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Technology as Problem-Solving Procedures and Technology as Input-Output Relations: Some Perspectives on the Theory of Production

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Technologies as problem-solving procedures and technologies as input-output relations: some perspectives on the theory of production*

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Abstract

In this work, inspired by Winter [2006], in fact of vintage 1968, we discuss the relation between three different levels of analysis of technologies, namely as (i) bodies of problem-solving knowledge, (ii) organizational procedures, and (iii) input-output relations. We begin by arguing that the "primitive" levels of investigation, "where the action is", are those which concern knowledge and organizational procedures, while in most respects the I/O representation is just an ex post, derived, one. Next, we outline what we consider to be important advances in the understanding of productive knowledge and of the nature and behaviors of business organizations which to a good extent embody such a knowledge. Finally, we explore some implications of such "procedural" view of technologies in terms of input-output relations (of which standard production functions are a particular instantiation). We do that with the help of some pieces of evidence, drawing both upon incumbent literature and our own elaboration on micro longitudinal data on the Italian industry.

Keywords:
Theory of Production, organizational routines, problem-solving knowledge, production function, micro-heterogeneity

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1 Introduction

The long-hidden essay by Sid Winter, "Toward a Neo-Schumpeterian theory of the Firm", at last published in a forthcoming issue of *Industrial and Corporate Change*, raises a few fundamental challenges to economic analysis which to a good extent continue to remain challenges after more than a third of a century. They concern the nature of technologies and their relation with individual and collective knowledge; the ways economists do (and ought to) represent them; the characteristics of technological and organizational learning; and the implications of all this in terms of theory of the firm. Certainly, not bad at all for a short essay! Building on some seminal intuitions of this work, here we shall discuss where one has taken (or not taken) those ideas since, offer some evidence which largely corroborates the early hints and flag some areas of analysis which remain in need of urgent intervention.

The basic intuition, which is also the central point of departure of this essay is that a fully-fledged interpretation of technologies and their dynamics - that is, technological innovation - entails three complementary levels of analysis. The <u>first</u> one pertains to the *nature of knowledge* upon which technological activities - including of course production - draws. From this angle of observation, one investigates the types of knowledge bases and skills which are called upon in, say, the transformation of pieces of iron, plastic, glass, etc. into a finished car. And dynamically, one studies the ways such a knowledge is accumulated and improved.

The conception, design, and production of whatever artifact, however, involve (often very long) sequences of cognitive and physical acts. In the example of a car one goes from the activities of design to the development of a prototype all the way to the actual production. And, in turn, at a more detailed observation, at each step one finds a complex sequence of operations generally undertaken by different but coordinated people in association with different tools and machines. This <u>second</u> level of description, which we may call *procedural*, is deeply intertwined with the analysis of how business organizations actually work, since big "chunks" of activities occur within single organizational entities rather than being mediated through the market.

Finally, <u>third</u>, precisely the same activities - seen above in terms of sequences of procedure eliciting diverse type of knowledge - may be also described in terms of the list of inputs which come, under various headings, into the production process and of what finally comes out. This *input-output* description is of course the one most familiar to economists, with all refinements on the purported relations between inputs and outputs themselves featuring in "production functions", "production possibility sets", and the like.

In all that a crucial question regards the relationships between these three levels of analysis of production activities. Winter's essay addresses precisely that question suggesting that the "primitive" levels of investigation, "where the action is", are those which concern knowledge and organizational procedures, while in most respects the I/O representation is just an ex post, derived, one. Indeed, a lot of work - a good deal of which of evolutionary inspiration - has gone into the economics of knowledge and innovation, on the one hand, and into the study of organizations as problem-solving entities, on the other.

Granted that, what are the implications for the theory of production, *narrow sense*, that is in terms of sheer relations between inputs and outputs? And what does the evidence tell us about it? In the following, we shall address these issues.

In Section 2 we briefly outline what we consider to be important advances in the understanding of productive knowledge and of the nature and behaviors of business organizations which to a good extent embody such a knowledge. Next, in Section 3, we explore some implications of such "procedural" view of technologies in terms of input-output relations (of which, to repeat, standard production functions are a particular instantiation). Together we offer some pieces of evidence, drawing both upon incumbent literature and our own elaboration on micro longitudinal data on the Italian industry.

2 Technologies as (knowledge-ridden) problem solving activities

There are a few things which we know better now as compared to the time when Sid Winter was writing his essay around 1968. They come mostly from various attempts to "open up the technological blackbox" - to use a famous expression of Nate Rosenberg -, and complementary attempts to "open up the organizational blackbox".

2.1 Technological paradigms and trajectories

A variety of concepts have been put forward to define the nature of technology and technological innovation: *technological regimes, paradigms, trajectories, salients, guidepost, dominant design* and so on. The names are not so important. More crucially, these concepts are highly overlapping in that they try to capture a few common features of technological activities and of the procedures and directions of technical change. Let us consider some of them.

The notion of *technological paradigm* which shall be for the time being our yardstick is based on a view of technology grounded on the following three fundamental ideas (see Dosi [1982] and Dosi [1984]).

First, it suggests that any satisfactory description of "what is technology" and how it changes must also embody the representation of the specific forms of knowledge on which a particular activity is based, which cannot be reduced to a set of well-defined blueprints. It primarily concerns problem-solving activities involving - to varying degrees - also tacit forms of knowledge embodied in individuals and organizations.

In this view technology is a set of pieces of knowledge ultimately based on selected physical and chemical principles, know-how, methods, experiences of successes and failures and also, of course, physical devices and equipment.

Second, paradigms entail specific heuristic and visions on "how to do things" and how to improve them, often shared by the community of practitioners in each particular activity (engineers, firms, technical societies, etc.), i.e. they entail collectively shared cognitive frames (Constant [1980]).

Third, paradigms often also define basic templates of artifacts and systems (i.e. "dominant designs[1]"), which over time are progressively modified and improved. These basic artifacts can

[1]Incidentally note that the notion of dominant design is well in tune with the general idea of technological paradigms but the latter do not necessarily imply the former. A revealing case to the point is pharmaceutical technologies which do involve specific knowledge basis, specific search heuristics, etc. - i.e. the strong mark of paradigms - without however any hint of dominant design. Molecules, even when aimed at the same pathology, might have quite different structures: in that space, one is unlikely to find similarities akin those linking even a Volkswagen Beetle 1937 and a Ferrari 2000. Still, the notion of "paradigm" holds even in the former case in

also be described in terms of some fundamental technological and economic characteristics. For example, in the case of an airplane, their basic attributes are described not only and obviously in terms of inputs and production costs, but also on the basis of some salient technological features such as wing-load, take-off weight, speed, distance it can cover, etc. Similar examples of technological invariance can be found e.g. in semiconductors, agricultural equipment, automobiles and a few other micro technological studies (Sahal [1981]; Grupp [1992]; Saviotti [1996]).

What is interesting here is that technical progress often seems to display patterns and invariance in terms of some basic product characteristics. Hence the notion of *technological trajectories* associated with the progressive realization of the innovative opportunities underlying each paradigm - which can in principle be measured in terms of the changes in the fundamental techno-economic characteristics of artifacts and production processes. The core ideas involved in this notion of trajectories are the following.

Each particular body of knowledge (each paradigm) shapes and constraints the rates and direction of technical change, in a first rough approximation, irrespectively of market inducements. In fact, technical change is partly driven by repeated attempts to cope with technological imbalances which it itself creates[2]. As a consequence, one should be able to observe regularities and invariance in the pattern of technical change which hold under different market conditions (e.g. under different relative prices) and whose disruption is mainly correlated with radical changes in knowledge-bases (in paradigms).

Moreover a rather general property, by now widely acknowledged in the innovation literature, is that learning is often *local* and *cumulative*. “Locality” means that the exploration and development of new techniques and product architectures is likely to occur in the neighborhood of the techniques and architectures already in use (Atkinson and Stiglitz [1969]; David [1975]; Antonelli [1995]). “Cumulativeness” stands for the property that current technological developments often build upon past experiences of production and innovation, proceed via sequences of specific problem solving junctures (Vincenti [1990]), and in several circumstances also lead to microeconomic serial correlations in successes and failures.

The literature on technological knowledge and technological change has offered, of course, plenty of insights also into the detailed mechanisms through which innovative search occurs, on the sources of knowledge on which it draws and on their intersectoral differences. (For critical surveys, Dosi [1988], Freeman [1994] and Dosi et al. [2005]). For the purpose of this work, however, let us content ourselves with the basic idea that *there is a structure to technological knowledge, and dynamically to the patterns of technological innovation* which tend to be relatively invariant, linked as it is to specific routes to the solution of particular problems (e.g. going from iron oxide to steel and from steel to a steel-made combustion chamber with certain technical characteristics). Together, to repeat, major changes in such knowledge structures tend to come from major discontinuities in underlying paradigms.

All we have said so far is from the angle of “technology as knowledge”. However, a good deal of “economically useful” technological knowledge is nowadays mastered by business firms, which even undertake in some developed countries a small but not negligible portion of the efforts aimed at a more speculative understandings of the physical, chemical, biological

terms of underlying features of knowledge bases and search processes.

[2]This is akin to the notion of reverse salient (Hughes [1983]) and technological bottlenecks (Rosenberg [1976]): to illustrate, think of increasing the speed of a machine tool, which in turn demands changes in cutting materials, which leads to changes in other parts of the machine...

properties of our world (i.e. they also undertake "basic science[3]"). How does all that relate with the structure and behaviors of firms themselves?

2.2 Knowledge, routines, and capabilities in business organizations

Possibly one of the most exciting, far from over, intellectual enterprises developed over the last decade has involved the interbreeding between the evolutionary economics research program, (largely evolutionary inspired) technological innovation studies and an emerging competence/capability-based theory of the firm. The roots rest in the pioneering organizational studies by Herbert Simon, James March and colleagues (Simon [1969]; March and Simon [1993]; Richard M. Cyert [1992]; March [1988]) and in the equally pioneering explorations of the nature and economic implications of organizational routines by Nelson and Winter [1982] (with follow-ups such as those in Cohen et al. [1996]; Teece et al. [1997]; Dosi et al. [2000b]; the *Special Issue of Industrial and Corporate Change*, 2000, edited by Mie Augier and James March (Augier and March [2000]); Montgomery [1995]; and Foss and Mahnke [2002]).

It is familiar enough to most readers that business firms "know how to do certain things" - things like building automobiles and computers - and know that with different efficacy and revealed performances. In turn, what does "organizational knowledge" mean? What are the mechanisms that govern how it is acquired, maintained and sometimes lost? As several authors in the just cited works suggest, organizational knowledge is in fact a fundamental link between the social pool of knowledge, skills, discovery opportunities, on the one hand, and the rates, directions, economic effectiveness of their *actual* exploration, on the other.

Distinctive organizational competences/capabilities[4] bear their importance also in that they persistently shape the destiny of individual firms - in terms of e.g. profitability, growth, probability of survival - and, at least equally important, their distributions across firms shape the patterns of change of broader aggregates such as particular sectors or whole countries.

