p.	+6.4 p.p.
Change in Labor Share (Production)	LS^{prod}	+0.6 p.p.	-0.0 p.p.	-0.0 p.p.
Within-Firm Contribution		+1.8 p.p.	+2.1 p.p.	+3.8 p.p.
Reallocation Contribution		-1.2 p.p.	-2.1 p.p.	-3.9 p.p.
Change in Profit Share (Production)		0	+0.0 p.p.	+0.2 p.p.
Aggregate Elasticity of Substitution	$\overline{\sigma}$	0.750	1.007	—

Note: The changes in different aggregate variables in the calibrated model with nhCES production functions, in the data (when the corresponding measure available), and in the calibrated benchmark model with homothetic CES production functions. p.p. stands for "percentage points." % changes are expressed relative to the respective baseline in each model and in the data.

IT shock.

The first four rows of the table show the main four aggregate variables of the model. In response to the fall in the price of IT, aggregate output rises by around 6% and the price index falls by around 7%.[71] Examining the same aggregate variables in the model with homothetic CES production function, we find a slightly smaller aggregate output response to the IT shock of around 4%. The difference between the aggregate responses in the two models stems from their different implications for returns to scale, which is endogenous in our model and is exogenous in the benchmark. The IT shock in our model raises the aggregate productivity by raising the returns to scale, especially among larger firms with higher levels of IT intensity.

Comparing the response of the mass of active firms N between the two models, we find diverging predictions: whereas our model predicts a *fall* of over 3% in the mass of active firms, the CES benchmark predicts a *rise*. In contrast with the benchmark model, our model's prediction is in line with the sizable fall observed in the data in the number of firms per worker, by over 14%, over the period.[72] The difference between the two models is driven by the fact that in our model the benefits of IT disproportionately accrue to large firms, due to the correlation patterns shown

[71]This result suggests that the fall in IT prices can explain around 20% of the rise in output per worker in France, which rose by around 29% between 1990 and 2007. We do not include this number in Table 5 since an important part of the rise in output per worker should be attributable to the aggregate productivity *growth*, which lies outside of our stationary model.

[72]For this result, we rely on the SIRENE dataset, which is distinct from the BRN and RSI datasets. Section 3 of the online appendix reports the evolution of the number of firms per worker in France, provides more details on the SIRENE dataset, and why we prefer this source for measuring the number of firms.

in Figure 6a. Entrants are on average smaller and therefore face stronger competition, leading to a shift in the allocation of non-IT inputs from the entry to the production sector.

Table 5 further presents the response of a number of other aggregate variables that relate to the macro facts in Section 5.1. The shares of top 1% and 5% of firms in total sales rise in the data rise by 8.1 and 6.4 percentage points, respectively (see Figure 5a). As we should expect based on Figures 7b and 6a, our model indeed predicts a sizable reallocation from small and low-IT intensity firms to large and high-IT intensity firms, leading to a rise in industry concentration. The rise in the two proxies of industry concentration in our model are 5.4 and 2.7 percentage points (66% and 42% of the observed rise in the data). The benchmark CES model also predicts a rise in concentration, but one that is quantitatively about half as large: 3.0 and 1.4 percentage points (37% and 21% of the observed rise in the data), respectively.

As we saw in Section 5.1, the data suggests that the stability of the aggregate labor share masks sizable compositional changes. Table 5 shows that a positive contribution of 3.8 percentage points from the within effect is accompanied by a negative contribution of 3.9 percentage points from the reallocation effect.[73] Our model also predicts a negligible response to the IT shock in the labor share of the production sector, along with a positive and negative contribution of around 2.1 percentage points from the within and across-firm effects, respectively (55% of the observed changes in the data). In contrast, the benchmark CES model predicts a reallocation effect of only 1.2 percentage points (30% of the fall in the data). Once again, accounting for nonhomotheticity results in a response to the IT shock that is around twice as large as that of the benchmark CES model.

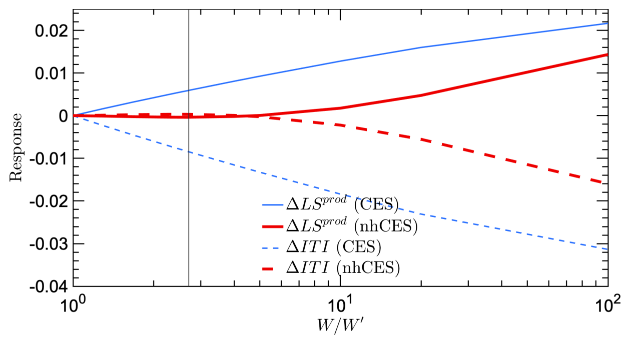
Table 5 also shows that data suggests a negligible change in the aggregate profit share. In the benchmark CES model, the aggregate profit share is exogenous. In our model, the aggregate profit share is endogenous but responds negligibly to the IT shock.[74]

Finally, we extend the analysis by studying the response of the model to IT shocks of different magnitudes. Figure 8 compares the responses to the shock examined in Figure 7 and Table 5 (indicated by the vertical dotted black line) with smaller or larger drops in the relative IT prices. As shown in Table 5, our model implies an aggregate elasticity of substitution $\overline{\sigma} = 1.007$, which is very close to 1 and much higher than the micro elasticity of $\sigma = 0.225$. The corresponding value under the benchmark CES model is substantially smaller ($\overline{\sigma} = 0.750$). As a result, Figure

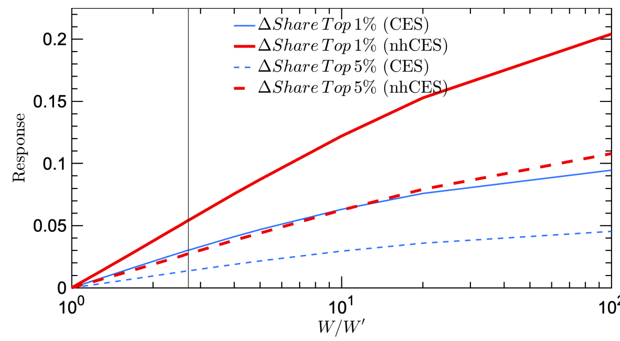
[73]Figure 5b shows that the within-firm component of the aggregate labor share shows a sizable drop of around 1 percentage point in the last year of our data, from 2006 to 2007. To avoid this confound, Table 5 reports the cumulative change from 1990 to the average between 2006 and 2007. The cumulative change in the within-firm component is 4.3 percentage points by 2006 and falls to 3.3 percentage point to 2007.

[74]By definition, the share of economic profits is 1 minus the sum of the labor and capital shares. Section 3 of the online appendix discusses how we construct our measures of capital share in the French economy that allows us to compute the aggregate profit share. As with the labor share, we also find the aggregate share of capital to be stable in the 1900-2007 period.

Figure 8: Aggregate Responses as a Function of the Size of IT Shock



(a) IT Intensity/Labor Share



(b) Concentration

8a shows that if the relative IT price fall by up to one order of magnitude from their baseline W, the model behaves close to a Cobb-Douglas aggregate production function. Thus, the aggregate labor share and IT intensity remain fairly stable. In contrast, the lower aggregate elasticity of substitution under the CES model implies that the labor share sharply rises and the IT intensity falls in response to such shocks. For stronger IT shocks, these variables begin to respond even in our model, but the magnitude of their responses remain smaller compared to that generated under the CES benchmark. Figure 8b compares the responses of market concentration, showing that the rise in concentration is monotonic and around twice larger in our model compared to the benchmark CES model.[75]

6 Conclusion

In this paper, we presented novel data on the investment and capital stocks of firms in software and hardware in the universe of French firms. In our data, we found that the intensity of IT demand strongly and robustly correlates with firm size, using a broad set of different measures of IT intensity and firm size. Moreover, we argued that a production function featuring nonhomotheticity of IT factor demand fits this empirical regularity, as well as an observed negative correlation between firm size and labor share. The latter holds assuming an elasticity of substitution between IT and non-IT inputs that falls below unity, and stems from lower degrees of returns to scale predicted by the model for larger firms.

We applied an identification strategy to estimate the production function and found that IT demand is indeed nonhomothetic and that the elasticity of substitution between IT and non-IT is below one. These results imply that the marginal product of IT, relative to the marginal product

[75] Figure 23 in the online appendix compares the responses of aggregate output and the mass of active firms, showing that these responses are also monotonic and broadly follow the same patterns discussed in the case of Table 5.

of non-IT inputs, grows in firm size. We further provided a simple theoretical general equilibrium model of industry dynamics to study the aggregate implications of the firm-level nonhomotheticity of the production function. In particular, we showed that the resulting model predicts, just as we find in the data, that the observed fall in the price of IT results in a reallocation of market shares across firms toward those firms with higher IT intensity and typically larger size and market shares.

In our framework, technological advances in information technology reduce the price of IT as a factor input and lead to strong productivity gains at both micro and macro levels. Despite the fact that they are biased toward larger firms and raise market concentration, markets allocate resources efficiently across productive units. In emphasizing the potentially efficient aspects of the recent trends, our paper contrasts with a number of recent contributions that instead focus on their potentially distortionary consequences (e.g., De Loecker et al., 2020; Baqaee and Farhi, 2020; Aghion et al., 2019). This line of work interprets the trends in market concentration and labor share through the lens of variations in markups and market power. In contrast, the current paper emphasizes the fact that these trends may in part stem from the nature of technological advances that lower the organizational costs of scale.

Nevertheless, these two accounts of the recent trends are not mutually exclusive. Consider, for instance, using an alternative demand aggregator such as Kimball preferences instead of the CES specification in Equation (2). This alternative specification allows for a monotonically increasing relationship between markups and relative firm size (see, e.g., Edmond et al., 2018). We can rely on the results of Section 5 to draw insights about the response of this modified model to the rise of IT within and across firms. There, we saw that with the fall in IT prices in our model, due in part to nonhomotheticity in IT demand, the relative output of large firms rise while the relative output of small firms falls. With endogenous markups, the within-firm response in markups becomes heterogeneous across firms, rising for large and falling for small firms.[76] In addition, the resulting cross-firm reallocations lead to a shift of market shares toward high-markup firms and away from low-markup firms. These patterns are in line with those documented by De Loecker et al. (2020).

