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Total factor productivity growth and convergence in the petroleum industry: Empirical analysis testing for convexity

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ABSTRACT

While economic theory acknowledges that some features of technology (e.g., indivisibilities, economies of scale and specialization) can fundamentally violate the traditional convexity assumption, almost all empirical studies accept the convexity property on faith. In this contribution, we apply two alternative flexible production technologies to measure total factor productivity growth and test the significance of the convexity axiom using a nonparametric test of closeness between unknown distributions. Based on unique field level data on the petroleum industry, the empirical results reveal significant differences, indicating that this production technology is most likely non-convex. Furthermore, we also show the impact of convexity on answers to traditional convergence questions in the productivity growth literature.

1. Introduction

Indivisibility implies that inputs and outputs are not necessary perfectly divisible and also that scaling up or down the entire production process in infinitesimal fractions may not be feasible. Start-up and shut-down cost in electricity generation are just one good example (O'Neill et al., 2005). Scarf (1986, 1994) stresses the importance of indivisibility in selecting among technological options. Economies of scale and specialization (implied by the presence of indivisibilities and other forms of non-convexities in production) entail that higher per-capita production increases the extent of the market, facilitates the division of labor, and increases the efficiency of production.[1] These economically important features of technology, together with the well-known case of externalities, fundamentally violate the convexity of the production possibility set (see Farrell, 1959, for an overview). However, in traditional empirical analysis (e.g., traditional parametric production analysis, or even nonparametric production analysis), these features are dismissed through the imposition of the convexity axiom. In reality, it is clear that non-convexities in production are sufficiently important to explain behavior in some industries and are critical in the development of the new growth theory (see, e.g., Romer, 1990, on nonrival inputs). In a similar vein, McFadden (1978) already recognized that the importance of convexity in production analysis lies in its analytic convenience rather than its economic realism.

Therefore, given its relevance to both economic theory and associated empirical analysis, one cannot ignore the potential impact of non-convexity.[2] However, almost no previous studies have directly tested for the existence of non-convexity in production using rigorous statistical techniques. Nevertheless, non-convexities in production play an important role in the theoretical micro-economic literature and have been studied for decades (see, e.g., Frank, 1969 or Villar, 1999). For instance, the general equilibrium theory of non-convex technologies has been thoroughly analyzed (e.g., Bobzin 1998; Joshi, 1997, or more recently, Chavas and Briec, 2012). Recently, operational methods to derive linear prices supporting a competitive equilibrium in markets with non-convexities based on mixed integer programming have been devised (e.g., O'Neill et al., 2005).

In this contribution, we apply two alternative flexible production models using nonparametric specifications of technology and test the validity of the non-convexity assumption in production. One non-convex specification of production technology (NCP) is the Free Disposable Hull model (initiated by Deprins et al. (1984)). It only imposes the assumption of strong or free disposability of both inputs and outputs. Another more common technology specification adds convexity to these strong disposability axioms to form a convex nonparametric production model

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[1] Wibe (1984) shows that scale elasticity is generally larger than one for all output levels when reviewing studies of engineering production functions.

[2] Even if this implies the risk of producing less "elegant" results than with standard approaches: in particular, empirical results are harder to report because they become local rather than global in nature (see infra).

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(CP) (see, e.g., the seminal article of Farrell (1957), or Afriat (1972), Färe et al. (1994), among others). Based on distance functions as representations of technology (and their interpretation as efficiency indicators) computed relative to both these non-convex and convex nonparametric specifications of technology, following Briec et al. (2004), we test the significance of the differences using Li's (1996) nonparametric test of closeness between two unknown distributions resulting from independent or dependent observations. Obviously, if convexity of technology is questionable, then also the more specific assumption of convexity of either input or output sets separately is doubtful.

Simar and Wilson (2008) develop a complementary view on the statistical properties of these convex and non-convex nonparametric frontier estimators that highlights a kind of asymmetry in imposing both assumptions. If the true production possibility set is convex, then CP and NCP estimators are consistent and should yield approximately the same estimates for large datasets, though the NCP model normally has a slower rate of convergence. However, if technology is non-convex, then the NCP model remains consistent while the CP model offers an inconsistent approximation.

These nonparametric specifications require large data sets for production technologies to avoid the small sample error problem. Furthermore, to avoid any aggregation bias, the analysis should ideally focus on firm-level data with sufficient detail regarding the production process. Here, we apply this test of convexity to unique field-level data from the petroleum industry in the US Gulf of Mexico over the period from 1947 to 1998. Although the production possibility set of oil and gas development and exploitation is acknowledged to be non-convex in part of the literature (see, e.g., Devine and Lesso, 1972 and further arguments below), we are unaware of there being previous economic studies that put this assumption to an empirical test. Hence, whether the above NCP methodology yields a relevant reference technology in this industry becomes a most interesting empirical question for testing.