"Competencies" and "capabilities" build on ensembles of organizational routines. In turn, the latter (i) as thoroughly argued by Nelson and Winter [1982], embody a good part of the memory of the problem-solving repertoires of any one organization; (ii) entail complementary mechanisms of governance for potentially conflicting interests (for a more detailed discussion see Dosi and Coriat [1998]), and, (iii) might well involve also some "meta-routines", apt to painstakingly assess and possibly challenge and modify "lower level" organizational practices (the more incremental R&D activities, and recurrent exercises of "strategic adjustment", are good cases to the point).

In this view, routines and other recurrent organizational practices may be interpreted as a set of problem-solving procedures in turn composed of elementary physical acts (such as moving a drawing from an office to another or boring a piece of iron on a machine tool) and elementary cognitive acts (such as doing a certain calculation).

[3]See Pavitt [1991] and Rosenberg [1990].

[4]In the literature, the two terms have often been used quite liberally and interchangeably. In the introduction to Dosi et al. [2000b] and more explicitly in Dosi et al. [2000a] one proposes that the notion of capability ought to be confined to relatively purposeful, "high level" tasks such as e.g. "building an automobile" with certain characteristics, while "competences", for sake of clarity might be confined to the ability to master specific knowledge bases (e.g. "mechanical" or "organic chemistry" competences). Clearly, such notion of competences/capabilities largely overlaps with what has come to be known as the "competence view of the firm".

This *procedural* view of technology is indeed quite complementary to the foregoing knowledge-centered one. One could even state that the procedural perspective simply means viewing "knowledge in action". Indeed, it is helpful to think of complex problem-solving activities - as most contemporary industrial activities in fact are - as problems of design of complex sequences of actions, rules, search heuristics[5], drawing at each point of the sequence upon specific skills and pieces of knowledge.

2.3 Division of labor, decompositions, complementarities

Can one "unbundle" the foregoing sequences of tasks and assess on whatever measure the effectiveness of each "elementary component"[6]?

It turns out that the effectiveness of such "procedural systems" in most circumstances is at best only *partly-decomposable*, in that it cannot be neatly separated into the effectiveness of single acts which could then be added together into the overall effectiveness of the sequence. That is, *complementarities are endemic*. So, for example, a very effective problem-solving sequence may be that in which agent A does x, followed by B doing y, and C doing z. Conversely a sequence with A doing z might increase the overall performance if C turns to action k, but decreases it other things being equal... Hence, marginal contributions to the effectiveness of components (i.e. "acts" in problem-solving procedures and physical components in technological systems) can rapidly switch from negative to positive values and vice versa, depending on which values are assumed by other components. For instance, adding a more powerful engine could amount to decrease the performance and reliability of an aircraft (Vincenti [1990]) if other components are not simultaneously adapted. Similarly, major innovations often appears only when various elements which ere already known for a long time are recombined and put together under a different frame (cf. Levinthal [1998] for a detailed account of the development of wireless communication). By the same token, introducing some routines, practices or incentive schemes, which have proven superior in a given organizational context, could prove harmful in a different one where other elements are not appropriately co-adapted.

Such aspects are present even in the simplest production technologies. Consider for example team production as exemplified by Alchian and Demsetz [1972]: two workers lifting a heavy load. Additional individual efforts generally rise team production, but when the levels of effort applied by the two are disproportionate, this might result in the load being turned over and falling, thus sharply decreasing the output of the team itself.

In a growing literature, including works by Marengo and colleagues (cf. Marengo et al. [2000] and Marengo and Dosi [2005]) one begins to offer explicit formal accounts of the foregoing view of technology, and dynamically, of the search thereof in terms of *combinatorics of elementary cognitive and physical components*. The formal apparatus is then put to use in terms of "comparative dynamics", studying for example the comparative efficiency properties of different problem-decompositions and patterns of division of labor; the outcomes and speeds of convergence of different search strategies in the problem-solving space; and the effects thereof of diverse organizational structures.

As noted in the introduction to this work, however, one still lacks any systematic link between the procedural perspective, just sketched out, which lives in the space defined by "bits of knowledge" and by the presence or absence of a particular physical and cognitive

[5]For some example in the case of so called "Complex Product Systems" cf. Dosi et al. [2003].

[6]For more details see Marengo and Dosi [2005].

components, on the one hand, and the more mundane world of "what comes in and what goes out" the production process.

3 The (missing) links between the evolution of problem-solving knowledge and input-output relations

Let us elaborate on the illustrative example, originally put forward by Richard Nelson and Sid Winter, of *making a cake*. This involves inputs, both of the "variable" kind - flour, butter, eggs, etc. - and "fixed" ones - including spoons, pots, ovens, etc. -. And, clearly, there is an output, a cake, possibly with a variable taste, caloric content, etc.

Apparently, the input-output characterization is straightforward: a vector x of inputs for y (possibly a vector) of output(s). However, just turn the question to your grandmother: "how do I make a cake?". Suppose for a moment that the old lady answers "max price times output minus price of inputs times their quantities". Anyone would take that as ultimate evidence of old-age *dementia*. Needless to say, such an answer is also totally uninformative on how to make a cake. And so is of course the more sophisticated answer suggesting that the cake and flour, butter, sugar, etc. are related through, say, a degree-one homogeneous function! (In fact the latter statement would only further confirm the mental disorder of the poor lady...).

Of course, the appropriate answer to the question on how to make a cake entails a series of procedures: "...mix a couple of eggs and one ounce of butter into a pound of flour...". This procedural story does involve statements on quantities (the two eggs, the ounce of butter, etc.) but such quantities make sense only in relation to specific sequences of operations[7]. Moreover note that the relation between such quantities and relative prices is at best indirect: one needs certain ingredients in order to make a cake, and needs them irrespectively of their price (except perhaps "local" forms of substitution, such as margarine vs. butter).

One earlier discussion of technological paradigms implies indeed that these considerations hold well beyond the example of the cake and are pertinent to the generality of production activities. Moreover, one should expect individual agents (typically firms) to develop distinct "ways of doing things", relatively persistent over time, associated with their equally persistent organizational routines (incidentally, recall pioneering Leibstein's "X-efficiency" which tries to capture in a somewhat blackboxed way such links between "ways-of-doing-things" and revealed efficiency: see Leibenstein [1966]).

Given that, what are the implications of such properties of technologies in terms of distribution of input coefficients and their dynamics over time?

How do firm-specific combinations of routines and "pieces of knowledge" reflect into the revealed distributions of input coefficients? In order to answer the question one requires firm-level (or plant-level) longitudinal panel data. Indeed, they have become increasingly available. And with that a few "stylized facts" have emerged[8]. They include:

[7] In this respect it is worth mentioning the *funds-flows* theory of production which, while falling short of an explicit procedural representation of production activities, attempts to nest the use of inputs into an explicit temporal sequence flagging when the inputs themselves are used (i.e. when the flows of their services are called upon): cf. Georgescu-Roegen [1970] and the reappraisal and the applications in Morroni [1992].

[8] See among others Baily et al. [1992], Baldwin [1998], Jensen and McGuckin [1997], Power [1998], Rumelt [1991], Foster et al. [2001], Bartelsman and Dhrymes [1998], Bartelsman et al. [2005], Bottazzi et al. [2003], Chew et al. [1990], and the discussions in Bartelsman and Doms [2000] and Dosi [2005] together with the earlier insights from Nelson [1981], and Nelson [1991].

(i) wide asymmetries in productivities, both across firms and even within them;

(ii) equally wide heterogeneity in relative input intensities; and,

(iii) high degrees of intertemporal persistence in the above properties.

We shall illustrate such "stylized facts" with the help of some evidence drawn especially from Italian firm-level data (cf. See the Appendix for some statistical details). However, it might be useful to start with some considerations on the notion of "productivity" itself.

3.1 Input efficiencies: a first digression on the notion of "productivity"

As well known, there are two commonly used measures of production efficiency, namely labour and total factor productivity (TFP).

It should come as no surprise (see also below) that, despite its obvious limitations, we tend to prefer a measure based on the net output (that is the "real" value added) per employee or, even better, per worked hours. The reason for this preference lies in the dubious elements which make up conventional production functions, in turn the instrument necessary to yield the TFP measure.

It follows from our foregoing discussion that technologies essentially involve *complementarities* among inputs - so that it makes little sense to separate the "contribution" of each "factor" to the final output. Indeed, such a "decomposition" exercise makes as much sense as disentangling the separate contributions of butter, eggs, sugar, etc. to the making of a good tasting cake. As Nelson puts it:

> "If factors are complements, growth is superadditive in the sense that the increase in output from growth of inputs is greater than the sum of the increases in output attributable to input growth calculated one by one holding other inputs constant at their base level in each sub-calculation" (Nelson [1981], p. 1053)

There is in fact a more recent literature on "superadditivity[9]" (needless to say, with little or no reference to the earlier original insights) trying to reconcile within more flexible (more "general") functional forms of production functions a notion of complementarity with the usual assumptions on micro maximization and market equilibrium (again, see also the concluding remarks below).

The bottom line in our view, however, is that one typically lives in a technological world characterized by micro coefficients which are fixed in the short-term (i.e. each firm basically masters just the technique actually in use), while in the longer-term techniques change essentially due to learning and technical progress. Conversely, if this is the case, it does not make much sense to distinguish changes along any purported production function vs. changes of the function itself.

3.2 Asymmetries in productivity

Come as it may, an overwhelming evidence concerning both labor productivity and TFP, at all levels of disaggregation, suggest widespread differences in production efficiency across firms and across plants which tend to be persistent over time (cf. the evidence cited in footnote 8).

[9] See Milgrom and Roberts [1990] and Milgrom and Roberts [1995].