Lastly, we note that our results may have implications for the current approaches to the estimation of markups and their variations across firms following De Loecker and Warzynski (2012). This approach relies on the estimation of output elasticities of a given variable input, e.g., labor in our setting, in order to infer markups. As emphasized recently by Demirer (2020), accounting for factor-augmenting productivity, IT biased productivity in our setting, is important to account for the endogenous variations in output elasticities. In our model, Equation (14) suggests that the output elasticity of labor is given by $(1-\alpha)\frac{1-\Omega_i}{\gamma+\epsilon\Omega_i}$, which is decreasing in IT cost share Ω_i and therefore

[76] We note, however, that the rise (fall) of markup among large (small) firms in turn curbs the first-order effect of the rise of IT on output. In other words, under preferences with variable price elasticities, the output of large (small) firms rises (falls) less than that under our benchmark with constant price elasticities.

firm size. To the extent that the presence of nonhomotheticity ($\epsilon > 0$) intensifies the negative relationship between size and the output elasticity of labor, it may weaken the relationship between size and the implied markup.

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A Data

In this section, we provide further details about the sources of data used and describe the procedure we use to merge our different data sources, to clean the resulting dataset of outliers, and to compute the firm level capital stock for each asset-type. We also discuss the construction of local wages and report some summary statistics of IT investment.

A.1 Sources of Micro Data

BRN and RSI are our two principal sources of data on firm activity in the universe of French firms. These administrative data are based on tax returns and are available starting 1984. They cover firms affiliated with the two main French tax regimes: BRN (*Bénéfice Réel Normal*) and RSI (*Régime Simplifié d'Imposition*). The BRN is the standard regime and the RSI is a simplified regime intended for small firms. Depending on their domain of activity, firms with revenues above a certain threshold must be affiliated with the BRN regime.[77] These data provide information on the firm's number of employees, sales, value added, total and tangible investment, year of creation, industry, and location. Information on the disaggregated components of firm investment by asset types, including hardware investment, is available in the BRN files starting in 1989. While we rely on the whole sample of RSI and BRN firms for our measures of concentration and aggregate labor shares, we restrict our analysis of capital and investment to firms that appear at least once in the BRN dataset.

The EAE (*Enquête Annuelle d'Entreprises*) is a survey-based dataset collected every year from 1982 to 2007. The survey is conducted separately for each broad sector of the French economy (trade, transport, construction, manufacturing & utility, agrifood, and services), with some variation in the list of questions asked and the sampling methods used. Overall, the data comprehensively covers medium and large firms, i.e., those with more than 20 employees, and surveys a sample of the smaller ones.[78] Starting in the 1990s, large firms are surveyed with a more comprehensive questionnaire that includes questions about software investment of firms.[79] In the EAE files, missing values for software investment are coded as 0. Most these missing values correspond to the smaller firms, surveyed with the simplified questionnaire which does not include information on investments. We adopt the following strategy to ensure that we distinguish actual zeros from missing data: we impute as missing software investment of firms that report 0 investment and whose employment and sales reported the previous year are below the threshold necessary to be fully surveyed.

We use two additional sources of data. We rely on the employee-level DADS data to find information on the number of plants and the organizational structure of the firm in terms of the occupational mix of employees. We also use the Customs data for information on the number of exported products and destination countries, as additional proxies for the scope of operation of firms.

A.2 Data Cleaning

We start with the BRN and RSI files from 1990 to 2007, in which we drop firms that have invalid SIREN using the cross-validation algorithm used to generate SIREN numbers. They correspond to firms whose self-reported SIREN

[77] In 2007, the thresholds were 763,000 euros if the firm operates in trade or real estate sectors, and 230,000 euros otherwise.

[78] The only exception is manufacturing & utility, in which only the large firms are surveyed.

[79] The criterion for inclusion is based on the employment size of the firm at the end of the previous year. This more comprehensive questionnaire has been applied in select sectors starting in 1989, and has been extended to all sectors starting in 1995. For more details on the criteria for coverage in EAE (as well as the other datasets used in the paper), see Section 2.2 in the online appendix.

identifiers do not match the SIREN identifiers recorded by INSEE. We then collapse observations that are not unique in terms of SIREN-year. They correspond to firms that appear in both BRN and RSI regimes in the same year. Finally we drop 382,854 observations for which we cannot build industry codes. We restrict our sample to firms that have one or more employees, and that report positive sales, value-added, and wage bill (including taxes on labor). This leaves us with 15,202,967 firm-year observations. We use these data (labelled "BRN+RSI") to compute the decomposition of labor shares, concentration and some calibration moments from Table 4.

Using the French unique firm identifier (SIREN), we are able to match the observations from BRN-RSI to observations included in the EAE. For the rest of the paper, we construct measures of capital stock using the procedure described below, restricting our sample to firms that appear at least once in the BRN files.[80] After the construction of capital stocks, initialized at the start of the year 1990, we discard the first five years of data. We then drop observations with negative values added (8.51% of observations), negative wage bill (34 observations), no employee (19.4 % of observations), book capital per employee relative to the industry average that is outside of the 99.99% probability range of a fitted distribution (0.28% of observations) and observations in the top 0.1% for total investment per employee. There are 6,166,342 firm-year observations from 1995 to 2007 in these data (labelled "BRN"), of which 2,435,356 firm-year observations correspond to firms also surveyed at least once by the EAE (labelled "EAE").[81]

BRN firms are broadly representative of the aggregate French economy: they account for 74.9% of private value-added and 81.9% of private employment.[82] Table 1 reports summary statistics on the three samples, BRN + RSI, BRN, and BRN restricted to EAE firms.

To compute our measures of firm scale, we then match with the observations in the DADS and Customs data. Of the 6,166,342 observations in our BRN sample, 5,692,230 are also in DADS, and 1,665,474 correspond to exporting firms. Some firms in the DADS and Customs data are not present in the BRN files. DADS covers all employers with salaried workers, so include non-profits, households as employers, and public employers. Matched DADS observations have on average 36 employees according to the DADS, against less than 10 employees for unmatched firms. Matched customs firms declare total exports of 3.1 million euros on average, against less than 1.7 million euros for unmatched customs firms.

Finally, in the estimation, we further restrict our sample to EAE firms with positive software, hardware, and non-IT capital, positive labor and value added, and for which the location of the firm's headquarter is known. These last restrictions bring the number of observations in our estimation sample to 302,318.

A.3 Building Measures of Capital Stock

To compute capital stock measures, we apply the Perpetual Inventory Method. For each asset-type j, firm i, and year t, we build capital stocks using the following recursive formula:

$$K_{j,i,t} = K_{j,i,t-1}(1-\delta_j) + \frac{I_{j,t}}{W_{j,t}}, \tag{40}$$

[80] RSI only firms have average sales of 102 thousands euros, against 3,848 thousands euros for firms that appear in the BRN files at least once.

[81] BRN firms that are never surveyed in EAE have average sales of 3,809 thousands euros, against 13,583 thousands euros for surveyed firms.

[82] Tables 6–8 in the online appendix present some summary statistics on the representativeness of the BRN dataset for the aggregate private sector of France, excluding agriculture, real estate, and finance.

where $W_{j,t}$ stands for the price deflator for asset-type j at time t, and δ_j for the depreciation rate in asset-type j. Below, we discuss how we initialize this recursive formula for each asset-type and for each firm. We also discuss where we obtain the information on price deflators and depreciation rates from. Total capital stock is the sum of all asset-types stocks, which allows us to fully take into account the heterogeneity of investment composition across firms instead of using a common price and depreciation rate.

There are 273,181 unique firms in the EAE sample, totaling more than 2 million observations. For 25% of those firms, we do not impute any software investment values as these firms are present in the BRN & EAE data every year from their first entry to their exit. Among the remaining firms whose software stocks include some imputed values, more than two third of imputed zeros correspond to firms that typically first appear as small firms in the RSI sample, then as larger firms in the BRN sample, and then large enough to be sampled in EAE. Before the first year in which they appear in the EAE data, these firms have wirtually zero software stock and those years are dropped from regressions of log software intensity or from the estimation sample. The remaining cases correspond to firms that are not systematically sampled in EAE even after the first year that they are sampled because they remain close to the threshold of size that determines which firms are exhaustively surveyed by EAE. Similarly, there are 855,492 unique firms in the BRN sample, totaling more than 6 million observations. For 75% of these firms, we do not impute any investment values for the hardware and other non-IT investment data as these firms are present in the BRN data every year from their first entry to their exit.

Imputed values are not used in the regressions corresponding to the IT "investment" intensity of hardware and software in Figure 2 and Table 6. Moreover, as we restrict our sample to larger firms in Table 8, the share of firms whose software stocks include some imputed zeros drops considerably: fewer than 1% of firms have more than one imputed zero. In our estimation sample, the 302,318 observations corresponds to the 64,698 firms that have positive values, hardware, and other non IT capital stocks, and stocks of software larger than 10 euros. For these firms, the imputation method impacts the stocks of the software, hardware, or non-IT capital only if the firm appears in the BRN or EAE data in year $t-1$ and $t+1$ but not in year t. In practice, this impacts fewer that 1% of the firms in the cases of hardware and non-IT capital stocks, and fewer than 10% of the firms in the case of software stock.

