MODULARITY IN NEW MARKET FORMATION: LESSONS FOR TECHNOLOGY AND ECONOMIC POLICY AND COMPETENCE-BASED STRATEGIC MANAGEMENT

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ABSTRACT

In this paper we appraise the ways in which use of closed-system proprietary product architectures *versus* open-system modular product architectures *is likely to influence the dynamics and trajectory of new product market formation. We compare the evolutions of new markets in China for gas-powered two-wheeled vehicles (G2WVs) based (initially) on closed-system proprietary architectures and for electric-powered two-wheeled vehicles (E2WVs) based on open-system modular architectures. We draw on this comparison to suggest ways in which the use of the two different kinds of architectures as the basis for new kinds of products may result in very different patterns and speeds of new market formation. We then suggest some key implications of the different dynamics of market formation associated with* open-system

Research in Competence-Based Management, Volume 8, 131–165

ISSN: 1744-2117/doi: 10.1108/S1744-211720170000008006

modular architectures *for both the competence-based strategic management (CBSM) of firms and for technology and economic development policies of governments.*

Specifically, we suggest how the use of open-system modular product architectures as the basis for new products is likely to result in dynamics of new market formation that call for new approaches to the strategic management of innovation and product creation. We also suggest technology and economic development policies favoring use of open-system modular architectures may stimulate new market formation and related economic development by providing platforms for accelerating technology development and dissemination, facilitating the formation of an industrial base of assemblers and component suppliers, assisting new firms in building customer relationships, enabling more geographically diffused economic development within countries, and facilitating development of export markets. We also suggest directions for further research into the potential for open-system modular product architectures to enable bottom-of-the-pyramid innovation processes, frugal engineering in developing economies, and development of low-cost product variations more generally.

Keywords: Modularity; industry standards; technology development; economic development policy

1. INTRODUCTION

Research into the influence of technology on market development and economic growth has often represented technological development as a rather general and diffuse phenomenon. The pioneering work of Solow (1956, 1960), for example, represented technological progress as an accumulation of technical changes at the micro-economic level that broadly improves the efficiency with which an economy converts its inputs into outputs at the macroeconomic level. Subsequently, mainstream economic research has tended to characterize technological progress as originating from diffuse phenomena whose cumulative effect results in an outward shift in an economy's production frontier.

Although macro-economic studies of productivity improvements resulting from advances in mechanization and transportation improvements and more recently in computerization and automation are a stock-in-trade of development and macroeconomic research, microeconomic investigations into how *alternative approaches to designing products* may affect the rate and scope of new product market formation and the rates of technology and economic development associated with new products are the exception, not the rule. In particular, the potential influence of alternative ways in which technology can be "packaged" into useful new products – i.e., the potential influence of alternative kinds of *product architectures* – have rarely been considered in theoretical and empirical analyses of technology's influences on market formation, industry structures, and economic development (Sanchez and Mahoney, 1996, 2013).

By contrast, in the last 20 years research focused on competitive and cooperative business strategies has generated a substantial stream of theory development and empirical research investigating the micro-level influences of *product architectures*[1] on firms' product strategies and their macro-level influences on the patterns and rates of new market formation that directly affect economic development (Sanchez and Mahoney, 1996; Baldwin and Clark, 2000; Schilling, 2000; Sanchez, 2008). In particular, strategic uses of *modular product architectures*[2] in creating new products and supporting industrial and market processes have been shown to lead to lower costs for both product development and production and significant reductions in overall development time and resource requirements – and at the same time to enable the introduction of more product variations to serve diverse market needs and more rapid technological upgrading of products (Sanchez, 1995, 1999; Sanchez and Collins, 2001; Worren, Moore, and Cardona, 2002).

Subsequent research into strategic uses of *open-system modular product architectures*[3] has also confirmed that a number of macro-level industry effects occur when significant numbers of firms begin to adopt common modular product architectures that incorporate "industry standard components" connected through "industry standard interfaces." These macro-level effects include (i) the rapid and widespread growth of a supplier base of firms specializing in the development and production of standard modular components, (ii) the rise of many small to medium development and/or assembler firms that can use standard components provided by the supplier base to configure and/or produce new products, and (iii) decreased levels of vertical integration required to establish new product markets, resulting in increased "vertical disaggregation" and (often) greater geographic distribution of economic activities spawned by a new product market (Sanchez and Mahoney, 1996; Hoetker, 2006; Funk, 2008).