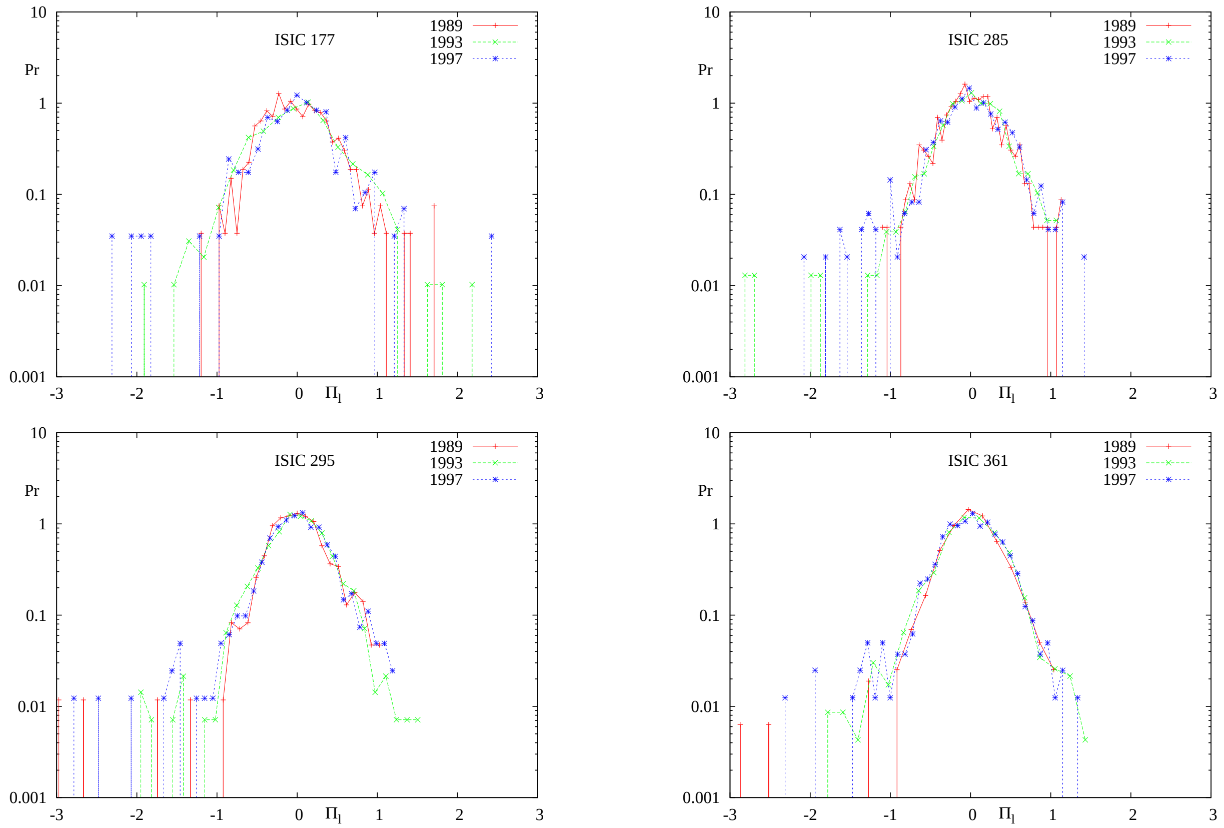

Figure 1: Distributions of Labor Productivity by sectors: normalized values. Source: Our elaboration of Italian (ISTAT MICRO.1) data (for the definition of the sectors, see Tables 1 and 2

Our Italian data are well in tune with such stylized facts. Figure 1 presents the distribution in some 3-digit sectors[10] of (normalized) value added (VA) per employee, that is:

$$\pi_i(t) = \log \Pi_i(t) - \langle \log \Pi_i(t) \rangle \tag{1}$$

whereby, $\Pi_i(t) = VA_i/N_i$ and $\langle \log \Pi_i(t) \rangle \equiv$ mean (log) value added (VA) per employee (N) averaged over all firms in any particular sector, in each year.

Moreover, as shown in Table 1, such productivity differentials are quite stable over time, just with some relatively mild regression-to-the-mean tendency[11].

The general picture is characterized by general and profound heterogeneity across firms, also with respect to capital-output ratios and relative input intensities.

First, note that not surprisingly different industrial sectors significantly differ in their mean labor productivity and capital intensities (cf. Table 2).

Second, together with the already noted asymmetries in labor productivity, one observes equally remarkable inter-firm differences in capital-output ratios (see Figure 2). Could such differences be due primarily to some intrinsic heterogeneity *across different lines of activity* as opposed to inter-firm differences *within* the same line of activities? Interestingly, disaggregation does *not* appear to reduce heterogeneity: as an illustration, compare the distributions on the right-hand side of Figure 2, concerning 3-digit subsets of the 2-digit sectors on the left-handed side. As Griliches and Mairesse [1999] vividly put it:

[10]The selection of the sectors we chose to present here come from a numerosity criterion: The top four

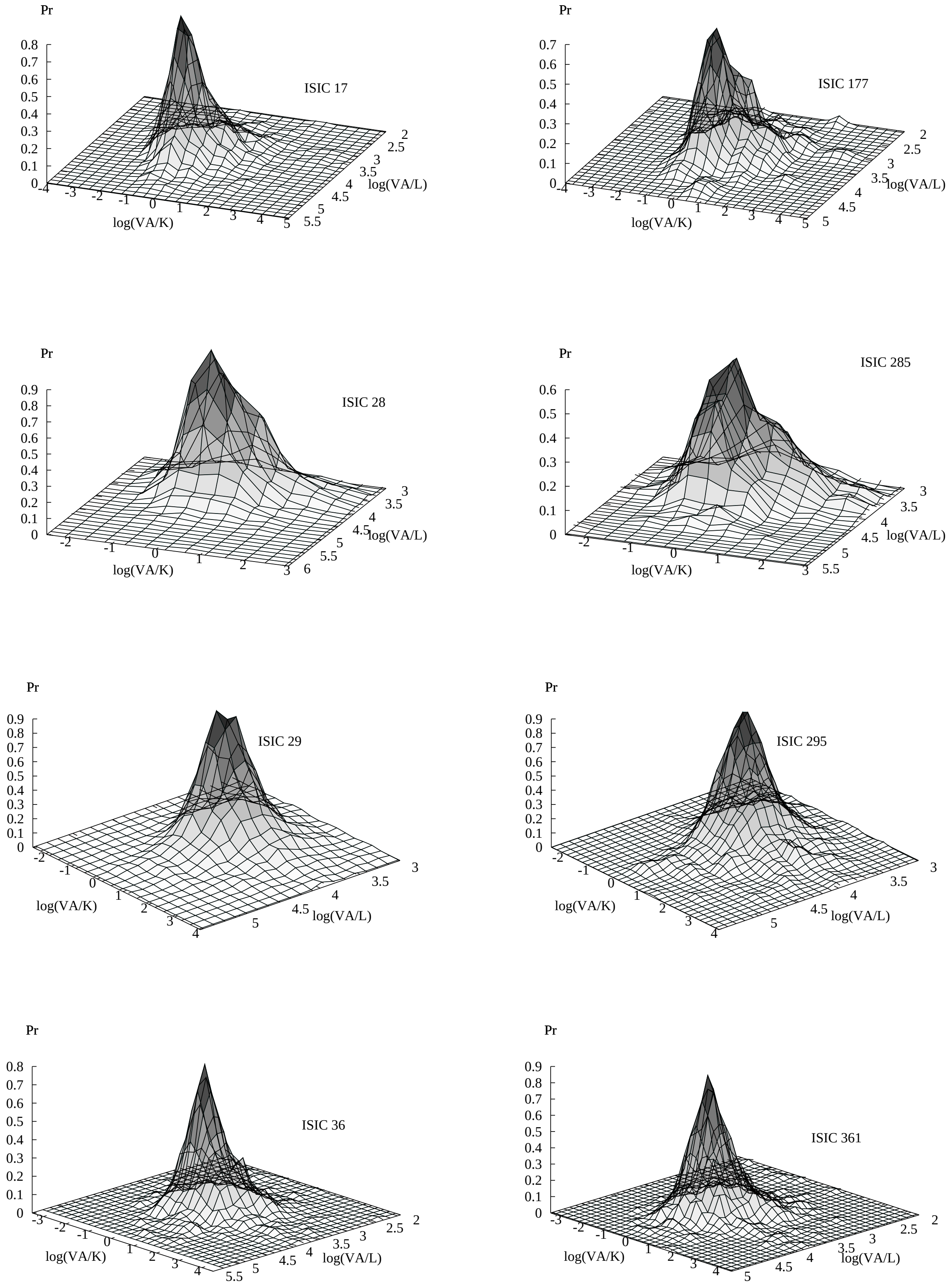

Figure 2: Labor Productivities and input intensities: the microdistributions. **(Left Side)** Kernel density estimate of $(\log(VA/K), \log(VA/L))$ in 1997 for 4 different manufacturing sectors at 2 Digit. **(Right Side)** Kernel density estimate of $(\log(VA/K), \log(VA/L))$ in the same year for some nested sectors at 3 digit.

SECTOR	ISIC Code	Labor Prod. AR(1)	Labor Prod. Std.Dev.	Π_l Growth rates AR(1)	Π_l Growth rates Std.Dev
Production & processing of meat	151	1.0021	0.0016	-0.3446	0.0915
Knitted & crocheted articles	177	1.0056	0.0023	-0.2877	0.1005
Wearing apparel & acc.	182	1.0035	0.0012	-0.3090	0.0871
Footware	193	1.0029	0.0019	-0.3903	0.0793
Articles of paper and paperboard	212	1.0053	0.0008	-0.3027	0.0603
Printing and services related to printing	222	0.9962	0.0011	-0.4753	0.1103
Plastic products	252	1.0030	0.0010	-0.3150	0.0557
Articles of concrete, plaster & cement	266	0.9985	0.0016	-0.4572	0.0979
Metal products	281	1.0034	0.0012	-0.4125	0.0715
Treatment, coating of metal & mech. engin.	285	1.0051	0.0013	-0.1846	0.0679
Special purpose machinery	295	1.0011	0.0011	-0.3040	0.0495
Furniture	361	0.9994	0.0001	-0.4472	0.0808

Table 1: AR(1) coefficients for Labor Productivity in levels and first differences. Labor Productivity (Π_l) is deflated according to the sectoral output price index.

> "we (...) thought that one could reduce heterogeneity by going down from general mixtures as "total manufacturing" to something more coherent, such as "petroleum refining" or "the manufacture of cement". But something like Mandelbrot's fractal phenomenon seems to be at work here also: the observed variability-heterogeneity does not really decline as we cut our data finer and finer. There is a sense in which different bakeries are just as much different form each others as the steel industry is from the machinery industry."

3.3 Further evidence on technological asymmetries: wage-profit frontiers

A way of appreciating the differences among the techniques mastered by each firm entails the identification of the *wage-profit frontiers* associated with it[12].

Assume for simplicity homogeneous output and labor. To make it even simpler assume the absence of intermediate goods. Hence output coincide with value added. (Note, however, that if the ratios of intermediate inputs to "physical" net output were roughly constant across firms within the same activity, the simpler relation would directly apply also to the more realistic one).

Consider the following variables: K = capital stock; r = gross return on capital; Y =

two-digit sectors in terms of firms population in our sample and the 3-digit sectors with more than 200 firms.

[11]For the estimation technique see Chesher [1979].

[12]Such a formal instrument was commonly used within the so-called "capital controversy" (cf. Harcourt [1972]. On its use in order to characterize different forms of technical progress, see Schefold [1976].