Initialization

We initialize the stock of each asset-type in 1989 ($t=0$) assuming first that in each of the 38 industries s for which aggregate data is available, the ratio of total investment to total stock in our sample is equal to the ratio of investment $\bar{I}^s_{j,0}$ to stock $\bar{K}^s_{j,0}$ in the aggregate data:[83]

$$\sum\nolimits_{i\in s} K_{j,i,0} = \frac{\sum_{i\in s} I_{j,i,0}}{\bar{I}^s_{j,0}} \times \bar{K}^s_{j,0}, \tag{41}$$

where $\frac{\sum_{i\in s} I_{j,i,0}}{\bar{I}^s_{j,0}}$ is typically below 1 (0.469 on average, see Section 2 of the online appendix). This allows us to construct an industry-level stock for our sample of firms. Then, we assume that the share of each firm in that industry-level stock is given by the share of the firm average investment across all years in that asset-type $I^m_{j,i,0}$ to the sum of the average investments in that asset-type of all firms in that industry. At year 0, the imputed value of the stock of asset j of firm

[83] The aggregate industry levels of stocks and investment are provided by INSEE at the 38 industries level. We use net values of capital at constant replacement cost, which already account for previous years capital depreciation. We report the resulting aggregate capital stocks by broad industries in the online appendix.

i in industry s is then given by:

$$K_{j,i,0} = \frac{I^m_{j,i,0}}{\sum_{i\in s} I^m_{j,i,0}} \times \frac{\sum_{i\in s} I_{j,i,0}}{\bar{I}^s_{j,0}} \times \bar{K}^s_{j,0}. \tag{42}$$

A.4 Measures of Local Wages

As we will discuss in Section 4, in our identification of the production function we rely on the series for the price of software relative to wages at the local level. The BRN and RSI files contain information about the municipality where the headquarters of the firm are located, as well as the 5-digits industry to which the firm belongs. We use this information to construct measures of average wages by 2-digits industry at the level of local employment area (*Zone d'emploi*).[84] We further rely on an instrument for the relative price of IT that follows the standard logic of Bartik (1991), relying on local variations on the industrial composition of employment. We compute an instrument capturing the predicted change in the labor demand in each employment area, based on the interaction of the initial composition of the wage bill in each employment area and the change in each industry's employment at the national level.

B Robustness of Facts

In this section, we provide additional results on the relationship between IT intensity and firm scale. We also provide more details on the reduced-form identification strategy to estimate the elasticity of relative IT demand to size.

B.1 Within-Industry Results

We examine the cross-sectional relationship between the scale of operation of the firm and the intensity of IT demand applying regressions of the form:

$$IT\,Intensity_{it} = \eta\, Size_{it} + FE_{k_{it}t} + FE_{a_{it}} + FE_{c_{it}} + \nu_{it}, \tag{43}$$

where $IT\,Intensity_{it}$ denotes a measure of the relative demand for IT inputs for a firm i in an industry k at time t, $Size_{it}$, denotes the a proxy of firm-i scale at time t, and $FE_{k_{it}t}$ stands for a flexible set of industry-time fixed effects (at the 3-digit level). In addition, we further add age $FE_{a_{it}}$ and cohort $FE_{c_{it}}$ dummies to control for potential patterns of IT adoption in some specifications.[85] Table 6 presents the results corresponding to the first three rows of Figure 3, as well as those for the levels of IT intensity measures in investment terms. Columns 3-4 and 7-8 show additional

[84] There are 364 employment areas, defined in 1990 as geographical units with more than 25,000 workers within which most of the workforce commutes. See the online appendix for details about the construction of local wages.

[85] It is well-known that one cannot jointly identify age, cohort, and year fixed effects due to their collinearity. For this exercise, we apply one of the normalizations suggested by Deaton (2018) and attribute the growth of the dependent variable to year and cohort effects. We then use the age effect to capture fluctuations in the dependent variable that average to zero over the life of the firm. In effect, this consists of rewriting the set of age dummies FE_a as $FE^*_a = FE_a - [(a-1)FE_{a=2} - (a-2)FE_{a=1}]$ and regressing (1) excluding all dummies corresponding to the first year, the first cohort, and ages 1 and 2. The results do not change with or without including theses cohort/age/year fixed effects.

Table 6: Regressions of Measures of IT Intensity on Log Firm Size

	IT Intensity of Labor				IT Intensity of Capital				IT Intensity of Cost	
	Workers	Workers	Wage Bill	Wage Bill	Total	Total	Tangible	Tangible	Costs	Costs
Panel 1 : Software (Stock)										
Size (proxied by sales)	0.3650		0.3115		0.2779		0.2842		0.2996	
	(0.0031)		(0.0031)		(0.0032)		(0.0032)		(0.0030)	
Size (proxied by VA)		0.3458		0.2933		0.2899		0.2980		0.2834
		(0.0033)		(0.0033)		(0.0034)		(0.0035)		(0.0033)
Observations	575,594	575,686	575,579	575,676	530,334	530,395	529,045	529,104	575,655	575,755
R2	0.2396	0.2356	0.2281	0.2249	0.2346	0.2341	0.2350	0.2346	0.2314	0.2286
Panel 2: Software (Investment)										
Size (proxied by sales)	20.5010		0.5034		4.4246		5.2615		0.4286	
	(0.1070)		(0.0029)		(0.0277)		(0.0348)		(0.0025)	
Size (proxied by VA)		21.1063		0.5191		4.7405		5.6491		0.4409
		(0.1131)		(0.0030)		(0.0293)		(0.0368)		(0.0026)
Observations	1,145,874	1,146,068	1,145,917	1,146,115	1,127,629	1,127,816	1,117,482	1,117,639	1,146,512	1,146,707
R2	0.0911	0.0896	0.0840	0.0829	0.0820	0.0826	0.0756	0.0762	0.0829	0.0817
Panel 3 : Hardware (Stock)										
Size (proxied by sales)	0.2630		0.2031		0.2134		0.2279		0.1993	
	(0.0007)		(0.0007)		(0.0008)		(0.0008)		(0.0007)	
Size (proxied by VA)		0.1991		0.1289		0.1705		0.1884		0.1279
		(0.0008)		(0.0008)		(0.0009)		(0.0009)		(0.0008)
Observations	2,839,365	2,839,569	2,839,373	2,839,754	2,755,218	2,755,436	2,756,088	2,756,211	2,840,459	2,840,804
R2	0.4188	0.4068	0.3823	0.3718	0.4163	0.4104	0.4491	0.4435	0.3474	0.3367
Panel 4 : Hardware (Investment)										
Size (proxied by sales)	41.1954		0.8812		17.1734		19.7820		0.7486	
	(0.1841)		(0.0052)		(0.0571)		(0.0712)		(0.0037)	
Size (proxied by VA)		32.2761		0.5930		15.7131		18.2151		0.5411
		(0.1894)		(0.0054)		(0.0587)		(0.0732)		(0.0038)
Observations	4,340,454	4,341,159	4,340,014	4,340,853	4,366,163	4,366,860	4,302,290	4,302,802	4,344,803	4,345,554
R2	0.1647	0.1607	0.1386	0.1353	0.1860	0.1826	0.2409	0.2384	0.1478	0.1438

Note: In panels 2 and 4, the dependent variable is IT investment intensity and in panels 1 and 3 it is the logarithm of IT stock intensity. Standard errors are reported in brackets. In columns (1)-(4) we report results of IT intensity of labor, in columns (5)-(8) we report results for IT intensity of capital, and in columns (9) and (10) we report results of IT intensity of cost. The independent variable is the logarithm of firm size either proxied by sales or value added. The time period is 1995-2007. In panels 1 and 2 the sample is all firms sampled by EAE, and in panels 3 and 4, the sample is BRN firms. All columns include a full set of 3-digit industry classification fixed effects interacted with year fixed effects and a full set of cohorts fixed effect (pre 1980, 1980-1993, 1993-1995 ... 2005-2007) and normalised age fixed effects. For investment intensities semi-elasticities, units matter for interpretation. The units for the IT intensity of labor, capital, and cost are euros per worker, euros per thousand euros of capital, and euros per thousand euros of cost, respectively. Imputed values of the "investment" measures are dropped from the analysis. A semi-elasticity of 20.5 of software investment per worker to sales means that raising sales by a factor of 2 raises software per worker by $20.5 \log 2 = 14$ euros. An elasticity of 0.365 of sofware stock per worker to sales means that raising sales by a factor of 2 raises software stock per worker by 36.5%.

results for alternative measures of labor and capital inputs, either over the wage bill or tangible capital. The coefficients remain sizable, significant, and comparable with our main measures of intensity in every case.

Table 7 presents the results of regressions in which $Size_{it}$ variable in Equation (43) is measured by the number of international markets (destination countries) and the number of exported products. On average, exporting to a new market is associated with an increase in IT intensity of around 2% to 3% and exporting a new product with an increase of around 0.5% to 0.8%. Table 7 also presents the results of regressions of log stock intensity on the firm's number of plants and the number of occupational layers. The latter measures are constructed from the DADS data following Caliendo et al. (2015a). On average, adding a new plant is associated with an increase in the software (hardware) intensity of firms by 0.15% (0.40%), while adding an occupational layer with an increase of more than 20% (around

Table 7: Regressions of Log IT Intensity of Capital On Measures of Firm Scale

	IT Intensity of Labor				IT Intensity of Capital				IT Intensity of Cost	
	Workers	Workers	Wage Bill	Wage Bill	Total	Total	Tangible	Tangible	Cost	Cost
Panel 1 : Software (Stock)										
Number of plants	0.0015		0.0014		0.0014		0.0016		0.0013	
	(0.0002)		(0.0002)		(0.0002)		(0.0002)		(0.0002)	
Number of occupational layers		0.2623		0.2230		0.2558		0.2603		0.2250
		(0.0047)		(0.0047)		(0.0049)		(0.0050)		(0.0047)
Observations	562,858	562,858	562,997	562,997	518,716	518,716	517,470	517,470	563,027	563,027
R2	0.2214	0.2255	0.2143	0.2173	0.2237	0.2276	0.2238	0.2278	0.2186	0.2217
Number of destination countries	0.0276		0.0243		0.0225		0.0232		0.0238	
	(0.0004)		(0.0004)		(0.0004)		(0.0004)		(0.0004)	
Number of products		0.0065		0.0059		0.0054		0.0056		0.0057
		(0.0002)		(0.0002)		(0.0002)		(0.0002)		(0.0002)
Observations	278,803	278,803	279,590	279,590	261,609	261,609	261,144	261,144	279,902	279,902
R2	0.1958	0.1871	0.1887	0.1817	0.1867	0.1806	0.1875	0.1811	0.1921	0.1854
Panel 2: Hardware (Stock)										
Number of plants	0.0040		0.0040		0.0036		0.0040		0.0039	
	(0.0001)		(0.0001)		(0.0001)		(0.0001)		(0.0001)	
Number of occupational layers		0.0986		0.0700		0.1124		0.1251		0.0735
		(0.0009)		(0.0009)		(0.0010)		(0.0010)		(0.0009)
Observations	2,696,655	2,696,655	2,698,300	2,698,300	2,622,236	2,622,236	2,622,998	2,622,998	2,698,872	2,698,872
R2	0.3913	0.3933	0.3632	0.3640	0.4003	0.4027	0.4319	0.4347	0.3275	0.3286
Number of destination countries	0.0337		0.0299		0.0258		0.0272		0.0291	
	(0.0002)		(0.0002)		(0.0002)		(0.0002)		(0.0002)	
Number of products		0.0084		0.0078		0.0068		0.0071		0.0076
		(0.0001)		(0.0001)		(0.0001)		(0.0001)		(0.0001)
Observations	553,427	553,427	555,879	555,879	546,058	546,058	546,478	546,478	555,847	555,847
R2	0.2831	0.2628	0.2533	0.2366	0.3129	0.3033	0.3339	0.3237	0.2226	0.2058