Further, strategic management research has suggested that adoption of open-system modular architectures that are available to and used in common among firms in an industry accomplishes these macro-level industry effects through three important micro-level consequences of using modular architectures for new product designs (Sanchez and Mahoney, 1996; Schilling, 2000; Sanchez, 2008).

First, a standardized way of decomposing an architecture into specific kinds of functional components and a standardized set of interface specifications for interrelating components in an architecture creates an *information structure* that can provide *embedded coordination* of development and production activities among the firms participating in an industry (Sanchez and Mahoney, 1996). In effect, the information structure of component and interface specifications in a modular architecture provides industry participants with essential understanding of both (i) the kinds of components that will be used in the products the industry provides, and (ii) how the interfaces between all components need to be designed so that all the modular components used by the industry will "plug and play" together reliably in the product architecture. In effect, the existence of an open-system modular architecture accessible to all interested firms reduces the scope of technological knowledge an individual firm must have to participate in an industry as a component specialist or assembler, thereby facilitating entry of entrepreneurs and stimulating growth of a component supplier base for a new product market.

Second, by establishing the standard kinds of modular components that will be used in configuring new products, a modular industry architecture helps to achieve economies of both scale and scope that can stimulate formation and growth of a new market (Sanchez, 2008; Stephan et al., 2008). Economies of scale are likely to be achieved as some firms begin to specialize in one or more specific kinds of components and expand production to serve demand for standard components by the industry's assembler firms. Economies of scope may be achieved when specialist component suppliers adopt modular designs at the component level and begin to produce variations of standard types of components that can be used to configure a broader range of final product variations. Increasing economies of both scale and scope encourage the growth of a product market by reducing product costs and by facilitating the configuration of more product variations to serve varying customer needs and preferences.

Third, a standardized modular industry architecture provides a relatively well-defined and stable technical environment that reduces uncertainty about the component-level technologies that will be used in an emerging new industry, thereby substantially lowering the risk that firms would face relative to developing firm-specific technologies and component designs. Specialist firms may therefore be more willing to undertake further development of standard component-level technologies that result in improved product performance and cost reductions. As Sanchez (2000b) has suggested, it is no coincidence that the contemporary industries showing the highest rates of sustained technological progress – such as computers, telecommunications, and consumer electronics – are also the industries that have adopted the most highly modularized and standardized technologies and product architectures.

In this paper we elaborate a number of aspects of the impacts that open-system modular architectures may have on the formation of new product markets in general and on the pattern and rate of technological progress and economic development in particular. Our discussion seeks to contribute to our understanding of (i) the economic benefits that may be derived from adopting open-system modular architectures as the basis for a new product market; (ii) the ways in which the use of open-system modular architectures calls for new concepts, processes, and competences in the strategic management of firms; and (iii) the role that open-system modular architectures can play in facilitating new market formation, technological progress, and economic development.

Our discussion is developed in the following way.

In section 2, we draw on research into the development dynamics and trajectories of gasoline-powered two-wheeled vehicles (G2WVs) and electric-powered two-wheeled vehicles (E2WVs) in China to analyze the role of product architectures in the formation of markets for G2WVs and E2WVs in China. In so doing, we undertake to shed new light on the co-evolutionary interactions and dynamics of market concepts, product architectures, technological progress, government regulation, market strategies, and industry structures in the development of new product markets. In particular, we suggest how the adoption of open-system modular architectures in these vehicle markets not only helped those markets to grow at very high rates in China, but also facilitated the development of technological and architectural capabilities that within a decade made Chinese firms major players in the Asian G2WV market and the largest producers and exporters of E2WVs in the world.

In section 3 we draw on our analysis of the formation of the G2WV and E2WV markets in China to suggest some lessons for technology and economic development policy. We suggest some basic propositions about the positive influences that use of open-system modular architectures can have on the rate and pattern of technology development likely to be found in a new product market, on the development of firm capabilities for building and maintaining customer relationships in new markets, on the development of export markets, and on industrial and economic development in general.

Section 4 considers some implications of our analyses for the theory and practice of competence-based strategic management of firms.

Section 5 suggests directions for further research into the architectural perspective and derived propositions developed in this paper. We suggest the need for further research to clarify the potential for open-system modular production networks to offer a viable alternative to industrial clusters as a policy instrument for stimulating economic development. We also suggest directions for research to clarify the potential contributions of open-system modular design to bottom-of-the-pyramid innovation processes, frugal engineering methodologies focused on serving the needs of developing economies, and the innovation of low-cost products generally.