SECTOR	ISIC Code	1989		1991		1994		1997	
		Π	VA/K	Π	VA/K	Π	VA/K	Π	VA/K
Production & processing of meat	151	4.24 (0.428)	-0.346 (0.764)	4.34 (0.551)	-0.417 (0.811)	4.33 (0.429)	-0.629 (0.838)	4.36 (0.513)	-0.378 (1.29)
Knitted & crocheted articles	177	3.74 (0.421)	0.123 (0.805)	3.83 (0.44)	0.094 (0.829)	3.9 (0.576)	0.243 (0.946)	3.86 (0.508)	0.211 (1.16)
Wearing apparel & accessories	182	3.60 (0.502)	0.67 (0.860)	3.61 (0.547)	0.640 (0.933)	3.66 (0.542)	0.701 (0.916)	3.71 (0.581)	0.809 (1.27)
Footwear	193	3.67 (0.363)	0.455 (0.784)	3.74 (0.420)	0.547 (0.814)	3.81 (0.510)	0.622 (0.858)	3.79 (0.553)	0.793 (1.16)
Articles of paper and paperboard	212	4.30 (0.338)	-0.299 (0.658)	4.35 (0.372)	-0.401 (0.680)	4.41 (0.474)	-0.401 (0.755)	4.48 (0.454)	-0.210 (1.15)
Printing and services related to printing	222	4.44 (0.335)	0.187 (0.654)	4.49 (0.345)	0.173 (0.737)	4.47 (0.369)	0.091 (0.778)	4.32 (0.507)	0.0481 (1.21)
Plastic products	252	4.30 (0.379)	-0.307 (0.627)	4.37 (0.424)	-0.405 (0.614)	4.43 (0.535)	-0.369 (0.813)	4.40 (0.473)	-0.128 (1.03)
Articles of concrete, plaster & cement	266	4.31 (0.417)	-0.478 (0.601)	4.34 (0.454)	-0.543 (0.682)	4.34 (0.454)	-0.441 (0.722)	4.40 (0.449)	-0.128 (0.995)
Metal products	281	4.11 (0.365)	0.225 (0.721)	4.20 (0.397)	0.136 (0.733)	4.11 (0.451)	0.0099 (0.885)	4.26 (0.436)	0.423 (1.07)
Treatment & coating of metals; general mechanical engin.	285	4.08 (0.350)	-0.203 (0.698)	4.10 (0.349)	-0.326 (0.755)	4.18 (0.391)	-0.174 (0.865)	4.24 (0.435)	0.11 (1.29)
Special purpose machinery	295	4.41 (0.361)	0.343 (0.696)	4.45 (0.319)	0.262 (0.772)	4.48 (0.385)	0.253 (0.805)	4.49 (0.393)	0.456 (0.0966)
Furniture	361	4.04 (0.425)	0.0076 (0.788)	4.12 (0.337)	-0.0235 (0.706)	4.13 (0.387)	-0.06 (0.784)	4.10 (0.384)	0.047 (0.0947)

Table 2: Sectoral specificities in Input/Output Relations: Mean Labor Productivities ($\Pi = VA/L$), and Capital Intensities (VA/K). Constant price log variables; standard errors in brackets.

output (in our simplified example $= VA$, the value added); $w =$ monetary wages; $P_y =$ output price index ($\sim$ deflator for value added); $Y_r =$ deflated output; $v = K/Y =$ capital-output ratio; $\tilde{w} =$ real wages; L = Labour input; $\Pi = Y_r/L =$ Labor productivity.

Thus, by definition,

$$rK + wL = Y_r P_Y \tag{2}$$

and rearranging,

$$r\frac{K}{Y} + \frac{w}{P_Y}\frac{L}{Y_r} = 1$$

Then, since $K/Y = v$, $w/P_Y = \tilde{w}$ and $L/Y_r = 1/\Pi$, we can rewrite it as:

$$rv + \frac{\tilde{w}}{\Pi} = 1 \tag{3}$$

Equation (3) yields a linear relation between real wages and profits, given the technique. It defines a *wage-profit frontier (WPF)* which is the locus of income distributions compatible with it.

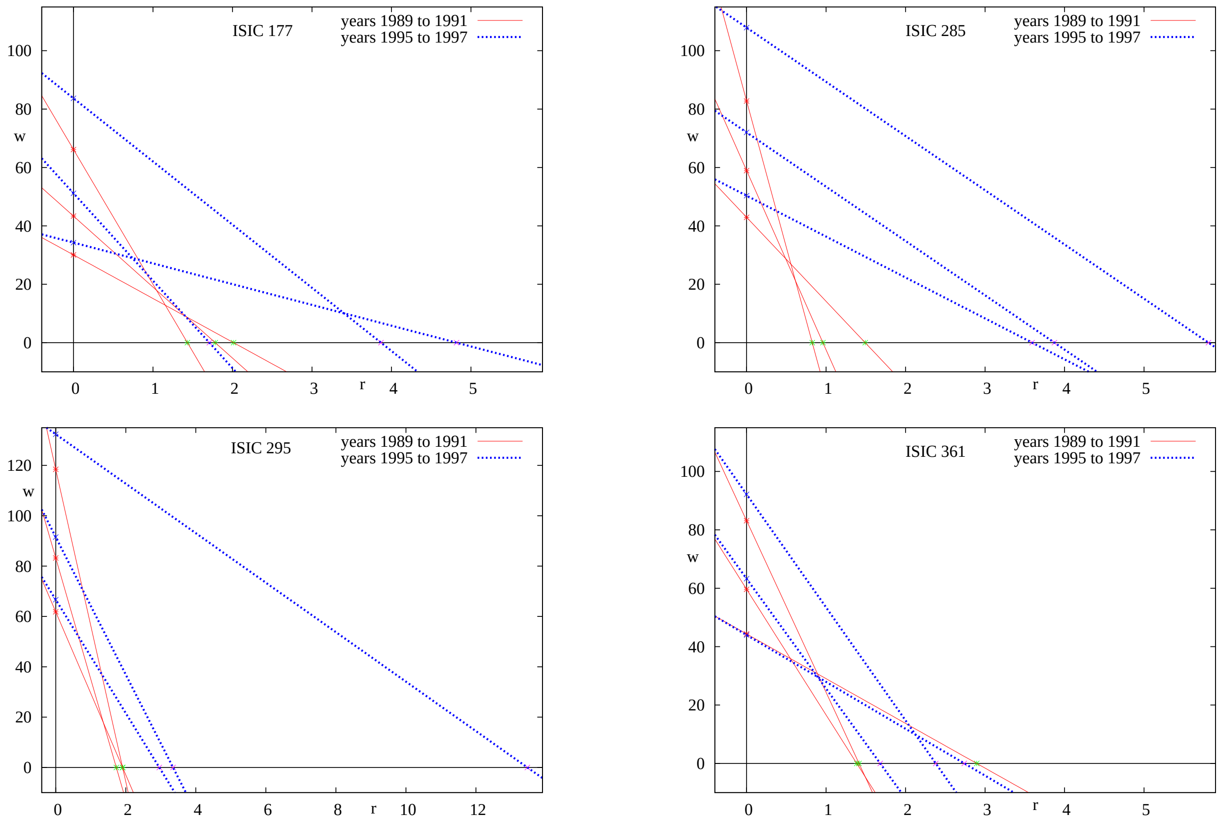

Figure 3: Wage-Profit frontier. Empirical estimate for the mean values over the periods 1989-91 and 1995-7.

Just rewrite equation (3) as $\tilde{w} = (1 - rv)\Pi$, clearly, for $r = 0$, $\tilde{w} = W = \Pi$, i.e. all product goes to wages, while, conversely, $\tilde{w} = 0$ yields the maximum rate of profit consistent with that technique.

It is straightforward that one can always rank techniques *given a wage (or profit) rate*. Moreover, if both intercepts of a certain technique are greater than those of another, it follows that the former dominates the latter irrespectively of relative prices.

Of course, one can speculate on many combinations among different wage-profit frontiers, of which the standard "production function" is just a particular case. But, what does the empirical evidence tell us? Figure 3 presents the WPFs over three quantiles (bins) ordered in terms of their y-intercept, that is, their associated labor productivity. As one can see, widespread asymmetries among firms are the norm, frequently displaying ensembles of techniques which dominates many others for the whole range of notional relative prices[13].

Over time, as Figure 3 shows, techniques basically change by the movement "outward" of the associated WPF's, interestingly displaying both increasing labor productivity and increasing maximum attainable profit rates: hence technical progress appears to be in many circumstances both labor- and capital-saving. What is the interpretation of this evidence?

In our view, an evolutionary account is quite straightforward in that it predicts persistent heterogeneity in production efficiencies (and in the degrees of innovativeness: cf. the discussions in Dosi [1988], Dosi [2005] and Freeman [1994]), as the outcome of idiosyncratic capa-

[13] As a term of comparison, notice that in a standard production function world, the envelope of all *notional* WPFs would look like a hyperbola while the empirical observation at any t for identical relative prices across firms would concentrate around a prevailing WPF (plus some noise).

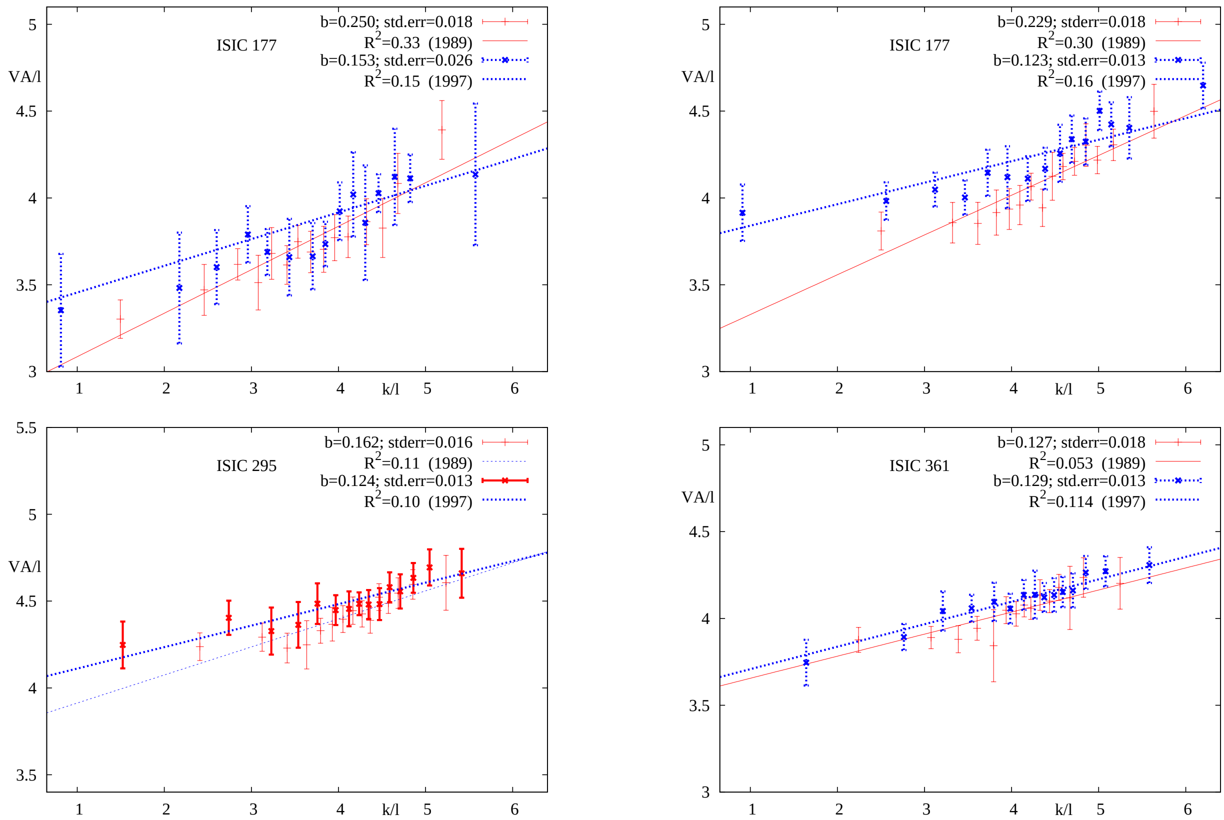

Figure 4: Labor Productivities and Capital/Labor Ratios. Bin plots and OLS estimates. Error bars display 2 standard errors. K and VA at constant prices.

bilities (or lack of them), mistake-ridden learning and forms of path-dependent adaptation. Differences in innovative abilities and efficiencies (together with differences in organizational set-ups and behaviors) we suggest make-up the distinct corporate "identities" which in turn influence those different corporate efficiencies revealed by the evidence ranging from the foregoing Italian one to that presented in the works cited above (cf. footnote 8, together with the insightful discussion in Winter [1982] and Winter [1987]).