Note: In all panels the dependent variable is the logarithm of IT stock intensity. Standard errors are reported in brackets. In columns (1)-(4) we report results of IT intensity of labor, in columns (5)-(8) we report results for IT intensity of capital, and in columns (9) and (10) we report results of IT intensity of cost. The time period is 1995-2007. In panel 1 the sample is all firms sampled by EAE, and in panel 2 the sample is BRN firms. All columns include a full set of 3-digit industry classification fixed effects interacted with year fixed effects and a full set of cohorts fixed effect (pre 1980, 1980-1993, 1993-1995 ... 2005-2007) and normalised age fixed effects. A semi-elasticity of 0.0276 of software stock per worker to the number of destination countries means that exporting to one new country raises software stock per worker by 2.76%.

10%).

A number of potential issues may complicate the interpretation of our results. First, we may be concerned that small firms face some fixed cost of adopting IT, may not perfectly report their IT investment, or may face different costs of IT compared to large firms in our data. Second, we may be concerned that small firms covered in our data are not representative of all small firms in the French economy. To address these concerns, we show that the relationship between firm size and IT intensity also appears among large firms in our data. Figure 2 already shows that the positive relationship between size and IT intensity is fairly consistent across different brackets of size, particularly in the case of software where the issues of selection and measurement error are less pronounced.[86] To address this issue more

[86] As we already mentioned, the hardware data includes office furniture investments, which biases our measure of hardware intensity upward particularly for middle-size firms for which office capital may constitute the largest share of their capital stock. See footnote 24 for a discussion of how this issue appears in Figure 2. With regard to selection, note that the source of our hardware data, includes firms that have voluntarily chosen to file in the BRN tax regime below certain revenue thresholds. It is likely that small firms selecting to file in the BRN regime expect higher future growth, which may also be correlated with currently higher IT intensities. This would make small firms in the BRN

Table 8: Regressions of IT Intensity of Cost on Log Firm Size, by Bins of Employment

	IT Intensity of Cost									
	[1; 50[	[50; 100[	[100; 250[	[250; 1000[	≥ 1000	[1; 50[	[50; 100[	[100; 250[	[250; 1000[	≥ 1000
Panel 1 : Software (Stock)										
Size (proxied by sales)	0.2871	0.2528	0.2199	0.2861	0.2761					
	(0.0057)	(0.0136)	(0.0140)	(0.0185)	(0.0370)					
Size (proxied by VA)						0.2159	0.2202	0.1959	0.2906	0.3024
						(0.0065)	(0.0167)	(0.0170)	(0.0213)	(0.0395)
Observations	379,543	91,406	66,022	30,925	6,375	379,603	91,430	66,030	30,933	6,375
R2	0.2506	0.2132	0.2216	0.2716	0.3715	0.2478	0.2117	0.2202	0.2705	0.3718
Panel 2: Hardware (Stock)										
Size (proxied by sales)	0.0812	0.7282	0.5073	0.2934	0.1400					
	(0.0009)	(0.0061)	(0.0058)	(0.0070)	(0.0127)					
Size (proxied by VA)						-0.0343	0.5140	0.3700	0.2135	0.0911
						(0.0010)	(0.0074)	(0.0070)	(0.0082)	(0.0132)
Observations	2,563,488	132,537	93,307	41,372	8,295	2,563,741	132,577	93,338	41,393	8,295
R2	0.3752	0.3428	0.3847	0.3817	0.4572	0.3735	0.2960	0.3525	0.3647	0.4514

Note: In both panels the dependent variable is the logarithm of IT stock intensity of cost. Standard errors are reported in brackets. In columns (1)-(5) and (6)-(10) we report results of regressions for firms in various bins of total number of employees: less than 50 employees, 50 to 100, ... up to more than 1000 employees. The independent variable is the logarithm of firm size either proxied by sales or value added. The time period is 1995-2007. In panel 1 the sample is all firms sampled by EAE, and in panel 2, the sample is BRN firms. All columns include a full set of 3-digit industry classification fixed effects interacted with year fixed effects and a full set of cohorts fixed effect (pre 1980, 1980-1993, 1993-1995 ... 2005-2007) and normalised age fixed effects. An elasticity of 0.2871 means that raising sales by a factor of 2 raises the IT intensity of cost by 28.71%.

directly, Table 8 replicates the results of Table 6 on the IT intensity of cost for samples of firms in different brackets of employment size. The results for the IT intensity of software clearly demonstrates that the relationship between size and IT intensity is fairly robust across different brackets of firm size, with the coefficients between 0.2 and 0.3. Again, the results show more variability in the case of hardware data, but the coefficients are still nonmonotonic, first increasing and then decreasing.

sample unsuitable representatives for the sample of all small French firms. In contrast, the source of our software data, the EAE dataset, contains a representative sample for firms with fewer than 20 employees.

Table 9: Regressions of IT Intensity on Log Firm Size (Within Firm)

	IT Intensity of Labor				IT Intensity of Capital				IT Intensity of Cost	
	Workers	Workers	Wage Bill	Wage Bill	Total	Total	Tangible	Tangible	Costs	Costs
Panel 1 : Software (Stock)										
Size (proxied by sales)	0.2042		0.1455		0.3422		0.3533		0.1702	
	(0.0326)		(0.0327)		(0.0337)		(0.0338)		(0.0326)	
Size (proxied by VA)		0.2161		0.1432		0.3296		0.3379		0.1621
		(0.0288)		(0.0288)		(0.0297)		(0.0298)		(0.0287)
Observations	233,654	233,376	233,507	233,189	221,456	221,319	221,676	221,614	233,548	233,230
R2	0.8361	0.8325	0.8319	0.8281	0.8313	0.8270	0.8311	0.8272	0.8327	0.8288
Panel 2 : Hardware (Stock)										
Size (proxied by sales)	0.2612		0.1686		0.3706		0.3765		0.1874	
	(0.0097)		(0.0097)		(0.0101)		(0.0102)		(0.0095)	
Size (proxied by VA)		0.1470		0.0437		0.2482		0.2533		0.0660
		(0.0081)		(0.0082)		(0.0084)		(0.0085)		(0.0080)
Observations	248,038	249,026	248,995	250,111	244,282	245,286	243,095	244,175	248,466	249,591
R2	0.8689	0.8691	0.8467	0.8466	0.9078	0.9077	0.9177	0.9175	0.8485	0.8493

Note: The dependent variable is the logarithm of IT stock intensity. Standard errors are reported in brackets. In columns (1)-(4) we report results of IT intensity of labor, in columns (5)-(8) we report results for IT intensity of capital, and in columns (9) and (10) we report results of IT intensity of cost. The independent variable is the logarithm of firm size either proxied by sales or value added. The time period is 1995-2007. In panel 1 the sample is all firms sampled by EAE, and in panel 2, the sample is BRN firms. All columns include a full set of firm fixed effects, and 3-digit industry classification fixed effects interacted with year fixed effects. An elasticity of 0.2042 of sofware stock per worker to sales means that raising sales by a factor of 2 raises software stock per worker by 20.42%.

B.2 Within-Firm

Table 9 reports the results of the following regression:

$$IT\,Intensity_{it} = \eta\,Size_{it} + FE_{kt} + FE_i + \nu_{it}, \tag{44}$$

where FE_i is a firm fixed effect and FE_{kt} stands for the industry-time fixed effects. The specification allows us to examine the within-firm relationship between firm size and IT intensity. The table shows that the results of the previous section are *not* driven by a potential confounding cross-sectional relationship between IT-biased productivity and size.

The within-firm estimates in Table 9 still leave us with the possibility that the residual ν_{it} in Equation (44) could be correlated with size. To identify the contribution of nonhomotheticity to the correlation between size and IT intensity, we rely on demand shocks to different export destinations of firms as an exogenous source of variation in their expected potential for growth. To the extent that firms take advantage of these opportunities to expand their activities, we should find a first stage effect of the instrument on firm sales and value added. The idea behind this strategy has been used in a number of recent papers (e.g., Hummels et al., 2014; Mayer et al., 2015; Aghion et al., 2017; Garin and Silveiro, 2017; Panon, 2019). As we will see below, our specifications identify the within-firm relationship between size and IT intensity. As a result, our key identification assumption is that the *variations in value of the demand shock measures above are uncorrelated with firm-level residual ν_{it}'s in Equation* (44).

Export Demand Shock Instruments We construct the product-destination-level export demand shocks for firm i at time t as

$$ds_{it}^{P} = \sum_{np} \Lambda_{inp,0} \left(imp_{np,t}^{-FR} - \overline{imp_{p,t}^{-FR}} \right), \tag{45}$$

where Λ_{inp} denotes destination-n/product-p share of firm-i exports, imp_{np}^{-FR}, the destination-n/product-p log import from all countries except France, and $\overline{imp_{p,t}^{-FR}}$ the product-level average value of the log import across all other destinations. With this specification, we avoid including the component of demand in any given product-destination that might be driven by potential productivity shocks to all French exporters.