Furthermore, a topic that has received widespread attention with the appearance of endogenous growth theories is the question of convergence in productivity levels (see Islam, 2003 for a survey). In view of the importance of non-convexities for growth theory (Romer, 1990), we consider the suggestion by Bernard and Jones (1996, p. 1043) that "future work on convergence should focus much more carefully on technology". In particular, we investigate the issue of convergence/divergence in total factor productivity change using a recent discrete time Luenberger productivity indicator (Chambers, 2002) computed relative to nonparametric technology specifications, while testing for the significance of the eventual differences between the CP and NCP models. The very length of the observation period provides ample scope to test the impact of the convexity assumption on the eventual convergence of total factor productivity growth rates.

The choice between non-convexity and convexity in measuring total factor productivity change relates to the nature of technical change. The NCP model has the advantage of eventually allowing for local instead of global technical change (see, e.g., the discussion in Tulkens, 1993, and infra). Note that we believe this is the first paper defining local and global technological change precisely. While this distinction between local and global technological change plays a role in some theoretical work (see, e.g., Atkinson and Stiglitz, 1969, among others), we are aware of only few empirical works raising this issue. If NCP is the true representation of technology, then previous empirical work on the convergence issue might not be reliable. Anticipating one of the key results, this study only finds convergence for the NCP model.

This contribution is structured as follows. Section 2 reviews the background literature. Section 3 presents the Luenberger productivity indicator as well as its underlying distance functions, the distinction between local and global technical change in our analysis, and the econometric models employed to test for convergence. Section 4 introduces the sample of petroleum field data from the Mexican Gulf. The next section presents the empirical results and provides the outcomes of the statistical tests. The final section offers some concluding remarks.

2. Non-convexity in production and in petroleum industry: Literature review

The literature on non-parametric production analysis (see e.g., Afriat, 1972 or Varian, 1984) typically uses convexity only as an instrumental regularity property of technology justified by the assumed economic optimization hypotheses. Thus, convexity is motivated by economic objectives (such as cost minimization or profit maximization) rather than being an inherent feature of technology. Similarly, the parametric approach (see, e.g., Bauer, 1990) sometimes imposes regularity restrictions on the parameters of cost, revenue and profit functions, but it does not systematically test for the convexity assumption of technology.

As a result, the impact of convexity in technology (or lack thereof) on the cost function is often ignored. While the general property of the cost function as non-decreasing in outputs is well known, it seems often forgotten that cost functions estimated on convex (non-convex) technologies are also convex (non-convex) in the outputs. Jacobsen (1970) was one of the first to point out that convexity of the cost function in the outputs is due to convexity of the technology (see proposition 5.2). In other words, a cost function estimated on a convex technology is smaller or equal to the same function estimated on a non-convex technology (see Briec et al., 2004).

Several empirical studies suggest violations of convexity in a wide variety of industries (e.g., Tone and Sahoo, 2003). Indivisibilities are an obvious feature of real-world production settings (see Scarf 1986, 1994). The phenomena of economies of scale and specialization have also been empirically tested in the literature. The empirical evidence of process analysis, which derives production relations directly from theoretical and practical engineering knowledge, has found evidence of violations of convexity (see Wibe, 1984). Economies of scale are especially well documented. For instance, Chenery (1949) studied engineering production functions of the pipeline transportation of natural gas and derived a (non-linear) cost function that exhibits economies of scale. Some evidence of increasing returns has been reported in, for example, chemical industries and the manufacturing of process equipment, air pollution control equipment, and biopharmaceutical equipment (e.g., see the survey in Wibe (1984)). Some other economic analyses documenting these types of violations of convexity include Yang and Rice (1994) and Borland and Yang (1995).

We provide an analysis of the offshore oil and gas industry, which faces substantial sunk cost investments in terms of development, exploration and knowledge, which are the main source of non-convexity in production (see Devine and Lesso, 1972, or Frair and Devine, 1975). This description is mainly based on the economic literature on petroleum production. This ignores the complex details of reservoir (e.g., "undersaturated" (oil) vs. "saturated" (oil and gas) reservoirs depending on temperature and pressure conditions; natural or artificial (mechanical or gas) lift; among others) and production (e.g., issues related to gas, oil and water separation, the design of the whole surface flow system, among others) engineering in petroleum production systems (see, for instance, Gua et al. (2007) for details).

Some details are essential to consider for our purpose. For instance, once an oil field is found after extensive seismic study