3.4 Relative input intensities and revealed efficiencies

Given the widespread heterogeneity across firms discussed so far, let us investigate whether the data display any regularity in the relationship between input intensities and productivities, in turn hinting at some underlying "production function" with the properties most often postulated by economists (e.g. decreasing returns with respect to single inputs).

In particular, recall that in the presence of a standard Cobb-Douglas, the function $Y/L = f(K/L)$ grows in K/L but has a negative second derivative. As a consequence K/Y (the capital/output ratio) should grow together with both K/L and Y/L.

Our evidence (see Figure 4) does suggest a positive correlation between value added per employee (our proxy for "net output") and K/L, which should be properly understood as an indicator of mechanization/automation of production (cf. Pasinetti [1977] However no correlation appears between our proxy of labor productivity and capital/output ratios, which is indeed the proper measure of "capital intensity" of production (Figure 5). Putting it another way, there are firms which use more efficiently or less efficiently *both labor and capital*. Hence,

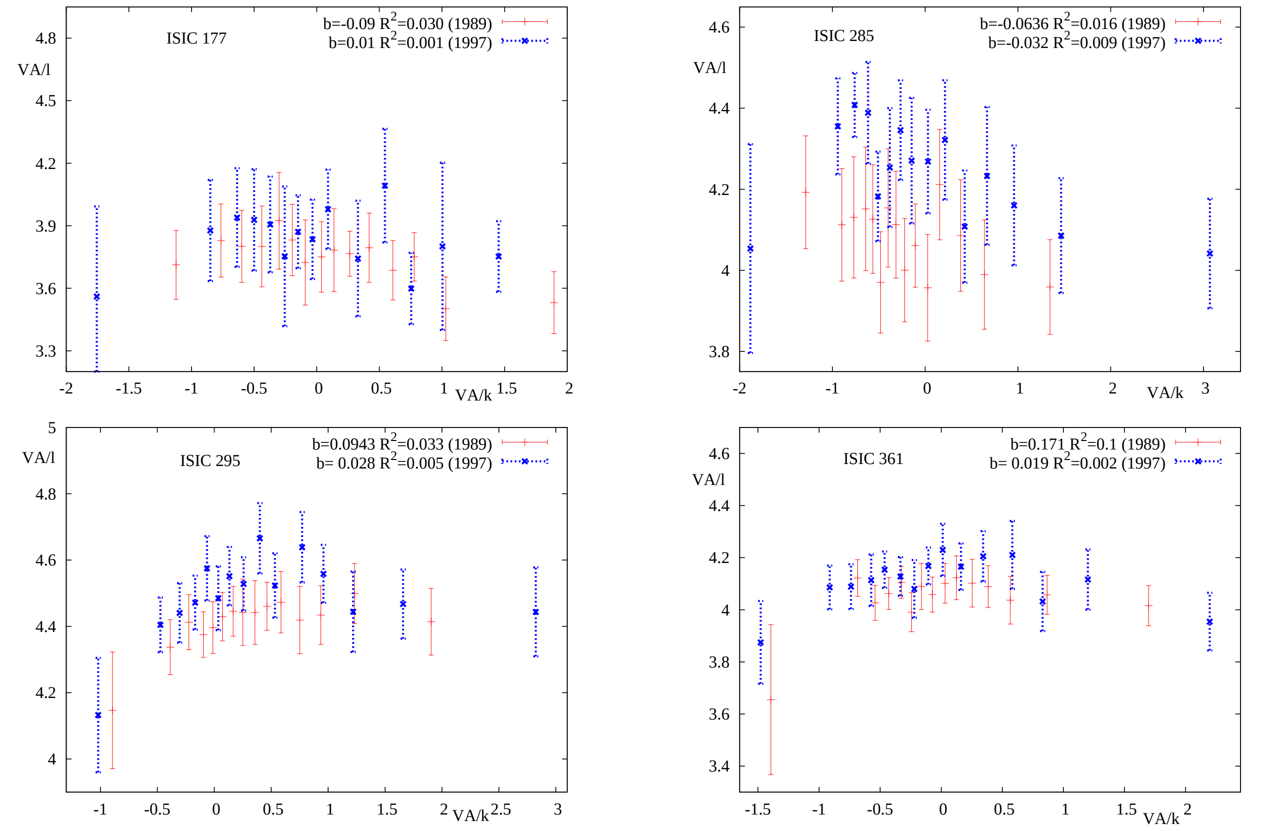

Figure 5: Labor Productivities and output/capital ratios. Bin plots and values of (insignificant) OLS estimates. Error bars display 2 standard errors. K and VA at constant prices.

in the language of production functions, they belong to different production functions, or, in a less arcane framework, this evidence witnesses, again, that different firms master techniques which can be unambiguously ordered as more or less efficient irrespectively of input prices.

3.5 Replication and scale

The procedural view of technology summarized above also bears far-reaching implications in terms of *replication* and *scale*. As Szulanski and Winter [2002] put it:

> "once a business is doing a good job performing a complex activity (...) the parent organization naturally wants to replicate the initial success. Indeed, one of the main reasons for being a big company rather than a small one is to capture on a grand scale the gains that come with applying smart processes and routines.
>
> Yet getting it right the second time is surprisingly difficult. Whole industries are trying to replicate best practices and manage organizational knowledge - but even so the overwhelming majority of attempts to replicate excellence fail." (pp. 62-63)

Difficulties in replication have to do with the distributed and partly tacit character of knowledge and its "hazy frontiers" (Winter [2005]): indeed an organization (and all of its members) do not precisely know what they know, and, even less so, they know the precise domain of applicability of such a knowledge ... Moreover, the endemic correlations among elementary skills and routines, discussed above, impede decomposition and "credit assignment":

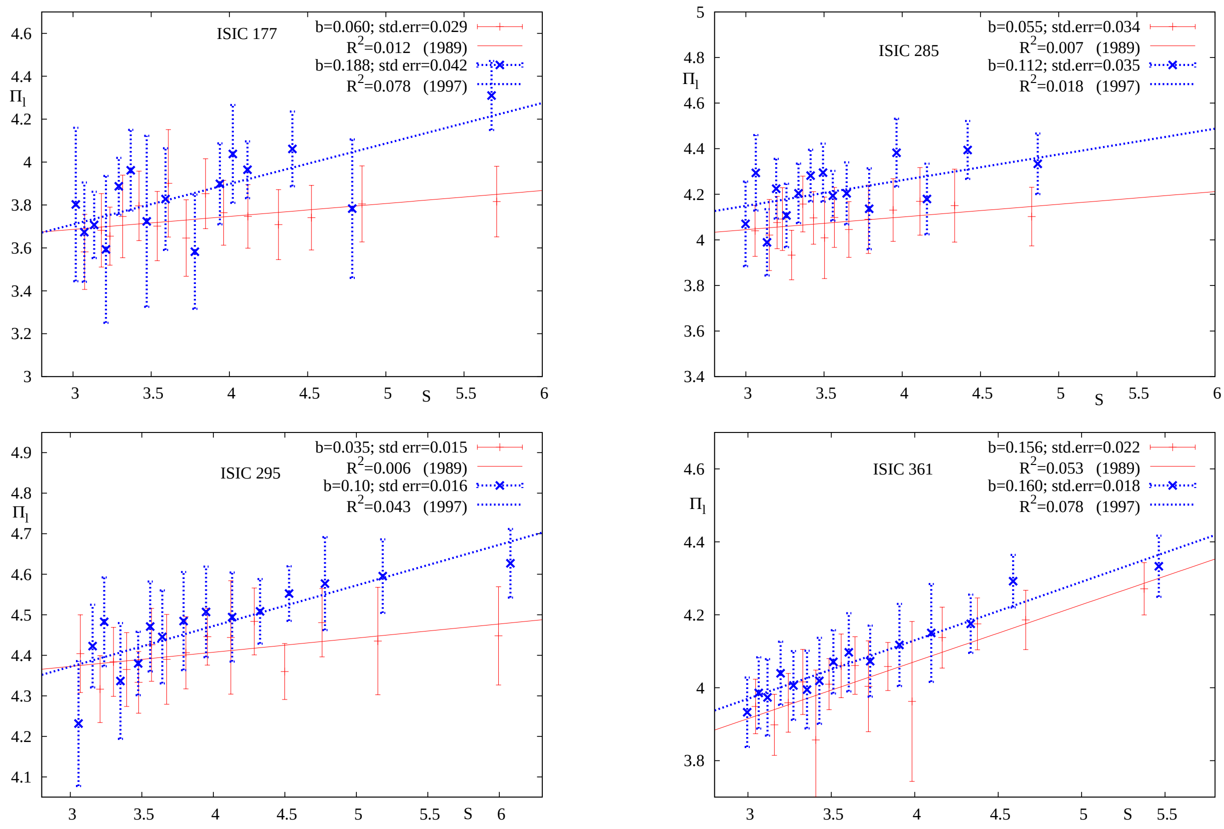

Figure 6: Size Vs VA per employee. Bin plots and OLS estimates. Error bars display two standard errors. Size is proxied by number of employees, VA at constant prices

that is, one can hardly map "being good at doing something" into the separate contributions of single operations and single pieces of knowledge. A *fortiori*, replication difficulties apply when the replicas involve "scaling up" or "scaling down". At the end of the day, the evidence does suggest some positive correlation between firm-size, on the one hand, and labor productivity as well as degrees of mechanization of production (K/L), on the other, but not with capital intensities (approximated by capital/output ratios), see Figures 6, 7, and 8.

Moreover, notice, first, that within each size class the inter-firm variance in labor productivities remains remarkably high.

Second, the average impact of sheer size on productivity appears to be rather low (cf. Table 3).

Third, and more importantly, the direction of causality is not at all clear: indeed it is likely to run both ways. That is, our evidence on Italian firms is consistent with the notion that *some economies of scale apply* - possibly associated with scale-biased forms of mechanization/automation of production. However, the opposite causality sign is likely to apply, too: relatively more efficient firms might be bigger because they are more efficient and not the other way round.