Data for Export Demand Shocks To construct the instruments, we use the French customs data that provides the value of the exports of firms by destination and product (at the nc8 level) spanning the 1995-2007 period. The data allows us to compute the share of each destination-n/product-p share of firm-i exports (Λ_{inp} in Equation 45) as the corresponding average for years 1995 and 1996. To build the product-level demand shocks in Equation (45), we rely on the COMTRADE bilateral Trade Flows Data, and in particular on the harmonized version of the data provided in the BACI dataset. This dataset includes the values of flows from each exporter to each importing destination as HS6 code product-level.[87] We use this information to compute for each product in each destination country the sum of all imports from all other countries, leaving out France. We construct the instrument ds_{it}^{P} for years 1997-2007.

Empirical Specification For the results of this section, we limit our attention to the sample of exporting firms. Table 5 of the online appendix compares the summary statistics of this sample with the sample of all firms. As is well-known, exporting firms are typically larger than other firms. The table shows that they are, in addition, also slightly more IT intensive than average firms (Fort et al., 2017).

Table 10 present the results of applying the following specification in the sample of exporting firms

$$IT\,Intensity_{it} - \overline{IT\,Intensity_i} = \eta(Size_{it} - \overline{Size_i}) + FE_{kt} + \nu_{it}, \tag{46}$$

where $IT\,Intensity_{it}$ denotes a measure of the relative demand for IT inputs for a firm i in an industry k at time t, FE_{kt} stands for a flexible set of industry-time fixed effects (at the 3-digit level), y_{it} is the sales or value added of the firm (depending on the specification), and $\overline{y_i}$ is the firm-level mean of log firm size y_{it}. We estimate Equation (46) with 2SLS, using the shocks defined in Equations (45) as instruments for $y_{it} - \overline{y_i}$. Results in Tables 10 (and 11) are provided with product demand shocks from 1997 to 2007.

The coefficients are positive and significant for the majority of specifications. They are also close in magnitude to, even if larger than, those reported in Table 9 for the within-firm effects. Note that the sample of firms in Table 10 is much smaller, only featuring relatively large exporting firms for which we can construct the instrument. Moreover, Table 11 presents the same estimates, when weighted by each firm's initial share of exports in total sales to avoid relying on firms for which exports constitutes a very small share of sales (see e.g. Aghion et al., 2017). The weighted results are typically smaller in both magnitude of the estimates and the standard errors.[88]

[87] We use the concordance procedure made available by Van Beveren et al. (2012) to map CN8 products code over time, and to more aggregated HS6 product codes.

[88] Note that the only negative coefficients in Table 11, for the hardware intensity of costs, change sign and are positive in Table 10.

Table 10: Reduced Form Identification of the Elasticity of IT Intensity on Log Firm Size

	IT Intensity of Labor				IT Intensity of Capital				IT Intensity of Cost	
	Workers	Workers	Wage Bill	Wage Bill	Total	Total	Tangible	Tangible	Costs	Costs
Panel 1 : Software (Stock)										
Size (proxied by sales)	1.3035		0.7505		1.0834		0.9512		1.0362	
	(0.2586)		(0.2519)		(0.2533)		(0.2581)		(0.2522)	
Size (proxied by VA)		1.5605		0.8848		1.1500		1.2513		1.2316
		(0.3362)		(0.3322)		(0.3275)		(0.3359)		(0.3289)
Observations	104,640	103,570	104,988	103,844	100,130	99,011	100,322	99,215	105,120	103,982
Panel 2 : Hardware (Stock)										
Size (proxied by sales)	1.5525		1.0627		1.1301		1.1174		0.1637	
	(0.0834)		(0.0775)		(0.0756)		(0.0749)		(0.0696)	
Size (proxied by VA)		1.9002		1.3000		1.4004		1.3815		0.1901
		(0.1196)		(0.1046)		(0.1019)		(0.1008)		(0.0872)
Observations	99,096	98,119	99,821	98,905	99,744	98,873	99,715	98,795	99,772	98,876

Note: The dependent variable is the demeaned logarithm of IT stock intensity. Standard errors are reported in brackets. In columns (1)-(4) we report results of IT intensity of labor, in columns (5)-(8) we report results for IT intensity of capital, and in columns (9) and (10) we report results of IT intensity of cost. The independent variable is the logarithm of firm size either proxied by sales or value added, instrumented by product demand shocks. The time period is 1997-2007. In panel 1 the sample is all exporting firms sampled by EAE, and in panel 3, the sample is exporting BRN firms. All columns include a full set of 3-digit industry classification fixed effects interacted with year fixed effects. An elasticity of 1.3035 of sofware stock per worker to sales means that raising sales by a factor of 2 raises software stock per worker by 130.35%.

Table 11: Reduced Form Identification of the Elasticity of IT Intensity on Log Firm Size (Weighted)

	IT Intensity of Labor				IT Intensity of Capital				IT Intensity of Cost	
	Workers	Workers	Wage Bill	Wage Bill	Total	Total	Tangible	Tangible	Costs	Costs
Panel 1 : Software (Stock)										
Size (proxied by sales)	0.5656		0.3196		0.4419		0.5192		0.5422	
	(0.2615)		(0.2514)		(0.2632)		(0.2523)		(0.2499)	
Size (proxied by VA)		0.8018		0.4519		0.7278		0.8511		0.6926
		(0.3666)		(0.3617)		(0.3784)		(0.3556)		(0.3510)
Observations	102,481	101,439	102,803	101,685	98,146	97,067	98,336	97,264	102,939	101,826
Panel 2 : Hardware (Stock)										
Size (proxied by sales)	0.6962		0.3597		0.5328		0.4892		-0.0341	
	(0.0874)		(0.0842)		(0.0848)		(0.0827)		(0.0793)	
Size (proxied by VA)		0.9066		0.4598		0.7853		0.6865		-0.0474
		(0.1430)		(0.1287)		(0.1246)		(0.1162)		(0.1266)
Observations	96,370	95,434	97,066	96,194	97,036	96,218	97,006	96,136	97,021	96,171

Note: The dependent variable is the demeaned logarithm of IT stock intensity. Standard errors are reported in brackets. In columns (1)-(4) we report results of IT intensity of labor, in columns (5)-(8) we report results for IT intensity of capital, and in columns (9) and (10) we report results of IT intensity of cost. The independent variable is the logarithm of firm size either proxied by sales or value added, instrumented by product demand shocks. The time period is 1997-2007. In panel 1 the sample is all exporting firms sampled by EAE, and in panel 3, the sample is exporting BRN firms. All columns include a full set of 3-digit industry classification fixed effects interacted with year fixed effects. An elasticity of 0.5656 of sofware stock per worker to sales means that raising sales by a factor of 2 raises software stock per worker by 56.56%. Estimation is weighted by the share of export in total sales in 1995-1996.

C Additional Theoretical Results

C.1 Firm-Level Production Function and Organizational Complexity

Following Lucas (1978), we distinguish between technology and organization as two distinct aspects of firm productivity. The technology of production is simply the idea (or, blueprint) describing how to transform inputs to the desired output. However, even if firms pursue the same technology, they may still differ in the organizational efficiency with which they implement it. Accordingly, we assume that a firm is characterized by an *organizational input* O as well as its *technological efficiency* A. The output Y of the firm is given by

$$Y = [A\,\mathcal{X}(O, X_N)]^{\frac{1}{\gamma}}, \tag{47}$$

where the parameter $1/\gamma$ controls the degree of returns to scale, and where $\mathcal{X}(\cdot,\cdot)$ is a CES aggregator of the bundle of non-IT inputs X_N and the organizational input O:

$$\mathcal{X}(O, X_N) = \left(O^{\frac{\sigma-1}{\sigma}} + X_N^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}. \tag{48}$$

The key assumption is that, while the technology is an exogenous constant $A \equiv e^{\theta}$, the organizational input of the firm endogenously varies according to:

$$O = X_I \times Y^{-\epsilon} \times e^{\phi}. \tag{49}$$

Equation (49) assumes that organizational input O depends on an intrinsic firm-level organizational efficiency e^{ϕ}. In addition, it also allows for diminishing returns to the organizational input as the output Y rises, due to potential increase in organizational complexity. Finally, it allows for the firm to raise its organizational input by adjusting its level of IT inputs X_I.

Combining Equations (47)-(49), we arrive at our specification of nhCES production functions provided in Equation (9). The construction above provides a specific interpretation of the nonhomotheticity of IT demand in Equation (10): larger firms optimally choose higher IT intensities in response to the fall in their organizational efficiency due to higher complexities of production.

Discussion Equation (47) assumes that *organization* is a firm-specific factor that may potentially generate decreasing returns. This assumption is by no means novel. In his Principles of Economics, Marshall identifies organization as a fourth factor of production, in addition to labor, capital, and land. Coase (1937) argues that "decreasing returns to the entrepreneur function" is a key factor in determining the boundary of the firm. To justify firm-level decreasing returns, McKenzie (1959) defines a firm-specific *entrepreneurial input*, Lucas (1978) refers to it as the *managerial talent* of the firm's manager, and Atkeson and Kehoe (2005) interpret it as the *organizational capital* of the firm. Our concept of organizational input is also in line with the concept of the firm-level *economic competencies* that is considered to be a core component of the intangible capital of firms (Haskel and Westlake, 2018).

At least since Williamson (1967), many economic theories have provided micro-foundations for such firm-level organizational limits to scale.[89] These models offer various mechanisms through which the complexities of coordi-

[89]Some approaches emphasize the agency issues inherent in delegation and the formation of hierarchies (see Mukherjee, 2012, for a review), while others focus on the complexities of solving allocative decisions within the firm (see Garicano and Van Zandt, 2012). In particular, in theories of knowledge hierarchies the complexity of the process

nation and communication, both within the firm and also between the firm and its buyers and suppliers, may rise as the firm scale grows. Equation (49) offers a stylized account of such organizational limits to scale, inspired by the span-of-control model of Lucas (1978) (nested in our model for the case of $\sigma = 1$).[90] The latter focuses solely on the limits to the ability of a manager to supervise production over increasing scales of inputs. In contrast, Equation (49) accounts for the organizational limits to the scale in terms of firm output Y. A larger scale of output Y brings about complexities that stem from organizing production tasks over larger scales of inputs and outputs. On the input side, the firm potentially has to find and coordinate with more intermediate suppliers, hire more or different types of workers, procure more machines, and manage across a large set of inputs. On the output side, it has to potentially manage larger inventories, coordinate with more buyers or across more markets, provide support services to a larger set of customers, organize larger scale marketing efforts, and solve larger delivery or distribution problems.