Section 6 offers conclusions and a summary of the intended contributions of the paper for both technology and economic development policy and for competence-based strategic management.

2. TWO-WHEELED VEHICLES IN CHINA: AN ARCHITECTURAL PERSPECTIVE ON NEW MARKET FORMATION AND TECHNOLOGICAL PROGRESS

In this section, we adopt an architectural perspective in analyzing the trajectories of new market formation, technological progress, and industrial development in the G2WV and E2WV markets in China between 1991 and 2009, and we undertake to identify important differences and commonalities in the architectural evolutions of the two product markets. We specifically consider the ways in which viable market concepts were established in the two product markets in China, the different trajectories of product architecture evolution in the two markets, and their resulting differences in patterns and rates of technological progress. We also consider how government regulations and competitive pressures influenced the emergence of open-system modular product architectures in the two markets, how competitive strategies adopted by firms differed in the two markets, and how various factors led to the adoption of different kinds of product architectures in the two markets.

2.1 Gasoline-Powered Two-Wheeled Vehicles (G2WVs)[4]

The entry and growth of firms in the Chinese G2WV industry occurred in three distinct phases during two decades beginning in the late 1980s.

The first phase began when state-owned enterprises either formed joint ventures with or obtained production licenses from Japanese motorcycle firms Honda, Suzuki, and Yamaha to manufacture specific motorcycle and scooter models for the Chinese market. Through the 1990s these Chinese firms produced a succession of motorcycle and scooter models that were designed and developed in Japan. Because both motorcycles and scooters had previously developed into mature product markets outside of China, both types of G2WVs could be provided to the new Chinese market in a range of engine and frame sizes to suit a variety of customer requirements and preferences. G2WVs therefore provided a relatively affordable and convenient means of personal transport that filled a broad market need not well served by other available means of personal transport (automobiles or bicycles). As the Chinese economy began to grow rapidly in the 1990s, the domestic G2WV market grew from just over one million units sold in 1991 to nearly 15 million sold in 2007 (Weinert et al., 2008; Yu et al., 2010), as shown in **Figure 1**.

The Chinese firms (typically state-owned enterprises) that created and served the domestic market for G2WVs initially relied on detailed design and production drawings provided by their Japanese licensors or partners. These firms sometimes produced key components like engines and chain drives used in the models they assembled, while other components and parts needed for the models were typically sourced from a small network of local manufacturers. As the G2WV market grew in size, the state-owned enterprises working

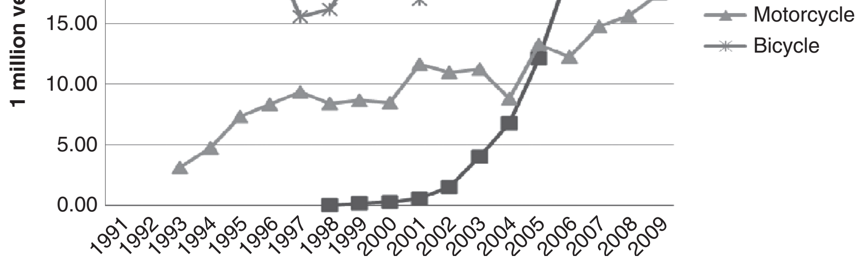

Figure 1. Sales of Bicycles, G2WVs, and E2WVs in China, 1991–2009
Source: Ruan, Hang, Wang, and Ma (2012)

with Japanese partners were largely limited to producing G2WV designs provided by Japanese firms' development centers in Japan.

A second and largely parallel process in the formation of the Chinese G2WV market began in the mid-1990s as a number of private firms began to copy Japanese motorcycle designs, often producing hundreds of thousands of unauthorized copies of popular Japanese models. These firms typically purchased Japanese motorcycle and scooter models and disassembled them to make production drawings of the components and parts required for each model. In some cases, assembler firms would make the production drawings themselves and send their drawings to potential component suppliers for production bids. In other cases, firms interested primarily in assembling and marketing G2WVs would send actual parts to suppliers who would then prepare production drawings for approval by the assembler firms. These two processes formed the basis of what Ge and Fujimoto (2004) describe as a "drawing-supplied system" versus a "drawing-approved system" of assembler-supplier relationships.

Through both processes, assembler firms created local networks of suppliers that produced copied parts in dozens of industrial and population centers in China. Some parts suppliers even developed catalogs of copied parts for a number of Honda, Suzuki, and Yamaha models, and sold these parts to multiple assemblers.

