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# When the sky is the limit on scale: From temporal to multiplicative scaling in process-based technologies

Mark Lehrer [a,*], Preeta M. Banerjee [b], I. Kim Wang [a]

[a] Strategy and International Business, Sawyer School of Management, Suffolk University, 120 Tremont St., Boston, MA 02108, USA
[b] Deloitte Development LLC, 1000 Winter St. Suite 2000, Waltham, MA 02451, USA

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ABSTRACT

The design evolution of two important process-based technologies, PCR DNA amplification and ERP software, was punctuated by discrete leaps in scale. From comparison of these technologies we distill a stage model centering on the phenomenon of increasing scale while clarifying just what the concept of scale means in the context of process-based technologies. Process-based technologies turn out to be distinctive because of the *temporal* aspect of scaling; although scaling up usually refers to spatial dimensions of scale, this research highlights the temporal dimension to scale. Temporal scaling can be complemented by multiplicative scaling, a design innovation enabling multiple processes to be performed in parallel. After highlighting different patterns of innovation from those that characterize manufactured products as conveyed by classic product-process lifecycle models, we reconcile our stage model with these classic lifecycle models: although the sequence of innovation phases is different, the overall evolution of the underlying economic logic motivating technology developers is actually rather similar.



## 1. Introduction

A major topic in technology management concerns the challenge of increasing the volume or scale of an innovation. For example, dominant design models of the product life cycle usually characterize the mature phases of the life cycle as one in which the innovative focus is on process innovation for the sake of greater large-scale production efficiency. From a slightly different perspective Sahal (1981, 1985) coined the expression of "learning by scaling" to describe the learning required to master the challenge of engineering larger-scale versions of products or systems. The need to scale up the size of technology products periodically leads to a sequence of multiple dominant designs over time (Frenken and Leydesdorff, 2000). As a general observation, many technology entrepreneurs and even many high-tech regions often develop innovative technology products but struggle with the challenge of scaling up production of such products once they have overcome obstacles to commercialization in their original application domain (Florida and Kenney, 1990).

However, the vast bulk of prior innovation research on the topics of volume and scale applies mainly to manufactured products, leaving the question open as to how issues of volume and scale play out in non-manufacturing domains, such as services (Barras, 1986) or – as examined here – in process-based technologies. It is important from the start not to confuse *process-based technologies* – by which we mean technologies based on a sequence of procedural steps that need to be performed – with the concept of *process innovation* used to describe improvements in the production of (mainly manufactured) items (OECD, 1997). Although the concept of process-based technologies has never been the subject of any dedicated study, this category of technologies is not new and appears to be generally understood by scholars. For example, several researchers specifically characterize nanotechnology as process-based (Linton and Walsh, 2008; Maine et al., 2012) and emphasize the process-based nature of nanotechnology as crucial for understanding innovation patterns specific to this technology.

The empirical focus of this study is on two important process-based technologies, polymerase chain reaction (PCR) DNA amplification and enterprise resource planning (ERP) software, whose development and design evolution was punctuated by multiple discrete leaps in scale. From comparison of these technologies we distill a stage model centering on the phenomenon of increasing scale while clarifying just what the concept of scale means in the context of process-based technologies. Process-based technologies turn out to be distinctive because of the *temporal* aspect of scaling. Whereas the scaling of *products* primarily alters their *size*, the scaling of *processes* primarily alters the *speed* with which they can be performed.

One of the salient performance dimensions of process-based technologies, in other words, is time compression. To make the matter less

* Corresponding author.
*E-mail addresses:* marklehrer@gmail.com (M. Lehrer), pbanerjee@deloitte.com (P.M. Banerjee), iwang@suffolk.edu (I.K. Wang).

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abstract, suppose the amount of time needed to replicate a strand of DNA is initially 48 hours. A technological design improvement reducing the time involved to 6 hours results in a temporal scaling-up factor of 8: one can perform the DNA amplification process 8 times as often in a given span of time. This is temporal scaling. Throughput is increased by accelerating the performance speeds of the underlying technological process.

As the title of our paper suggests, our analysis discloses a pattern of design evolution from a temporal stage of scaling up to a "multiplicative" stage of scaling up. In contrast to temporal scaling (enabling an order-of-magnitude reduction in the time needed to perform a given technology process), "multiplicative" scaling involve a configurational method for increasing throughput. Again, the DNA example makes the basic principle plain. As an alternative to temporal scaling, let us imagine a design innovation in DNA amplification products that still require 48 h to perform the process but are able to duplicate the DNA in 8 samples simultaneously. In terms of overall throughput, a "multiplicative" design improvement of this kind yields a statistically equivalent outcome to temporal scaling-up by the same factor of 8 (Fig. 1). In terms of overall efficiency, multiplicative scaling can have the same net throughput effect as temporal scaling.

The two approaches are not mutually exclusive, of course. Temporal scaling can be complemented by multiplicative scaling. In fact, our research on two highly disparate process-based technologies is suggestive of a stage model involving three basic stages: 1) refinement of the basic process design; 2) temporal scaling; 3) multiplicative scaling.

