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Rapid improvements with no commercial production: How do the improvements occur?

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ABSTRACT

This paper empirically examines 13 technologies in which significant cost and performance improvements occurred even while no commercial production occurred. Since the literature emphasizes cost reductions through increases in cumulative production, this paper explores cost and performance improvements from a new perspective. The results demonstrate that learning in these pre-commercial production cases arises through mechanisms utilized in deliberate R&D efforts. We identity three mechanisms – materials creation, process changes, and reductions in feature scale – that enable these improvements to occur and use them to extend models of learning and invention. These mechanisms can also apply during post-commercial time periods and further research is needed to quantify the relative contributions of these three mechanisms and those of production-based learning in a variety of technologies.

1. Introduction

Rapid improvements in the cost and performance of new technologies enable technological discontinuities (Christensen, 1997) and large improvements in productivity (Solow, 1957), two important issues within the fields of management and economics. But how do these improvements occur during what Dosi (1982) calls a technological trajectory? For cost, most of the literature focuses on the factory floor and links cost reductions with cumulative production. In what has been termed learning by doing (Arrow, 1962), costs fall as firms learn to produce a single design in a single factory more efficiently and thus with lower costs. Workers become better at tasks and firms introduce better work flows (Wright, 1936; Argote and Epple, 1990; Adler and Clark, 1991; Thornton and Thompson, 2001), better process control (Argote, 1999; Lapre et al., 2000), and automated manufacturing equipment (Utterback, 1994), and promote organizational learning (Benkard, 2000).

Some scholars consider cumulative production as a general proxy for effort and thus the driver of new product and process designs and thus improvements in performance and cost (Lieberman, 1984; Dutton and Thomas, 1984; Balasubramanian and Lieberman, 2010). This formulation which is sometimes called learning by experience suggests that all of the improvements in performance and cost for a technology can be considered endogenous to a model linking cumulative production to the improvements (Dutton and Thomas, 1984; Ayres, 1992; Weiss et al., 2010; Nagy et al., 2013) where the relative contribution of factory floor activities and new product and process designs are unclear. On the other hand, a few scholars have questioned the importance of cumulative production and demand and the possibility that R&D effort or time may be a better independent variable (Koh and Magee, 2006, 2008; Nemet, 2009; Nordhaus, 2009; Thompson, 2012; Funk, 2013a,b).

This paper attempts to better understand the impact of product and process design changes vs. factory floor activities on cost and performance by detailed analysis of improvements in cost and performance in a novel empirical domain. It focuses on new technologies that have experienced rapid improvements in cost and performance before commercial production has been started and it examines the specific mechanisms that enable these improvements to occur. An analysis of these mechanisms enables us to identify more specific modes of learning and to extend models of learning (Argote and Epple, 1990) into the pre-commercialization phase that some define as invention (Arthur, 2007). Our analysis suggests that key aspects of this learning include creating new materials, improving processes, and reducing scale and that this learning occurs in laboratories.

A second contribution of the paper is for theories of invention. Building from others (Fleming, 2001; Fleming and Sorenson,

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2001; Arthur, 2007), the three mechanisms for the improvements in cost and performance suggest that product and process design concepts are improved over time in a recursive process during a transition from invention to commercialization. We view this transition as part of a continuous process of learning in which the technology becomes economically feasible for a growing set of applications both before and after commercial production begins.

This paper first surveys the literature on improvements including learning curves and invention. Second, our methods of finding and analyzing new technologies that are experiencing rapid improvements with little or no commercial production are summarized. Third, time series data on the cost and/or performance of 13 different technologies are analyzed in order to examine the relationship between the rates of improvements and the levels of commercial production. Fourth, a detailed examination of the technical mechanisms that cause these improvements is presented. Fifth, we discuss the extent to which these mechanisms might contribute to improvements after the start of commercial production and the implications of these results for theories of learning and invention, for firm strategy, and for R&D policy.