Equation (49) further generalizes the benchmark span-of-control model by allowing firms to endogenously deploy IT in order to enhance their organizational efficiency. A sizable body of empirical work has documented the connection between IT and the organizational efficiency of the firm. Brynjolfsson and Hitt (2000) discuss numerous case studies that showcase the effect of IT on the organizational practices of businesses. A variety of firm-level cross sectional studies have documented the complementarity between IT adoption and organizational capital (e.g., Bresnahan et al., 2002; Brynjolfsson and Hitt, 2003; Baker and Hubbard, 2004). In particular, Bartel et al. (2007) use detailed firm-level data on setup times, run times, and inspection times to show how IT improves the efficiency of organizing multiple production processes within the firm. As another example, Bloom et al. (2014) find that the adoption of IT impacts the organization of the firm in terms of span of control over individual workers. In sum, IT allows firms to more effectively apply their technology or core competencies to a larger scale of inputs, across a wider range of activities, and to serve more buyers and markets.

C.2 Nonhomothetic Demand and Returns to Scale

In this section we examine the properties of general production functions that are compatible with nonhomothetic IT demand in Equation (6).The following lemma establishes two properties for the elasticities of substitution and scale of the production functions that give rise to nonhomothetic IT demand with a constant elasticity with respect to output.

Lemma 4. *Consider a continuous, differentiable, and monotonically increasing production function $Y = \mathcal{F}(X_N, X_I)$ such that the set $\{(X_N, X_I) \geq 0 \,|\, Y \leq \mathcal{F}(X_N, X_I)\}$ is strictly convex for all Y. Assume that the corresponding cost minimization problem yields factor demand functions satisfying Equation (6). Then, along any expansion path in the (X_N, X_I) -space*[91] *the production function satisfies the following two properties:*[92]

1. *The elasticity of substitution between IT and non-IT inputs is constant everywhere.*
2. *The production function is "not" homogeneous of a constant degree, that is, there is "no" $\epsilon > 0$ such that for all $Z > 0$ and all (X_N, X_I) the production function satisfies $\mathcal{F}(Z\,X_N,\, Z\,X_I) = Z^{\epsilon}\mathcal{F}(X_N, X_I)$.*

of dealing with production errors changes endogenously with the scale of operation (Garicano, 2000; Garicano and Rossi-Hansberg, 2006; Caliendo and Rossi-Hansberg, 2012). Another alternative follows the approach of Simon (1962) and examines the implications of bounded rationality and the limits to information processing (e.g., Van Zandt and Radner, 2001).

[90] Appendix C.3 provides a derivation of the Lucas span-of-control model in the special case of $\sigma = 1$, i.e., the case where the elasticity of substitution between technology and organization is unity.

[91] An expansion path is a curve with constant marginal rate of transformation $\mathcal{F}_I / \mathcal{F}_N \equiv (\partial \mathcal{F} / \partial X_I)/(\partial \mathcal{F} / \partial X_N)$.

[92] See proof in Section 1.4 of the online appendix.

We can alternatively state the result of Lemma 4 in terms of the properties of the cost function, when we fix relative factor input prices W_I/W_N. The first part of the lemma tells us that the elasticity of substitution $\partial\log(X_I/X_N)/\partial\log(W_I/W_N)$ only depends on relative input prices W_I/W_N, and not output Y. In other words, if we consider in the space of inputs (X_N, X_I) paths characterized by a constant marginal rate of substitution, the normal vectors to this curve form parallel vectors everywhere along the curve.

More importantly, the second part says that the cost elasticity, which is the reciprocal of the scale elasticity, *varies* with the scale of the firm output Y. In other words, if the IT factor input has a higher output elasticity than the non-IT factor input, their scale elasticity is bound to change when firms change their scale of operation. Specifically, the lemma rules out a constant-returns-to-scale (CRS) production function.

We may naturally wonder whether the scale elasticity rises or falls with output. The next lemma shows that to answer this question we need to impose further structure on the production function. More specifically, the answer to this question hinges on whether the two inputs are gross complements or gross substitutes.

Proposition 1. *Consider a production function $\mathcal{F}$ satisfying the conditions in Lemma 4. Assume, in addition, that the scale elasticity is constant in the limit that either input goes to zero, that is, there is some $\epsilon_k > 0$ such that for all $Z > 0$ we have*

$$\lim_{X_k \to 0} \frac{\mathcal{F}(ZX_N, ZX_I)}{\mathcal{F}(X_N, X_I)} = Z^{\epsilon_k}, \qquad k \in \{N, I\}.$$

Then, if the elasticity of substitution is less (greater) than 1 and non-increasing (nondecreasing) in the marginal rate of transformation $\mathcal{F}_I/\mathcal{F}_N$, the scale elasticity is monotonically decreasing (increasing) in output Y along a curve with constant marginal rate of transformation.[93]

Lemma 1 shows that, under fairly mild conditions on the production function, the relationship between scale elasticity and firm size is monotonic and depends on the elasticity of substitution between IT and non-IT inputs. In particular, when the elasticity of substitution is constant, with an elasticity of substitution below 1, larger firms have higher scale elasticities. The opposite is the case with an elasticity of substitution greater than 1. To better illustrate this result, below we will consider two extreme examples: the first being a production function with a zero elasticity of substitution between the two inputs and the second being the polar case with perfect substitutability. We will see that, as the firm size grows, the scale elasticity falls and rises in the first and second examples, respectively.

Example 1. Consider a nonhomothetic Leontief production function $Y = \mathcal{F}(X_N, X_I)$ defined implicitly through

$$Y = \min\left\{X_N, Y^{-\eta} X_I\right\}, \qquad \eta > 0.$$

In any cost minimizing solution, we have $Y = X_N = X_I^{1/(1+\eta)}$, which implies $X_I/X_N = Y^\eta$ satisfying condition (6). Given factor prices (W_N, W_I), the corresponding cost function is given by $C(Y; W_N, W_I) = W_N Y + W_I Y^{1+\eta}$. Therefore, the cost elasticity, which is the reciprocal of the scale elasticity, satisfies

$$\frac{\partial \log C}{\partial \log Y} = 1 + \eta\, \Omega_I(W_N, W_I; Y),$$

where we have defined $\Omega_I(W_N, W_I; Y) \equiv W_I Y^\eta/(W_N + W_I Y^\eta)$ as the cost share of IT-inputs. This share is monotonically increasing in the level of output Y, implying that the cost elasticity is increasing in output.

[93]See proof in Section 1.4 of the online appendix.

Example 2. Consider a linear production function $Y = \mathcal{F}(X_N, X_I)$ defined as

$$Y = X_N + Y^{\eta} X_I, \qquad 0 < \eta < 1.$$

Although strictly speaking, this production function does not satisfy condition (6), its factor demand and cost functions demonstrate quasi-nonhomothetic behavior. In particular, when the scale of output is small enough to satisfy $W_I/W_N \geq Y^{\eta}$, we have $X_N = Y$ and $X_I = 0$. On the other hand, when the scale of output is large enough such that $W_I/W_N < Y^{\eta}$, we have $X_N = 0$ and $X_I = Y^{1-\eta}$. The corresponding cost function is

$$C\left(W_N, W_I; Y\right) = \begin{cases} W_N Y, & W_I/W_N \geq Y^{\eta}, \\ W_I Y^{1-\eta}, & W_I/W_N \leq Y^{\eta}. \end{cases}$$

In stark contrast to Example 1, in this case the cost elasticity falls as output rises. With $W_I/W_N \geq Y^{\eta}$, the production function has constant returns to scale whereas for $W_I/W_N < Y^{\eta}$, the scale elasticity is $1/(1-\eta)$ strictly greater than 1.

The intuition for the result above is as follows. As output rises, Equation (6) implies that IT inputs grow faster than non-IT inputs because of their higher elasticity with respect to output. The rise in IT inputs raises the marginal product of non-IT inputs, which means that we have to further raise the non-IT input in order to again equalize the marginal product to the non-IT factor price. When the elasticity of substitution is below 1, the required rise in the non-IT input is sufficiently large to make the cost function increasingly convex as the output rises. The situation is reversed when the elasticity of substitution is greater than 1.

C.3 Connection to the Lucas' Span-of-Control Model

Lucas (1978) assumed that managerial productivity is heterogeneous across firms, and the equilibrium size of firms is determined through span-of-control limits. Specifically, he assumed that $X_N = f(K, L)$ is a constant-returns-to-scale aggregator of capital and labor, and the output is given by $Y = B\, g(X_N)$ where $g(\cdot)$ is a concave function and B is the managerial productivity of the firm. Comparing this specification with our construction in Section C.1, consider the case of $\gamma = 1$, Cobb-Douglas functional forms $f(K, L) = K^{\alpha} L^{1-\alpha}$, and $g(X_N) = X_N^{1-\phi}$.

Next, we provide a mapping between the specification above for the Lucas model and our construction in Section C.1. Without loss of generality, we generalize Equation (48) to $\mathcal{X} = \left(\xi^{\frac{1}{\sigma}} X_N^{1-\frac{1}{\sigma}} + (1-\xi)^{\frac{1}{\sigma}} O^{1-\frac{1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}$ with coefficients $\xi \in (0,1)$. Substituting the expression for O in this equation, we find

$$\mathcal{X} = \left(\xi^{\frac{1}{\sigma}} \left(X_N\right)^{\frac{\sigma-1}{\sigma}} + (1-\xi)^{\frac{1}{\sigma}} \left(e^{\phi} X_I Y^{-\epsilon}\right)^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}}. \tag{50}$$

Now, let us apply the l'Hopital's rule, to find the limit of the expression as $\sigma \to 1$:

$$\lim_{\sigma \to 1} \log \frac{\mathcal{X}}{X_N} = \theta + (1-\xi)\left(\phi + \log\left(\frac{X_I}{X_N}\right) - \epsilon \log Y\right) + \omega,$$

where ω is a constant.