There are also important theoretical consequences of all this: indeed the microeconomic evidence on the hurdles of replication, together with that on the size-specificity of different techniques, make the assumptions from standard production theory of additivity and divisibility (and the derived one of convexity) hard to accept (for a germane discussion, see Winter [2005]).

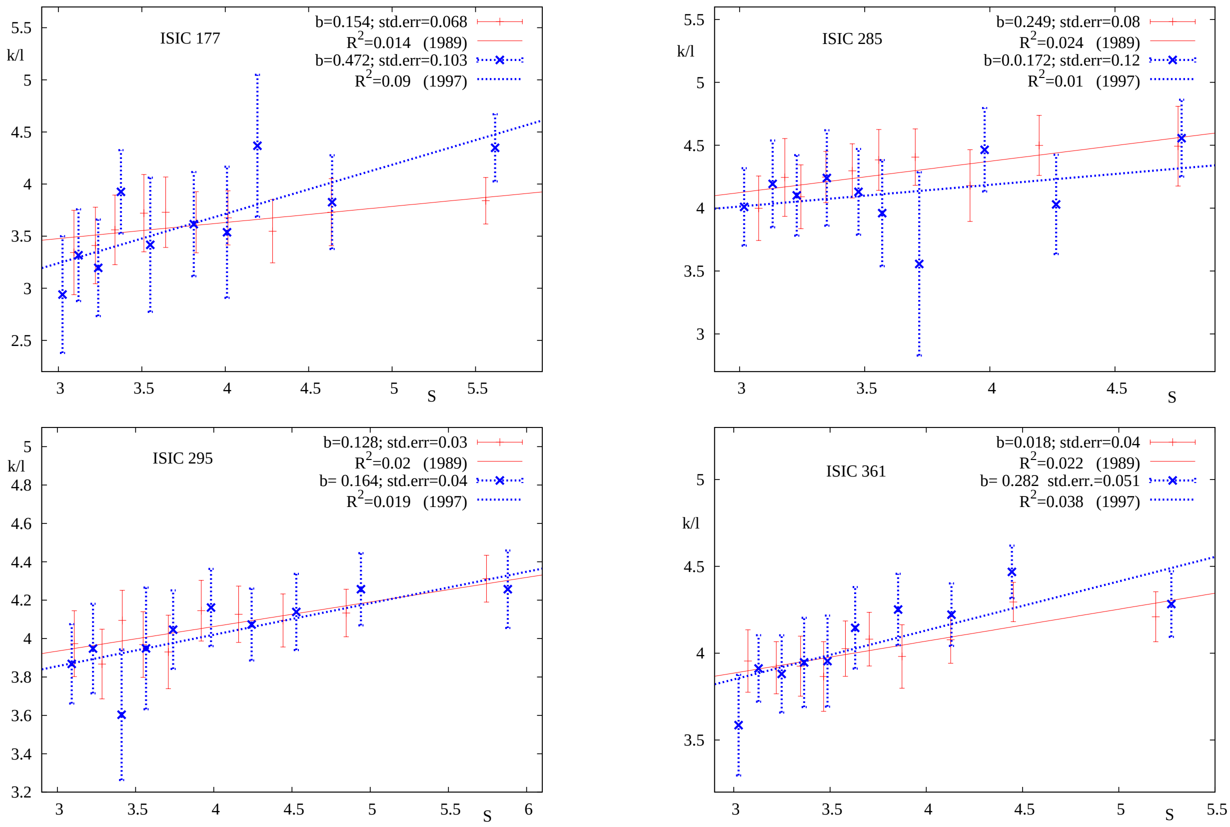

Figure 7: Relation Size - Capital/labor ratio. Size and Labor are proxied by number of employees. Error bars display two standard errors; K at constant prices.

3.6 Aggregation and income distribution

More than forty years ago Walters [1963] was already noting that:

> "After surveying the problems of aggregation one may easily doubt whether there is much point in employing such a concept as an aggregate production function. The variety of competitive and technological conditions we find in modern economies suggest that we cannot approximate the basic requirements of sensible aggregation except, perhaps, over firms in the same industry or from a narrow sections of the economy." (p. 11)

The evidence discussed above suggests indeed that one lacks the conditions of "sensible aggregation" even at the level of single industries.

Of course one can always try to reconstruct the revealed "production possibility sets" building on heterogeneous micro coefficients. By doing that, one is going to find, as shown by Hildenbrand [1981], that:

> "short-run efficient production functions do not enjoy the well-known properties which are frequently assumed in production theory. For example, constant returns to scale never prevail, the production functions are never homothetic, and the elasticities of substitution are never constant. On the other hand, the competitive factor demand and product supply functions [...] will always have definite comparative static properties which cannot be derived from the standard theory of production" (p. 1095)

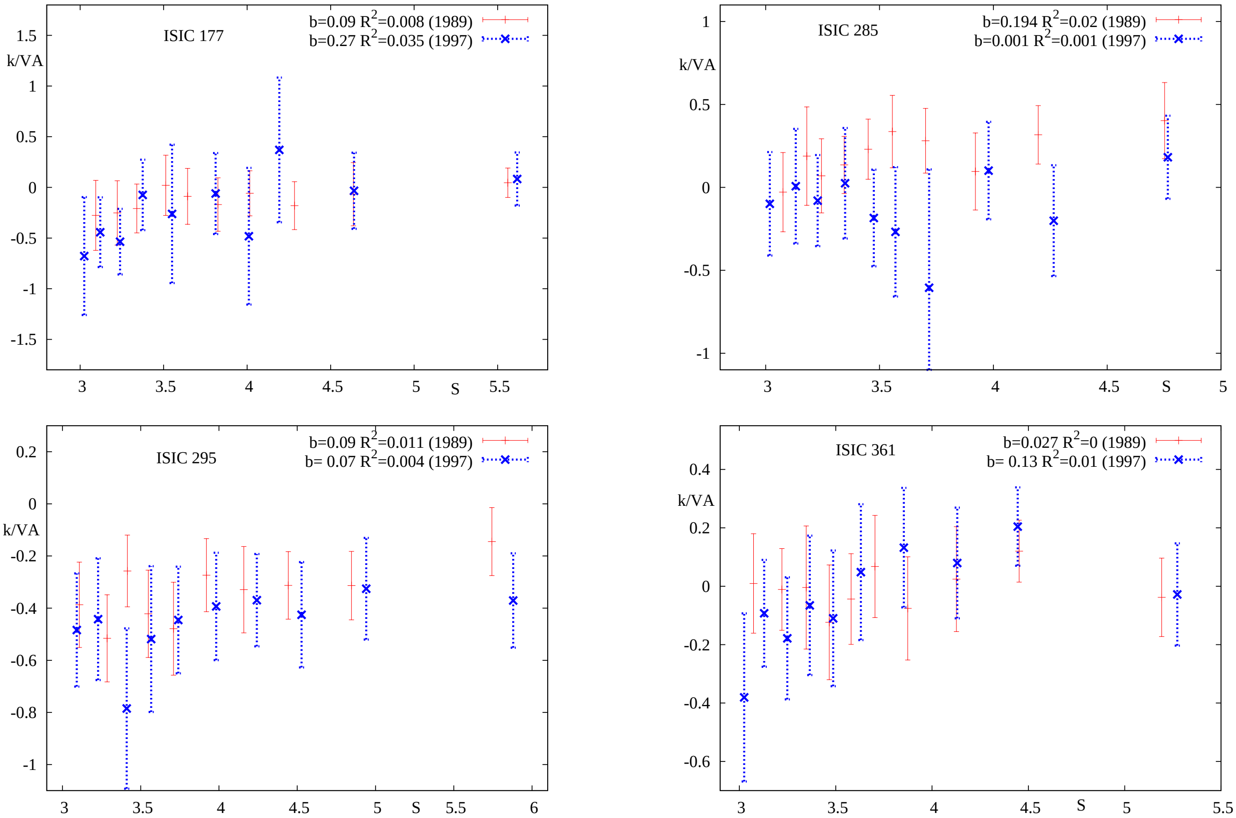

Figure 8: Size Vs (K/VA). Bin plots of Size (# of Employees) Vs. (K/VA). Errorbars display two standard errors. K and VA at constant prices.

Given these findings, it is remarkable how most of the discipline has stuck to a *theory* of production based on far from innocent assumptions concerning the access of agents to production knowledge (most often assumed to be free and identical across them) and on the nature of techniques themselves (additivity and divisibility are good cases to the point). Likewise, the economic discipline has stuck to an *empirics* of production based on a construct (the production function) mainly justified by its "nice" distributive properties (that is, relations between income distribution and apparent partial derivatives of output to inputs) rather than by any micro evidence on the distribution and dynamics of technical coefficients[14].

And, in all that, it failed to recognize that the apparent good fit of the function to the data is sheer algebraic outcome of the rough constancy of aggregate distributive shares. As shown by Shaikh [1974] and Shaikh [1980]:

> "(...)when the *distribution* data (wages and profits) exhibit constant shares, there exist broad classes of *production* data (output, capital, and labor) that *can always be related to each other through a functional form which is mathematically identical to a Cobb-Douglas "production function" with "constant returns to scale", "neutral technical change" and "marginal products equal to factors rewards"* (Shaikh [1980],

[14] In this context, all attempts to measure empirical distributions of micro technical coefficients are just welcome (cf. Simar and Wilson [2000], Balk [2001] and Briec et al. [2004] for contributions and discussions). In that, the less the imposed parametric structure, the less the appeal to convexity assumptions, the less the use of purported but unobservable profit-maximizing/cost-minimizing behaviors, all the better ...