2. Literature review

Since the publication of Wright's (1936) analysis of fighter jet costs in 1936, empirical analyses correlating cost reductions to cumulative production have grown extensively. These analyses plot straight lines of the log of cost vs. the log of cumulative production. As analyzed and named by Arrow, this formalism of learning by doing (Arrow, 1962) has been shown to be an important explanation for improvements in cost (Argote and Epple, 1990). The early work on learning curves was mostly done on single designs in specific factories and thus analyzed the impact of the factory level changes mentioned in the first paragraph of the introduction on factory productivity. Subsequently, learning curves have been applied to technologies that are manufactured with new designs and in new factories where the output variable might be cost or performance, albeit these models are now often called experience curves (Ayres, 1992; Dutton and Thomas, 1984). For example, the costs of ships (Thornton and Thompson, 2001), solar cells (Nemet, 2006), semiconductor memory, chemicals, primary metals, and food have been analyzed using this approach (Ayres, 1992; Nagy et al., 2013), across significant design changes and often throughout all global factories.

Linking cumulative production to reductions in cost or improvements in performance can lead to confusion about how the improvements in cost and performance are occurring. Some believe that such a linkage suggests most of the improvements are occurring on the factory floor while others note that cumulative production *indirectly* leads to improvements in performance. Increases in production are linked with expected future production and lead to increased incentive to perform process-related (Sinclair et al., 2000) and general R&D (Schmookler, 1966) where the findings from the increased R&D spending result in improvements in performance or cost. This argument is also implicit in Christensen's (1997) analysis of hard disk drives, computers and other "disruptive" technologies in that the emergence of a low-end product lead to increases in R&D spending and thus rapid improvements in the product, which leads to replacement of the dominant technology by the low-end innovation. This argument suggests that except for the "invention," all of the improvements in performance can be considered embedded in a model linking cumulative production to the improvements (Dutton and Thomas, 1984; Lieberman, 1984; Balasubramanian and Lieberman, 2010).

Other analyses plot (logs of) performance or costs vs. time for a specific technology and thus do not implicitly argue that cumulative production is a driver of these improvements. This is consistent with mathematical analyses that show cumulative production could simply serve as a surrogate for time (Sahal, 1979; Nordhaus, 2009; Nagy et al., 2013). For performance, this includes the number of transistors on a chip (Moore's Law), the luminosity per Watt of lighting (Azevedo et al., 2009), processing time or speeds of computers, information storage densities and capacities (Koh and Magee, 2006), and energy or power storage densities of batteries and engines (Koh and Magee, 2008). These studies, starting with Moore, have considered different designs and factories over time and typically plot "record setters" or best performers over time. Proposed mechanisms for these improvements in performance (and cost) include changes in product design (Utterback, 1994; Adner and Levinthal, 2001) such as novel combinations of components (Basalla, 1988; Iansiti, 1995) and changes in scale, both increases in production equipment size and reductions in feature size (Gold, 1974; Lipsey et al., 2005; Winter, 2008; Funk, 2013a,b). These mechanisms might occur in response to bottlenecks in a system of materials or components (Hughes, 1983; Rosenberg, 1969; Dosi and Nelson, 2010).

Building from the possibility that cumulative production may be a surrogate and that it cannot be distinguished as a causal variable from time (Sahal, 1979; Nordhaus, 2009; Thompson, 2012), we propose a novel approach to better understand the impact of new product and process designs and thus R&D on improvements in cost and performance. Our approach focuses on technologies that have experienced rapid improvements in time periods of both no and little commercial production. When we can find such technologies, we can exclude factory-floor mechanisms dependent upon commercial production such as better process control, automated equipment, or scale of production equipment and then identify other mechanisms that have caused the improvements apply in these cases. Second, we can then examine the extent to which these design changes might continue to impact on improvements in cost and performance after commercial production begins.

Since this analysis focuses on pre-commercialization, it can also help us better understand the process of invention. Most research on invention has focused on developing the concepts that form the basis of new technologies and this research describes a recursive process in which combinatorial search (Basalla, 1988; Fleming, 2001; Fleming and Sorenson, 2001; Arthur, 2007) is done. Recursion occurs in the development of concepts, their translation into working prototypes, and we believe their translation into economically feasible products. For working prototypes, problems and sub-problems often at the system and component levels are recursively solved until a working prototype emerges (Arthur, 2007). This paper's analysis explores the transition from technical to economic feasibility where recursion during the development of a series of working prototypes is found to be an important part of this transition.

3. Methodology

We looked for new technologies that have experienced rapid improvements in cost or performance (>10% per year) during time periods in which there was no commercial production. As a point of comparison we note that integrated circuits (ICs) have experienced improvements in the number of transistors per chip of greater than 30% per year – commonly known as Moore's Law. We looked for technologies that are experiencing rapid improvements because technologies with rapid improvements are more likely to have a large impact on improvements in productivity and lead to the