Substituting the expression above in Equation (47) with $\gamma = 1$, we find:

$$Y = e^{\omega + \frac{\theta + (1-\xi)\phi}{1+(1-\xi)\epsilon}} \times X_I^{\frac{1-\xi}{1+(1-\xi)\epsilon}} \times X_N^{\frac{\xi}{1+(1-\xi)\epsilon}}.$$

Comparing this equation with the Lucas specification $Y = BX_N^{1-\psi}$, we find that the two coincide if we set

$$\psi \equiv \frac{(1-\xi)(1+\epsilon)}{1+(1-\xi)\epsilon},$$
$$B \equiv e^{\omega + \frac{\theta + (1-\xi)\phi}{1+(1-\xi)\epsilon}} \times X_I^{\frac{1-\xi}{1+(1-\xi)\epsilon}}.$$

This expression is in line with the Lucas model, assuming that we take the input X_I of each firm to be an exogenous value.

C.4 A Fixed-Cost Model of IT

Consider the following fixed-cost-of-IT production function $Y = Z\mathcal{F}_{fc}(X_N, X_I)$ defined as

$$Y = \begin{cases} ZX_N, & X_I = 0, \\ \Delta_I Z\left(\frac{X_I}{\xi}\right)^{\xi}\left(\frac{X_N - \psi_I}{1-\xi}\right)^{1-\xi}, & X_I > 0, \end{cases}$$

where ψ_I and Δ_I are constants that captures the fixed cost of adopting IT (in units of non-IT inputs) and its corresponding productivity premium, respectively. In order for IT to be adopted by some firms, assume that $\Delta_I > W^{\xi}$, where W is the relative price of non-IT inputs. We can then show that the cost function is given by

$$\mathcal{C}(Y) = \begin{cases} \frac{Y}{Z}, & Y \leq Y^*, \\ \psi_I + \frac{W^{\xi}}{\Delta_I}\frac{Y}{Z}, & Y \geq Y^*, \end{cases}$$

where $Y^* = Z\psi_I/\left(1 - W^{\xi}/\Delta_I\right)$, denotes the threshold of firm size above which firms adopt nonzero IT inputs. Accordingly, the share of IT in total costs is given by

$$\Psi = \frac{WX_I}{\mathcal{C}(Y)} = \begin{cases} 0, & Y \leq Y^*, \\ \frac{\xi}{1+\psi_I \frac{\Delta_I}{W^{\xi}}\frac{Z}{Y}}, & Y \geq Y^*, \end{cases}$$

which increases from 0 to $\xi > 0$ as the size Y goes from zero to infinity.

We can characterize the output elasticity of relative demand and the elasticity of substitution between IT and non-IT inputs as follows. First, we calculate the the elasticity of relative demand with respect to output:

$$\frac{\partial \log(X_I/X_N)}{\partial \log Y} = \frac{\partial \log}{\partial \log Y}\left(\frac{\xi/W}{1-\xi+\psi_I \frac{\Delta_I}{W^{\xi}}\frac{Z}{Y}}\right) = \frac{1}{1+(1-\xi)\frac{W^{\xi}}{\psi_I \Delta_I}\frac{Y}{Z}} > 0.$$

This shows that the IT intensity is increasing in firm size both on the extensive and the intensive margins. However, this elasticity converges to zero as Y goes to infinity. Next, we derive the elasticity of substitution between IT and non-IT inputs

$$-\frac{\partial\log(X_I/X_N)}{\partial\log W}=-\frac{\partial\log}{\partial\log W}\left(\frac{\xi/W}{1-\xi+\psi_I\frac{\Delta_I}{W^\xi}\frac{Z}{Y}}\right)=1-\frac{1}{1+(1-\xi)\frac{W^\xi}{\psi_I\Delta_I}\frac{Y}{Z}},$$

which we find to be less than unity.

Finally, let us examine the returns to scale properties of the production function. First, the production function features increasing returns to scale for $Y\geq Y^*$. Second, the scale elasticity is decreasing in size for $Y\geq Y^*$, as its reciprocal the cost elasticity is given by

$$\mathcal{E}(Y)=\frac{\partial\log\mathcal{C}(Y)}{\partial\log Y}=\frac{1}{1+\psi_I\frac{\Delta_I}{W^\xi}\frac{Z}{Y}},$$

and increases from W^ξ/Δ_I to 1 as Y goes from Y^* to infinity.

C.5 Aggregate Elasticity of Substitution

To characterize the two components of Equation (30), the following lemma first presents the comparative statics of the IT cost share and output with respect to the relative IT price.

Lemma 5. *The response of IT share and the output of firms with productivity state $\boldsymbol{\vartheta}$ are given by*

$$\frac{d\widetilde{\Omega}(\boldsymbol{\vartheta})}{dw}=(1-\sigma)\widetilde{\Omega}(\boldsymbol{\vartheta})\left(1-\widetilde{\Omega}(\boldsymbol{\vartheta})\right)\frac{\left[1+\zeta\epsilon\left(\frac{dp}{dw}+\frac{dy}{\lambda dw}\right)\right]\left(1+\frac{\epsilon}{\gamma}\widetilde{\Omega}(\boldsymbol{\vartheta})\right)}{1+\frac{\epsilon}{\gamma}\widetilde{\Omega}(\boldsymbol{\vartheta})\left[1+\zeta\left(\gamma+\eta\left(1-\widetilde{\Omega}(\boldsymbol{\vartheta})\right)\right)\right]},\tag{51}$$

$$\frac{d\widetilde{y}(\boldsymbol{\vartheta})}{dw}=-\zeta\frac{\widetilde{\Omega}(\boldsymbol{\vartheta})\left[1+\frac{\eta}{\gamma}\left(1-\widetilde{\Omega}(\boldsymbol{\vartheta})\right)\right]-\left(\frac{dp}{dw}+\frac{dy}{\lambda dw}\right)\left(1+\frac{\epsilon}{\gamma}\widetilde{\Omega}(\boldsymbol{\vartheta})\right)}{1+\frac{\epsilon}{\gamma}\widetilde{\Omega}(\boldsymbol{\vartheta})\left[1+\zeta\left(\gamma+\eta\left(1-\widetilde{\Omega}(\boldsymbol{\vartheta})\right)\right)\right]},\tag{52}$$

where we have used the definitions $\eta\equiv(1-\sigma)\epsilon$, and where dp/dw and dy/dw are the responses of the aggregate price index and output to the change in the relative price of IT.[94]

Lemma 5 shows that the heterogeneity across firms in their responses of both IT intensity and market share only depends on their initial IT intensity $\widetilde{\Omega}(\boldsymbol{\vartheta})$. Due to the CES property of the production function, the response of IT intensity is proportional to $1-\sigma$, where σ is the elasticity of substitution between IT and non-IT inputs. In addition to this substitution, the response of IT intensity in Equation (51) partly depends on the response of the firm's output due to nonhomotheticity: if a firm's output grows, then its IT intensity rises. Equation (52) shows that, to the first order of approximation, the pass-through from IT price to the firm prices is in line with Equation (60) and proportional to the IT intensity $\widetilde{\Omega}(\boldsymbol{\vartheta})$ of firms. However, for firms with larger IT intensity $\widetilde{\Omega}(\boldsymbol{\vartheta})$, the full response is more complicated since the marginal cost function nonlinearly varies both in IT prices and in the size of the firm.

Using the results of Lemma 5, the following proposition characterizes the within and across firm components of the response of the aggregate IT cost share.

Proposition 2. *Assume that the ratio of fixed to average costs is small, i.e., $\psi/\overline{C}\ll 1$ and define:*

$$\overline{\overline{\Omega^n}}\equiv\int\int\left[\frac{\widetilde{\Omega}^n(\boldsymbol{\vartheta})}{1+\frac{\epsilon}{\gamma}\widetilde{\Omega}(\boldsymbol{\vartheta})\left[1+\zeta\left(\gamma+\eta\left(1-\widetilde{\Omega}(\boldsymbol{\vartheta})\right)\right)\right]}\right]\Lambda(\boldsymbol{\vartheta})\,d^2\boldsymbol{\vartheta},\qquad \textit{for } 0\leq n\leq 3,\tag{53}$$

[94] See the proof of this lemma and the next proposition in Section 1.4 of the online appendix.

Then, the within and across firm effects in Equation (30) are given by

$$\textit{Within-firm effect} = (1-\sigma)\left[1+\zeta\epsilon\left(\frac{dp}{dw}+\frac{dy}{\lambda dw}\right)\right]\left[\overline{\overline{\Omega}}-\overline{\overline{\Omega^2}}+\frac{\epsilon}{\gamma}\left(\overline{\overline{\Omega^2}}-\overline{\overline{\Omega^3}}\right)\right], \tag{54}$$

$$\begin{aligned}\textit{Across-firm effect} = &\left[1+\zeta\epsilon\left(\frac{dp}{dw}+\frac{dy}{\lambda dw}\right)\right]\left[\frac{\lambda-1}{\lambda\epsilon}\left(\overline{\overline{\Omega}}+\frac{\epsilon}{\gamma}\overline{\overline{\Omega^2}}-\overline{\Omega}\left(\overline{\overline{\Omega^0}}+\frac{\epsilon}{\gamma}\overline{\overline{\Omega}}\right)\right)\right.\\ &\left.+\frac{\eta}{\gamma}\left(\overline{\overline{\Omega^2}}-\overline{\overline{\Omega^3}}-\overline{\Omega}\left(\overline{\overline{\Omega}}-\overline{\overline{\Omega^2}}\right)\right)\right],\end{aligned} \tag{55}$$

where the latter term ignores the terms first-order in $\psi/\overline{C}$.

To unpack the different terms in Equations (54) and (55), let us first examine the special case of homothetic CES production functions.