SECTOR	ISIC Code	1989			1993			1997		
		α	β	R^2	α	β	R^2	α	β	R^2
Production & processing of meat	151	4.11 (0.132)	0.033 (0.032)	0.004	3.95 (0.113)	0.098 (0.028)	0.035	4.00 (0.160)	0.086 (0.04)	0.024
Knitted & crocheted articles	177	3.50 (0.117)	0.060 (0.029)	0.0117	3.16 (0.12)	0.18 (0.031)	0.06	3.143 (0.164)	0.188 (0.04)	0.078
Wearing apparel & accessories	182	2.83 (0.078)	0.192 (0.019)	0.096	2.614 (0.071)	0.2690 (0.019)	0.106	2.58 (0.091)	0.288 (0.0238)	0.141
Footwear	193	3.078 (0.089)	0.152 (0.023)	0.08	3.074 (0.094)	0.187 (0.025)	0.060	3.308 (0.140)	0.127 (0.037)	0.025
Articles of paper and paperboard	212	4.016 (0.096)	0.072 (0.023)	0.029	3.907 (0.099)	0.012 (0.024)	0.056	3.877 (0.121)	0.152 (0.03)	0.075
Printing and services related to printing	222	3.97 (0.082)	0.122 (0.0212)	0.07	3.901 (0.081)	0.154 (0.022)	0.079	3.78 (0.134)	0.014 (0.035)	0.04
Plastic products	252	4.076 (0.083)	0.057 (0.021)	0.011	3.799 (0.086)	0.154 (0.022)	0.048	3.778 (0.097)	0.15 (0.024)	0.05
Articles of concrete, plaster & cement	266	4.35 (0.013)	-0.011 (0.034)	0.001	4.249 (0.156)	-0.004 (0.041)	0.001	3.65 (0.156)	0.181 (0.041)	0.06
Metal products	281	3.758 (0.107)	0.09 (0.028)	0.027	3.786 (0.091)	0.091 (0.024)	0.02	3.63 (0.013)	0.166 (0.037)	0.04
Treatment & coating of metals; general mechanical engin.	285	3.877 (0.127)	0.055 (0.03)	0.006	3.742 (0.124)	0.099 (0.035)	0.012	3.801 (0.130)	0.11 (0.036)	0.018
Special purpose machinery	295	4.26 (0.064)	0.034 (0.015)	0.007	4.15 (0.058)	0.072 (0.014)	0.023	4.071 (0.068)	0.10 (0.017)	0.043
Furniture	361	3.44 (0.08)	0.156 (0.022)	0.05	3.382 (0.076)	0.193 (0.02)	0.068	3.48 (0.071)	0.16 (0.018)	0.078

Table 3: Size Vs Labor Productivity: OLS regressions. $\Pi(= VA/L) = \alpha + \beta(VA)$. Constant price Value Added. Labor is proxied by the number of employees. Standard Errors are in brackets. These estimates include those presented in Fig.6.

p. 92, italics in the original)[15]

Clearly, if one takes seriously these properties of aggregation, together with the properties of micro empirical data discussed above, one looses the easy link between purported (even if false or just tautological) "technical" aggregate relations, input prices, input demand functions and income distribution. With that, of course, one looses also any nicely behaved "duality property". By the same token one gains the possibility of genuinely *studying* the relations between e.g. technological characteristics of firms and micro income distribution, between technological change and inputs demands, and so on, rather than simply postulating them.

[15]The property had already been noted by Fisher [1971], who, on the ground of a simulation exercise found a "good fit of a Cobb-Douglas" even though the true relationships were far from yielding an aggregate Cobb-Douglas: "the view that constancy of the labor's share is due to the presence of an aggregate Cobb-Douglas production function is mistaken. Causation runs the other way and the apparent success of aggregate Cobb-Douglas production functions is due to the relative constancy of labor's share" (Fisher [1971], p. 306). See also Simon and Levy [1963] and Phelps-Brown [1957]. For fun, we just repeated the OLS cross-sectional estimates on our 3-digit sectors, alike Fisher [1971], and with no surprise we obtained excellent estimates with high significance and all R^2 above .7.

4 By way of a conclusion, where do we go here?

There is certainly a *pars denstruens* to this all argument, which we have already spelled out. Basically, it boils down to the rupture of any well-behaved correspondence between technological conditions and input market properties, in turn nested into maximizing micro behaviors and collective equilibrium assumptions.

There is a *pars construens* as well. It involves, first, the investigation of the properties of *distributions* over heterogeneous entities of variables like revealed productivities, relative input intensities, and their evolution over time.

A growing number of scholars has indeed began doing precisely what we could call *evolutionary accounting* (even if most do not call it that way!). The fundamental evolutionary idea is that distribution, (including, of course, their means, which end-up in sectoral and macro-statistics!) change as a result of (i) *learning* by incumbent entities; (ii) *differential growth* (that is, a form of *selection*) of incumbent entities themselves; (iii) *death* (indeed, a different and more radical form of selection); and (iv) *entry* of new entities.

The basic theoretical intuition is discussed at length in Nelson and Winter [1982] (see also Iwai [1984a] and Iwai [1984b], Dosi et al. [1995], and Metcalfe [1998], among others). Empirically, favored by the growing availability of micro longitudinal panel data, at last, an emerging line of research (see Baily et al. [1996], Foster et al. [2001], Baldwin and Gu [2006], among others, and the discussion in Bartelsman and Doms [2000]) investigates the properties of decomposition of whatever mean sectoral performance variable, e.g. typically productivity of some kind, of the following form, or variations thereof:

$$\begin{aligned}\Delta\Pi_t = &\sum_i s_i(t-1)\Delta\Pi_i(t) + \sum_i \Pi_i(t-1)\Delta s_i(t) + \\ &\sum_e s_e(t)\Delta\Pi_e(t) + \sum_f s_f(t-1)\Delta\Pi_f(t-1) + \\ &\text{(some interaction terms)}\end{aligned} \tag{4}$$

where Π = e.g. productivity (or, for that matter, some other performance variables), s = shares (in total output or value added or employment or total capital assets ...), while i is an index over incumbents, e over entrants, and f over exiting entities.

Many intriguing research questions follow. To begin with, how does the distribution evolve over time? Moreover, what is the relative balance between incumbent learning and market selection? What is the role of entry? What is the relative importance of bankruptcy mechanisms? On which time scale (i) learning, (ii) inter-incumbent competition, (iii) entry, (iv) exit exert their relative influence?

A second major research challenge concerns the *coupled dynamics* between the foregoing quantities and some underlying “idiosyncratic” covariates regarding, so to speak, the “identity cards” of individual firms - ideally revealing their *technological and organizational capabilities*. We have now quite a few surveys on innovative capabilities and innovative outputs (ranging from patent data to e.g. the EU Community Innovation Survey to many country-specific organizational surveys), but one is only beginning to exploit them.

Third, a tricky but fascinating set of questions regards precisely the mappings between *procedure-centered* and *input/output-centered* representations of technologies. Suppose to be able to develop some metrics - an exercise indeed already difficult - in the input/output space, and, also, albeit overly difficult and fuzzy, in the high dimensional "problem-solving space". Granted that, how do the respective dynamics map into each other? Do "small" changes in the knowledge/problem-solving space correspond roughly to "small" changes in input/output relations? And, if so, when does one empirically detect major discontinuities[16]? Can one detect paradigm changes also in the input/output space, *in general*, well beyond the examples given in the economics of innovation literature?

Fourth, there are propositions concerning production theory which are intuitively very reasonable – e.g. "firms try to save on inputs whose prices have augmented" – while, at the same time the standard "proof" is utterly far-fetched. The "proof" of the Shephard and Hotelling lemmas invoking the envelope theorem are archetypal examples. One knows how the standard argument goes. Suppose "the firm" (i.e. all firms, on average) is in some equilibrium, that is with equilibrium input intensities, equilibrium returns, etc. Next, suppose a shock to relative prices. Given the standard theory of production, the representative agent will adjust its optimal input combinations to the new relative prices and thereof decrease its demand of the relatively more expensive inputs. Hence the "well-behaved" notional demand curve for inputs.

Clearly this line of argument does not hold in the evolutionary worlds sketched out above. But does all this mean that the basic intuition on some negative price quantity *dynamics* does not apply? Rephrasing it in the knowledge-focused language, to what extent, *technological trajectories* of corporate and industry-wide learning can be affected by relative-price shocks?

Last but not least, fifth, a major challenge regards the possible links between microfounded analysis of production, such as those sketched above, with more aggregate representations of technological interdependences which try to account for input-output flows without making at the same time any binding commitment to "general equilibrium" assumptions. (Examples of such a modeling style with a "classical flavor" are Pasinetti [1977], and Kurz and Salvadori [1995]). These are just examples of a rich research agenda ultimately linking investigations at the levels of knowledge dynamics and organizational behavior with questions, more familiar to economists, addressing possible regularities in the input/output structure of the economy and its dynamics. In all this scientific enterprise, Winter's old contribution is still a fresh source of inspiration.

[16] A somewhat similar problem, which the authors of this paper found to be a tall challenging analogy is, in biology, the mapping between genetic structures and phenotypical characters which are in turn subject to environmental selection: see Stadler et al. [2001].

Appendix - Data

The elaborations on the Italian data draw upon the MICRO.1 databank developed by the Italian Statistical Office (ISTAT). MICRO.1 contains longitudinal data on a panel of several thousand Italian manufacturing firms with employment of 20 units or more over the period 1989-1997. Since the panel is open, due to entry, exit, fluctuations around the 20 employees threshold and variability in response rates, we consider only the firms that are present both at the beginning and at the end of our window of observation.

In order to control for mergers, acquisitions, and divestments, we build "super-firms" which account throughout the period for the union of the entities which undertake such changes. So, for example, if two firms merged at some time, we consider them merged throughout the whole period. Conversely, if a firm is spun off from another one, we "re-merge" them starting from the separation period. Ultimately, one ends up with a balanced panel of 8091 ("super") firms.

Note that firms above 20 employees account for just 11% of the universe of Italian manufacturing firms but they include 68% of the total employment (Bartelsman et al. [2004]).

References

A. A. Alchian and H. Demsetz. Production , information costs, and economic organization. *American Economic Review*, 62(5):777–95, 1972.

C. Antonelli. *The Economics of Localized Technological Change and Industrial*. Kluwer Academic Publishers: Boston, 1995.

A. B. Atkinson and J. E. Stiglitz. A new view of technological change. *Economic Journal*, 79(315): 573–78, 1969.

M. Augier and J. G. March, editors. *Industrial and Corporate Change. Roots and branches of organizational economics*, volume 9. 2000. Special Issue, pp. 555-788.

M. N. Baily, E. J. Bartelsman, and J. Haltiwanger. Downsizing and productivity growth: Myth or reality? *Small Business Economics*, 8(4):259–78, 1996.

M. N. Baily, C. Hulten, and D. Campbell. Productivity dynamics in manufacturing establishments. *Brookings Papers on Economic Activity: Microeconomics*, 4:187–249, 1992.

J. R. Baldwin. *The Dynamics of Industrial Competition: A North American Perspective*. Cambridge University Press, 1998.

J. R. Baldwin and W. Gu. Plant turnover and productivity growth in canadian manufacturing. *Industrial and Corporate Change*, forthcoming, 2006.

B. M. Balk. Scale efficiency and productivity change. *Journal of Productivity Analysis*, 15(3):159–183, 2001.

E. J. Bartelsman and P. J. Dhrymes. Productivity dynamics: U.s. manufacturing plants, 1972-1986. *Journal of Productivity Analysis*, 9(1):5–34, 1998.

E. J. Bartelsman and M. Doms. Understanding productivity: Lessons from longitudinal microdata. *Journal of Economic Literature*, 38(2):569–594, 2000.

E. J. Bartelsman, J. Haltiwanger, and S. Scarpetta. Microeconomic evidence of creative destruction in industrial and developing countries. Working Paper 04-114/3, Tinbergen Institute, Oct 2004.

E. J. Bartelsman, S. Scarpetta, and F. Schivardi. Comparative analysis of firm demographics and survival: Micro-level evidence for the oecd countries. *Industrial and Corporate Change*, 14:365–391, 2005.

G. Bottazzi, E. Cefis, G. Dosi, and A. Secchi. Invariances and diversities in the evolution of manufacturing industries. LEM Working Papers 2003/21, S. Anna School of Advanced Studies, 2003.

