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How a product's design hierarchy shapes the evolution of technological knowledge—Evidence from patent-citation networks in wind power

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ABSTRACT

We analyze how a product's design hierarchy shapes the focus of inventive activity and the expansion of the underlying body of knowledge, building on the complex-system perspective on technological evolution. This perspective suggests that the design hierarchy of a product can have an ordering effect on the evolution of commercialized artifacts, in particular when product design decisions on high levels of the design hierarchy set the agenda for subsequent variation and experimentation on lower levels. We extend this literature by analyzing the design hierarchy's effect on the evolution of the industry's knowledge base, using the case of wind turbine technology over the period 1973–2009. We assess the technological focus of patents along the core trajectory of knowledge generation, identified through a patent-citation network analysis, and link it to a classification of technological problems into different levels in the design hierarchy. Our analysis suggests that the evolution of an industry's knowledge base along a technological trajectory is not a unidirectional process of gradual refinement: the focus of knowledge generation shifts over time between different sub-systems in a highly sequential pattern, whose order is strongly influenced by the design hierarchy. Each of these shifts initiates the integration of new domains of industry-external knowledge into the knowledge base, thus opening windows of competitive opportunity for potential entrants with strong knowledge positions in the new focus of inventive activity. We discuss implications for the understanding of the competitive advantage of specific knowledge positions of firms and nations and technology policy for emerging technologies.

1. Introduction

High-technology capital goods, such as cars, power plants, and manufacturing equipment, are a key entry channel for new technology into the economy (Rosenberg, 1963). Some consider them the 'frontier' of the economic development of nations (Hidalgo et al., 2007). They also underpin those sectors – manufacturing, energy, trade, and transport – that are at the heart of the world's environmental challenges. Technological change in such products often takes the form of long periods of incremental innovations along established technological trajectories, interrupted only by the emergence of new technological paradigms (Clark, 1985; Constant, 1973; Dosi, 1982; Frenken, 2006). Understanding the factors that shape the 'natural' trajectories of technological evolution in high-technology capital goods is therefore critical for business strategy as well as economic and environmental policy (Acha et al., 2004; Davies and Hobday, 2005; Nelson and Winter, 1977).

A number of qualitative studies emphasize the 'guiding' influence of the technology-inherent hierarchy of design decisions – or *design hierarchy* – on the focus of innovative activity along technological trajectories (e.g., Hughes, 1983; Clark, 1985; Vincenti, 1990). In particular, evidence suggests that industry-wide movement *along* a common technological trajectory is associated with movement *down* the design hierarchy, in two principal ways: First, after a new trajectory has emerged, decisions about the overall product design often 'set the agenda' for subsequent change in sub-systems and individual components (Clark, 1985; Murmann and Frenken, 2006; Murmann and Tushman, 2002). Second, changes in sub-systems that perform the core functions of the product tend to

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precede changes in more peripheral sub-systems (Abernathy and Clark, 1985; Lee and Berente, 2013; Murmann and Frenken, 2006).

The movement along technological trajectories and down the design hierarchy implies change in the universe of commercialized designs – i.e., *evolution in the space of artifacts* – and in the underlying technological understanding and engineering heuristics—i.e., *evolution in the space of knowledge* (Dosi, 1982; Martinelli, 2012). The knowledge and artifact spaces are inextricably linked, as knowledge is embodied in artifacts, and the manufacturing and use of artifacts generates new knowledge (Rosenberg, 1982). But they are far from congruent: significant leaps in the design of artifacts may be the result of incremental gains of knowledge, and seemingly small changes in artifacts may require large changes in the underlying knowledge base (Funk, 2009; Martinelli, 2012). Despite the differences between evolutions in the two spaces, quantitative work on the guiding influence of the design hierarchy on technological trajectories has focused primarily on innovation and the evolution of artifacts (e.g, Saviotti and Trickett, 1992; Frenken et al., 1999; Frenken, 2006; Castaldi et al., 2009; Mendonça, 2012). With few exceptions (Lee and Berente, 2013; Rosenkopf and Nerkar, 1999), the influence of the design hierarchy on invention and the evolution of knowledge has received little attention.

To address this gap, we analyze how a product's design hierarchy influences the trajectory of knowledge generation. We do so in order to investigate the prevalent assumption that the development of an industry's knowledge base along the trajectory is predominantly a process of incremental growth and refinement, without abrupt shifts in the focus of inventive activity and changes in the importance and composition of industry-external knowledge. This assumption has shaped the innovation literature in two important ways. In particular, it is commonly assumed that movement down the design hierarchy leads to *the entrenchment of existing knowledge positions,* thus enhancing the competitive advantage of incumbent firms and nations through incremental knowledge growth and refinement. In contrast, movement up the hierarchy – through the creation of new trajectories – is associated with novel skills and expertise, thus opening windows of opportunity for new entrants (Abernathy and Clark, 1985; Bekkers and Martinelli, 2012; Henderson and Clark, 1990). A better understanding of how an industry's knowledge base evolves along the trajectory can thus contribute to improved managerial and policy decisions.