Beyond just this simple stage model, the case studies below shed light on a number of issues related to the concept of "learning by scaling" (Sahal, 1985). For one thing, the relationship between product and process innovation differs from that in product-process lifecycle models predicated on a phase of product innovation giving way to a primary emphasis on process innovation (Abernathy and Utterback, 1978). For another, in wide-application technologies like ERP and PCR the scaling up process can accompany learning on both the supply and demand side. Most prior research on learning by scaling focuses on supply-side phenomena (Narasimalu and Funk, 2011; Sahal, 1985; Slayton and Spinardi, 2016). Our study shows how the nexus between scaling and learning operates on the demand side as well: the appetite of ERP and PCR users for greater scale was stimulated by user learning about new applications of these technologies requiring greater scale.

Discussion proceeds as follows. Section 2 surveys relevant issues in prior literature on scaling and dominant designs. Section 3 explains the methodology of the study and the selection of PCR and ERP as a logical pair of technologies for study and comparison. Sections 4 and 5 contain brief case studies on the process-based technologies of PCR and ERP and on the design evolution of commercialized processes and products embodying these technologies. Section 6 discusses the implications of the case studies and our derived stage model. As in the literature on dominant designs, the focus of the analysis is on the nexus between design evolution and industry dynamics (Murmann and Frenken, 2006). The discussion of Section 6 fleshes out the interrelated issues of temporal scaling, the seeming insatiability of demand for greater scale, and the relationship between product and process innovation. Section 7 concludes with limitations and avenues for further research.

## 2. Theoretical background

Leaps in innovation resulting from new dominant designs often enable a change in scale of products or of production volumes (Abernathy and Utterback, 1978; Suarez and Utterback, 1995; Tushman and Murmann, 2003). With numerous variations this pattern has been shown to hold in many different industries, e.g., aircraft for civil aviation (Frenken and Leydesdorff, 2000; Slayton and Spinardi, 2016); the typewriter, calculator, TV, vacuum tube, and transistor industries (Suarez and Utterback, 1995) and the cement, container glass, flat glass, and minicomputer industries (Anderson and Tushman, 1990).

Sahal (1981) first underlined how dominant designs expand the scale of a technology. Often scale means physical size. The relevant scaling can be a "scaling-up" of wing span and fuselage length for civil aircraft (Frenken and Leydesdorff, 2000), or a "scaling-down" of vacuum tubes, transistors, and integrated circuits for computers (Cabral and Leiblein, 2001). Sahal (1981) and Slayton and Spinardi (2016) note that scaling can occur in dimensions beyond just overall product size, however, underlining especially the challenge of scaling up key components of products. The experience of the hard disk industry exemplifies both spatial and temporal scaling. The adoption of magnetic polarization increased the areal density, i.e., the volume of information stored on a given length of track of the hard disk drive (Christensen, 1997); meanwhile, the basic measurement unit of microprocessor clock speed advanced from MHz (megahertz) in 1990s to GHz (gigahertz) in early 2000 when semiconductor manufacturers deployed a narrower line width (Cabral and Leiblein, 2001). Although an exhaustive discussion of how the term "scale" has been used is beyond the purview of

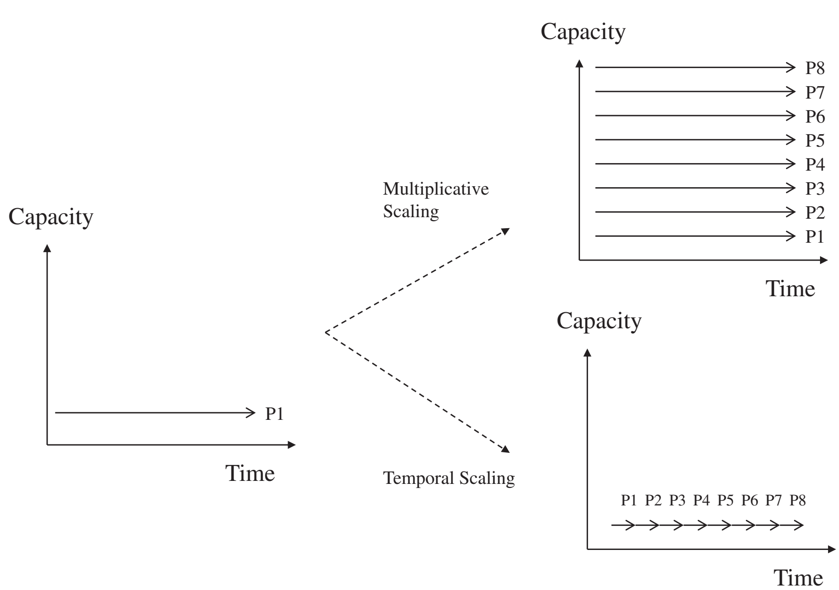


**Fig. 1.** Temporal & multiplicative scaling.