W. Briec, K. Kerstens, and P. V. Eeckaut. Non-convex technologies and cost functions: Definitions, duality and nonparametric tests of convexity. *Journal of Economics*, 81(2):155–192, 2004.

A. Chesher. Testing the law of proportionate effect. *Journal of Industrial Economics*, 27(4):403–11, 1979.

W. B. Chew, T. Bresnahan, and K. Clark. Measurement, coordination, and learning in a multiplant network. In R. S. Kaplan, editor, *Measures for Manufacturing Excellence*, pages 129–162. Harvard Business School Press: Cambridge, MA, 1990.

M. D. Cohen, R. Burkhart, G. Dosi, M. Egidi, L. Marengo, M. Warglien, and S. Winter. Routines and other recurring action patterns of organizations: Contemporary research issues. *Industrial and Corporate Change*, 5:653–698, 1996.

E. W. Constant. *The Origins of Turbojet Revolution.* John Hopkins University Press: Baltimore, MD, 1980.

P. A. David. *Technical choice, innovation and economic growth.* Cambridge University Press: Cambridge, MA., 1975.

K. Dopfer, editor. *The Evolutionary Foundations of Economics.* Cambridge University Press, Cambridge, 2005.

G. Dosi. Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research Policy*, 11:147–162, 1982.

G. Dosi. *Technical Change and Industrial Transformation.* London, Mcmillan, 1984.

G. Dosi. Sources, procedures, and microeconomic effects of innovation. *Journal of Economic Literature*, 26(3):1120–71, 1988.

G. Dosi. Statistical regularities in the evolution of industries. a guide through some evidence and challenges for the theory. LEM Working Paper 2005/17, Pisa, S. Anna School of Advanced Studies, 2005.

G. Dosi and B. Coriat. Learning how to govern and learning how to solve problems. on the co-evolution of competences, conflicts and organizational routines. In A. Chandler and O. S. Peter Hagström, editors, *The Dynamic Firm: The Role of Technology, Strategy, Organization, and Regions.* Oxford/New York, Oxford University Press, 1998.

G. Dosi, B. Coriat, and K. Pavitt. Competences, capabilities and corporate performances: Final report to the european union. Dynacom working paper, Pisa, S. Anna School of Advanced Studies, 2000a.

G. Dosi, M. Faillo, and L. Marengo. Organizational capabilities, patterns of knowledge accumulation and governance structures in business firms: an introduction. LEM Working Paper 2003/11, S. Anna School of Advanced Studies, 2006. forthcoming in J.P. Touffout (ed.) Organizational Innovation within Firms: Cheltenham, UK.

G. Dosi, M. Hobday, L. Marengo, and A. Prencipe. The economics of system integration: Toward an evolutionary interpretation. In A. Prencipe, A. Davies, and M. Hobday, editors, *The Business of Systems Integration*. Oxford University Press: Oxford and New York, 2003.

G. Dosi, O. Marsili, L. Orsenigo, and R. Salvatore. Learning, market selection and evolution of industrial structures. *Small Business Economics*, 7(6):411–36, 1995.

G. Dosi, R. R. Nelson, and S. Winter, editors. *The nature and dynamics of organizational capabilities*. Oxford University Press: Oxford, 2000b.

G. Dosi, L. Orsenigo, and M. Sylos-Labini. Technology and the economy. In N. J. Smelser and R. Swedberg, editors, *The Handbook of Economic Sociology*. Princeton University Press: Princeton and New York, 2nd edition, 2005.

F. M. Fisher. Aggregate production functions and the explanation of wages: A simulation experiment. *The Review of Economics and Statistics*, 53(4):305–325, 1971.

N. Foss and V. Mahnke, editors. *Competence, Governance, and Entrepreneurship - Advances in Economic Strategy Research*. Oxford University Press: Oxford and New York, 2002.

L. Foster, J. Haltiwanger, and C. J. Krizan. *New Developments in Productivity Analysis*, chapter Aggregate Productivity Growth: Lessons from Microeconomic Evidence. Chicago: University of Chicago Press, 2001.

C. Freeman. The economics of technical change: a critical survey. *Cambridge Journal of Economics*, 18:1–50, 1994.

N. Georgescu-Roegen. The economics of production. *The American Economic Review*, 60(2):1–9, 1970.

Z. Griliches and J. Mairesse. Production functions: The search for identification. In S. m Steiner, editor, *Econometrics and Economic Theory in the Twentieth Century: the Ragner Frisch Centennial Symposium*. Cambridge University Press: Cambridge, 1999.

H. Grupp. *Dynamics of Science-Based Innovation*. Springer Publishers: Berlin and Heidelberg, 1992.

G. C. Harcourt. *Some Cambridge Controversies in the Theory of Capital*. Cambridge University Press: Cambridge, 1972.

W. Hildenbrand. Short-run production functions based on microdata. *Econometrica*, 49(5):1095–1125, 1981.

T. P. Hughes. *Networks of Power: Electrification in Western Society 1880-1930*. Johns Hopkins University Press: Baltimore, MD, 1983.

K. Iwai. Schumpeterian dynamics: An evolutionary model of innovation and imitation. *Journal of Economic Behavior and Organization*, 1984a.

K. Iwai. Schumpeterian dynamics, part ii: Technological progress, firm growth and 'economic selection. *Journal of Economic Behavior and Organization*, 1984b.

B. J. Jensen and R. H. McGuckin. Firm performance and evolution: Empirical regularities in the us microdata. *Industrial and Corporate Change*, 6:25–47, 1997.

H. D. Kurz and N. Salvadori. *Theory of Production. A Long-Period Analysis*. Cambridge University Press: Cambridge, 1995.

H. Leibenstein. Allocative efficiency vs. x-efficiency. *The American Economic Review*, 56(3):392–415, 1966.

D. A. Levinthal. The slow pace of rapid technological change: Gradualism and punctuation in technological change. *Industrial and Corporate Change*, 7:217–247, 1998.

J. G. March. *Decision and Organization*. Blackwell: Oxford, 1988.

J. G. March and H. A. Simon. Organizations revisited. *Industrial and Corporate Change*, 2:299–316, 1993.

L. Marengo and G. Dosi. Division of labor, organizational coordination and market mechanisms in collective problem-solving. *Journal of Economic Behavior and Organization*, 58:303–326, 2005.

L. Marengo, G. Dosi, P. Legrenzi, and C. Pasquali. The structure of problem-solving knowledge and the structure of organizations. *Industrial and Corporate Change*, 9:757–788, 2000.

S. J. Metcalfe. *Evolutionary Economics and Creative Destruction*. London, Routledge, 1998.

P. Milgrom and J. Roberts. The economics of modern manufacturing: Technology, strategy, and organization. *The American Economic Review*, 80:511–528, 1990.

P. Milgrom and J. Roberts. Complementarities and fit: Strategy, structure, and organizational change in manufacturing. *Journal of Accounting and Economics*, 19:179–208, 1995.

C. A. Montgomery, editor. *Resource-Based and Evolutionary Theories of the Firm: Towards a Synthesis*. Kluwer: Dordrecht, 1^{st} edition, 1995.

M. Morroni. *Production Process and Technical Change*. Cambridge University Press: Cambridge, 1992.

R. R. Nelson. Research on productivity growth and productivity differences: Dead ends and new departures. *Journal of Economic Literature*, 19(3):1029–1064, 1981.

R. R. Nelson. Why do firms differ, and how does it matter? *Strategic Management Journal*, 12: 61–74, 1991.

R. R. Nelson and S. G. Winter. *An Evolutionary Theory of Economic Change*. The Belknap Press of Harvard University Press: Cambridge, MA, 1982.

L. L. Pasinetti. *Lectures on the Theory of Production*. Colombia University Press: New York, 1977.

K. Pavitt. What makes basic research economically useful? *Research Policy*, 20:109–119, 1991.

E. H. Phelps-Brown. The meaning of the fitted cobb-douglas function. *The Quarterly Journal of Economics*, 71:546–560, 1957.

L. Power. The missing link: Technology, investment, and productivity. *The Review of Economics and Statistics*, 80(2):300–313, 1998.

J. G. M. Richard M. Cyert. *A Behavioral Theory of the Firm.* Blackwell Business: Oxford, 2nd edition, 1992.

N. Rosenberg. *Perspectives on Technology.* Cambridge University Press: Cambridge, 1976.

N. Rosenberg. Why do firms do basic research (with their money)? *Research Policy*, 19:165–74, 1990.

R. P. Rumelt. How much does industry matter? *Strategic Management Journal*, 12:167–185, 1991.

D. Sahal. *Patterns of Technological Innovation.* Addison-Wesley: New York, 1981.

P. Saviotti. *Technological Evolution, Variety and the Economy.* Edward Elgar: Cheltenham UK, 1996.

B. Schefold. Different forms of technical progress. *The Economic Journal*, 86:806–819, 1976.

A. Shaikh. Laws of production and laws of algebra: The humbug production function. *The Review of Economics and Statistics*, 56:115–120, 1974.

A. Shaikh. Laws of production and laws of algebra: Humbug ii. In E. J. Nell, editor, *Growth, Profits and Property. Essays in the Revival of Political Economy*, pages 80–95. Cambridge University Press: Cambridge, 1980.

L. Simar and P. W. Wilson. Statistical inference in nonparametric frontier models: The state of the art. *Journal of Productivity Analysis*, 13:49–78, 2000.

H. A. Simon. *Science of the Artificial.* MIT Press: Cambridge, MA, 1969.

H. A. Simon and F. K. Levy. A note on the cobb-douglas function. *The Review of Economic Studies*, 1963.

B. M. Stadler, P. F. Stadler, G. P. Wagner, and W. Fontana. The topology of the possible: Formal spaces underlying patterns of evolutionary change. *Journal of Theoretical Biology*, 213:241–274, 2001.

G. Szulanski and S. Winter. Getting it right the second time. *Harvard Business Review*, 80:62–69, 2002.

D. J. Teece, G. Pisano, and A. Shuen. Dynamic capabilities and strategic management. *Strategic Management Journal*, 18:509–533, 1997.

W. G. Vincenti. *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History.* The John Hopkins University Press: Baltimore, MD, 1990.

A. A. Walters. Production and cost functions: An econometric survey. *Econometrica*, 31(1/2):1–66, 1963.

S. G. Winter. An essay on the theory of production. In S. H. Hymans, editor, *Economics and the world around it.* University of Michigan Press: Ann Arbor, MI, 1982.

S. G. Winter. Knowledge and competences as strategic assets. In D. J. Teece, editor, *The Competitive Challenge: Strategy and Organization for Industrial Innovation and Renewal.* Ballinger: Cambridge, MA, 1987.

S. G. Winter. Toward an evolutionary theory of production. In K. Dopfer, editor, *The Evolutionary Foundations of Economics*. Cambridge University Press: Cambridge, 2005.

S. G. Winter. Toward a neo-schumpeterian theory of the firm. *Industrial and Corporate Change*, 2006. forthcoming.