Corollary 2. *In the case of a homothetic production function, $\epsilon = 0$, the within and across firm effects in Equation (30) are given by*

$$\textit{Within-firm effect} = (1-\sigma)\left(\overline{\Omega}-\overline{\Omega^2}\right), \tag{56}$$

$$\textit{Across-firm effect} = -(\gamma\zeta-1)\left(\overline{\Omega^2}-\overline{\Omega}^2\right). \tag{57}$$

Equations (56) and (57) show that the signs of the two components critically depend on whether the two elasticities of substitution σ and λ exceed unity. In particular, when $\sigma < 1$ and $\lambda > 1$ the within-firm effect is positive while the across-firm is negative. The equations also generalize the results of Oberfield and Raval (2014) and Baqaee and Farhi (2018) to a non-CRS case. In particular, they show that if there are increasing returns to scale, $\gamma < 1$, the reallocation response is greater compared to the CRS case, and the reverse holds if there are decreasing returns, $\gamma > 1$. As with the CRS case, the relative size of the two components depends on the dispersion of IT intensity, as captured in the factor-payment-weighted variance of the IT cost share, $\overline{\Omega^2}-\overline{\Omega}^2$.

Comparing the results of Corollary 2 with those in the general case in Proposition 2, we first note that Equation (53) defines the four moments that account for the nonlinearities in the marginal cost function that stem from the nonhomotheticity. In addition, we find that in the nonhomothetic case, $\epsilon \neq 0$, the general equilibrium effect on the average firm's output affects the response. This effect is captured by the term $dp/dw + dy/\lambda dw$ in Equations (54) and (55) and implies a larger respones of the aggregate IT intensity to a fall in IT price relative to a CES benchmark if $\eta = (1-\sigma)\epsilon > 0$. Due to nonhomotheticity of IT demand, a change in factor prices that results in a larger average firm size leads to higher IT intensity for the average firm.

Partial Equilibrium Analysis In the remainder of this section, we provide a partial equilibrium analysis that aims to illustrate the different channels through which the presence of nonhomotheticity of IT demand modifies the aggregate response. Let us first examine the within-firm response of the IT cost share $\widetilde{\Omega}(\vartheta)$. The results of above show that:

$$\left.\frac{\partial\widetilde{\Omega}(\vartheta)}{\partial w}\right|_{(P,Y)\text{const.}} = \widetilde{\Omega}(\vartheta)\left(1-\widetilde{\Omega}(\vartheta)\right)\left[1-\underbrace{\left(\sigma-(1-\sigma)\epsilon\left.\frac{\partial\widetilde{y}(\vartheta)}{\partial w}\right|_{(P,Y)\text{const.}}\right)}_{\equiv\widetilde{\sigma}(\vartheta)}\right], \tag{58}$$

where we have defined an *effective* firm-level elasticity of substitution $\tilde{\sigma}(\boldsymbol{\vartheta})$, relying on the parallel between Equations (58) and (29).[95] In addition, we have defined the elasticity of output with respect to the relative price of IT, i.e., $\partial\tilde{y}(\boldsymbol{\vartheta})/\partial w \equiv \partial \log \tilde{Y}(\boldsymbol{\vartheta})/\partial w$. If the fall in IT prices raises the output of a firm, i.e., $\partial\tilde{y}(\boldsymbol{\vartheta})/\partial w < 0$, Equation (58) implies that nonhomotheticity ($\epsilon > 0$) leads to a higher effective elasticity of substitution in shaping the within-firm effect in Equation (30). Moving to the across-firm effect, the partial equilibrium response of the density of factor payments $\Lambda_C(\boldsymbol{\vartheta})$ is also directly tied to the elasticity of firm output through:

$$\left.\frac{\partial \Lambda_C(\boldsymbol{\vartheta})}{\partial w}\right|_{(P,Y,g)\text{const.}} \approx \frac{\lambda-1}{\lambda}\Lambda_C(\boldsymbol{\vartheta})\left.\frac{\partial\tilde{y}(\boldsymbol{\vartheta})}{\partial w}\right|_{(P,Y)\text{const.}}, \tag{59}$$

where we have assumed that the IT cost share is small, $\tilde{\Omega}(\boldsymbol{\vartheta}) \ll 1$. Therefore, the effect of nonhomotheticity on the response of output, $\partial\tilde{y}(\boldsymbol{\vartheta})/\partial w$, determines both the within-firm response (in Equation 58) and the across-firm response (in Equation 59).

Let us now examine the variations across firms in the elasticity of output with respect to IT prices. To the first order of approximation in IT cost share $\tilde{\Omega}(\boldsymbol{\vartheta})$, the elasticity is given by:

$$\left.\frac{\partial\tilde{y}(\boldsymbol{\vartheta})}{\partial w}\right|_{(P,Y)\text{const.}} \approx -\zeta\left(1+\frac{(1-\sigma)\epsilon}{\gamma}\right)\tilde{\Omega}(\boldsymbol{\vartheta}). \tag{60}$$

A fall in the relative price of IT lowers the average cost of each firm proportionally to its IT cost share $\tilde{\Omega}(\boldsymbol{\vartheta})$, which in turn raises the output with an adjusted demand elasticity $\zeta = \frac{\lambda}{1+\lambda(\gamma-1)}$. But this shock also raises the returns to scale, lowering the cost elasticity and the gap between marginal and average costs. Therefore, the pass-through of a fall in IT prices to the marginal cost of firms is higher due to the effect on their returns to scale. Equation (60) shows that this channel raises the elasticity of firm output to IT prices compared to the homothetic case by a factor of $(1-\sigma)\epsilon/\gamma$. Finally, the nonhomotheticity of IT demand and the resulting cross-sectional correlation between size and IT cost share shown in Equation (24), in combination with Equation (60), predict that the response of output is greater for larger firms. Therefore, the IT shock reallocates market shares toward larger firms and raises market concentration.

D Calibration Strategy

We use the results of Table 2 corresponding to the pooled sample of all industries for the parameters of the production function (ϵ,σ,γ), and the Markov process $\boldsymbol{\rho} = \left(\rho_{\theta\theta},\rho_{\theta\phi},\rho_{\phi\theta},\rho_{\phi\phi},\eta_\theta,\eta_\phi\right)$.[96] The first and second sets of rows in Table 3 revisit the values of these parameters. The table indicates the parameters that are directly estimated with "Estimated."

We can determine some of the remaining model parameters based on the estimation results despite the fact that

[95] We emphasize that the standard definition of the elasticity of substitution focuses on substitution patterns along a given isoquant. In this sense, as the name nhCES suggests, the elasticity of substitution here remains constant and equal to σ for all firms. The partial derivatives in the definition in Equation (58) additionally include the response of the firm output, keeping constant all general equilibrium variables except the relative price of IT.

[96] The only remaining parameter from Table 2 used for this exercise is the parameter α used for the patterns of labor share. As we explain below, we use the parameter α corresponding to the estimates from the manufacturing sector. The estimated values of the time-trend parameters $\left(\mu_\theta,\mu_\phi\right)$ are negligible and we set them to zero, in line with the stationary structure of the equilibrium of the model developed in Section 3.3.

they have not been directly estimated. In particular, the estimation results allow us to infer the values of the factor symmetric and IT-biased productivity states $\boldsymbol{\vartheta}_{it} = (\theta_{it}, \phi_{it})$ from Equations (32) and (33) and the productivity innovations $\boldsymbol{u}_{it} = \left(u_{\theta,it}, u_{\phi,it}\right)$ through Equation (31) for each firm i at time t in the data. We use the inferred productivity innovations to find estimated values for the variances $\left(\varkappa_\theta^2, \varkappa_\phi^2\right)$ of the two productivity innovations. The last row in the parameters of the productivity process in Table 3 presents the values of these variance parameters. The table indicates the parameters that we have determined indirectly based on the results of estimation with "Estimation."

The inferred values of productivity states further allow us to calibrate the distribution F of the productivity states of entrants in Equation (39). We rely on the productivity states inferred from the estimation to calibrate the parameters $\left(\xi_0, \overline{\theta}_o\right)$. Given the Pareto assumption and the independence of distributions of θ and ϕ in F, the right tail of the distribution of factor-symmetric productivity states must correspond to the largest entrants that we observe in our data. Therefore, we can infer the behavior of the tail of the distribution based on the estimated θs among the largest entrants (firms younger than one year). Similarly, we calibrate the variance $\varkappa_o^2$ of the distribution of IT-biased productivity states among entrants from data. Table 3 shows the values of these parameters that are found based on the estimation results. The remaining two parameters $\underline{\theta}_o$ and $\overline{\phi}_o$ of the distribution F require the knowledge of the *entire* distribution of productivity states. Since the there is some selection toward larger firms in the sample we use for estimation, we do not rely on our estimation results to calibrate these two parameters. We will shortly return to these parameters below.

Several model parameters can be directly matched to observable moments in the data, or values reported in prior work. Table 3 indicates the values of these parameters as "Calibrated." For the exogenous probability of exit, we calibrate its value to the average rate of exit of *large* firms in our sample of around $\delta = 0.04$. We calibrate the cost of entry χ to fit the number of firms per worker in our data ($N \approx 0.08$), given all other parameters of the model. These two parameters appear in the last two rows of the parameters of the process of entry and exit. Finally, we set the discount rate to $\varrho = 0.95$ and the elasticity of substitution among different firm products to $\lambda = 5$, values commonly assumed in the literature.

We are left with a set of three parameters $\left(\psi, \underline{\theta}_o, \overline{\phi}_o\right)$, including the fixed cost of operation ψ, and two parameters $\underline{\theta}_o$ and $\overline{\phi}_o$ corresponding to the distribution F of entrants. To calibrate these remaining parameters, we perform a search in the parameter space, targeting the following three data moments in year 1995: two measures of market concentration (the share of top 1% and 5% of firms in total sales) and aggregate IT intensity $\overline{\Omega}/\left(1+\psi/\overline{C}\right)$.[97] We use our firm-level data to calculate the first two data moments based on the pooled sample of BRN and RSI firms. For the last data moment, we rely on the macro data series to find the aggregate IT intensity. We cannot rely on the sample of EAE firms to calculate the aggregate IT intensity since the sample covers firms above a size threshold and is not representative of all firms. Table 3 indicates the three parameters calibrated based on this moment matching strategy with "Search."

[97]We begin the search with the following values: we use $\psi = 0$ and for $\left(\underline{\theta}_o, \overline{\phi}_o\right)$ we use the lower bound and the mean of the corresponding estimates in our sample of entrants. We describe the search procedure and the calibration of the productivity distributions with greater details in Section 5 of the online appendix.

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