In analyzing how a product's design hierarchy influences the trajectory of knowledge generation, this paper links two streams of literature: research on dominant designs and technological evolution in systemic artifacts on the one hand (e.g., Frenken and Nuvolari, 2004; Murmann and Frenken, 2006; Mendonça, 2012) and research on trajectories of knowledge generation on the other hand (e.g., Fontana et al., 2009; Barberá-Tomás et al., 2011; Epicoco, 2013). In particular, we develop a novel methodology that combines the manual, *categorical analysis of commercialized designs*, as employed in studies of dominant designs and technological evolution in systemic artifacts, with *patent-citation network analysis,* as employed in the literature on knowledge trajectories. This methodology allows us to bridge the artifact and knowledge dimensions by studying the influence of the design hierarchy, which derives from relationships between elements of the physical artifact, on the trajectory of knowledge generation in the industry. We apply this novel methodology to the case of wind turbine technology in the period 1973–2009.

The paper makes several distinct contributions to theory and methodology. *Theoretically*, we contribute to the literature on knowledge positions and competitive advantage (Bekkers and Martinelli, 2012; Choi and Anadón, 2014; Epicoco, 2013). Our findings suggest that the evolution of an industry's knowledge base along the technological trajectory is not a unidirectional process of gradual refinement but a sequential process that is structured by the design hierarchy: the focus of knowledge generation shifts over time between different sub-systems, with each shift initiating the integration of new domains of industry-external knowledge into the knowledge base—a pattern we call *creative sequences. Methodologically*, our analysis contributes to recent efforts to identify linkages and linking mechanisms between the evolution of knowledge and the evolution of artifacts (Bakker et al., 2012; Barberá-Tomás et al., 2011; Ethiraj, 2007; Martinelli, 2012). We extend the methodology developed by Verspagen (2007) and others to study the knowledge and the artifact dimensions of technological trajectories in an integrated way, which may facilitate a deeper understanding of the interaction between the two domains.

In the following, Section 2 lays out the paper's theoretical perspective and reviews the literature on technological evolution in systemic artifacts. Section 3 introduces the case of wind turbine technology and Section 4 presents the data sources and methodology. The results are presented in Section 5 and discussed in Section 6. Conclusions are summarized in Section 7.

2. Theoretical perspective

We use the word "technology" in the tradition of the literature on technological trajectories (e.g., Barberá-Tomás et al., 2011; Bekkers and Martinelli, 2012), to encompass physical artifacts (we focus on commercialized product designs in particular) as well as the underlying technological knowledge (i.e., the engineering practices, rules, heuristics, and formalized pieces of knowledge), not all of which is embodied in the physical artifacts. In line with the empirical literature on technological trajectories, in this paper we approximate knowledge with patented inventions and artifacts with commercialized product designs.

Technological products are conceptualized in this paper as *complex, systemic artifacts* (Murmann and Frenken, 2006; Saviotti, 1986; Tushman and Rosenkopf, 1992), consisting of interdependent subsystems and components that jointly enable the system to perform a number of functions, or *service characteristics*. The sub-systems and components are organized by a *product architecture,* which allocates system functions to the individual components and defines the interfaces between them (Baldwin et al., 2014; Clark, 1985; Simon, 1962).

Technological evolution in high-technology capital goods is understood as proceeding predominantly along technological trajectories through refinement within, and extension of, existing product architectures, interrupted from time to time by fundamental (or 'paradigmatic') changes in the product architecture (Constant, 1973; Dosi, 1982; Frenken, 2006). When discussing the influence of the design hierarchy on technological evolution in the following subsections, we are concerned with the design hierarchy's impact on the *focus of incremental innovative activity along technological trajectories* and *the direction of evolution* in the spaces of knowledge and artifacts.

2.1. The sequential pattern of innovation in systemic artifacts

Historians of technology have long noted the existence of sequential patterns of innovation in the evolution of technological artifacts (Constant, 1980; Hughes, 1983; Rosenberg, 1969; Vincenti, 1990). In this context, *sequential* means that technological progress is concentrated in only a small fraction of a product's components and possible directions of change, and that the focus of this concentration shifts over time between technological problems. The observed sequential pattern also implies that the focus of innovative activity is at least partly *collective,* in the sense that it can be