With as many as 400 assemblers and associated networks of parts suppliers in the Chinese G2WV market by the late 1990s, price competition became intense (Steinfeld, 2002). In response, both licensed and copying producers and their parts suppliers focused on reducing production costs through improving manufacturing efficiency, often achieving significant cost reductions that benefited consumers and stimulated market growth through falling prices. Subsequently, private Chinese assemblers began to export copied models to other countries in Asia, both as fully assembled models and as kits for local assembly.

However, because both assemblers and parts suppliers in China initially lacked the technological and architectural knowledge needed to develop new or improved G2WV models and parts on their own, assemblers typically sought temporary competitive advantages by being the first in their local market area to introduce new G2WV models developed outside of China (typically by Japanese firms, but later by European firms as well). The constant "churning" of new models and associated components, combined with production for various local markets rather than for the national market, prevented Chinese assemblers and component producers alike from achieving significant cost reductions through economies of scale. Thus, in spite of the rapid formation of a sizeable G2WV market in China, thin profit margins resulting from intense price competition and a failure to achieve significant scale economies in production, coupled with the constant "churning" of licensed or copied new models and associated components, provided little opportunity for either capital accumulation or technological and architectural capability development by Chinese firms in the G2WV market.

The third phase of evolution in the Chinese G2WV market began in the late 1990s, when Chinese G2WV producers turned to architectural reconfiguration of their G2WV designs as a means to achieve new levels of cost reductions in their fiercely price-competitive market. As Brown and Hagel (2005: 38-39) noted,

> …private assemblers redefined the Japanese companies' tightly integrated product architecture into one that was more flexible and modular but just as functional. The [resulting] Chinese system makes it possible for the assemblers to modularize production in parallel by outsourcing components and subassemblies to independent suppliers.

The ex-post modularization of Japanese and European G2WV designs by private Chinese firms in the late stages of G2WV market development in China not only abetted the development of an independent and more widely distributed supplier base, but also ended the technological lock-in (legal or *de facto*) of Chinese firms that licensing or copying of Japanese designs entailed. In effect, the modularization of G2WVs by private firms enabled them to begin their own technological developments of higher performing and/or more economical components. The subsequent development of less "tightly integrated" and more standardized kinds of modular components in the Chinese G2WV market enabled component suppliers to increase production volumes and reduce production costs through scale effects. The substantial cost reductions achieved by Chinese firms through adoption and production of standard modular components were a major factor in enabling these firms to maintain competitive product offers in their domestic market in the face of new competition from E2WVs in the late 1990s.

2.2 Electric-Powered Two-Wheeled Vehicles (E2WVs)[5]

The Chinese market for E2WVs began with the introduction of some early experimental models in 1995–1998, followed by the first mass-produced models in 1998. From 1998 to 2010 the E2WV market grew even more rapidly than the G2WV market in the 1990s, surpassing 20 million units annually by

2007 (see Figure 1). Notably, in contrast to the formation of the market for G2WVs, the rapid rate of E2WV market formation witnessed early on both the rise of large-scale E2WV producers and the achievement of significant technological progress by some Chinese firms in improving the performance of E2WVs.

We now consider some architectural and related aspects of the formation of the E2WV market in China that appear not only to have enabled the new market to grow at a very high rate, but also to have facilitated the development of both scale economies and the technological and architectural capabilities that subsequently enabled Chinese firms to become the largest producers and exporters of E2WVs in the world. We consider in turn how market concepts, product architectures, technological progress, government regulation, market strategies, and industry structures have interacted to influence the trajectory of market formation and technological progress in both the E2WV and G2WV markets in China.

2.2.1 Market Concepts

When new kinds of products are offered to a market, they are evaluated by individual consumers and by businesses for their potential to contribute in some useful way to consumers' lives or to firms' business processes. As individuals and businesses in a potential market learn about a new product concept and appraise its functions and performance levels for their potential utility, their collective appraisals form what Clark (1987) terms a "market concept" that characterizes the perceived benefits and costs associated with a product in its possible contexts of use (Kotler, 2002).

The rapid formation of the Chinese G2WV market in the 1990s was founded upon mature product concepts (gas-powered motorbikes and scooters) whose designs had become highly evolved through decades of prior development and were thus well adapted to various user requirements in most parts of the world. As a result, G2WV designs developed by Japanese firms for world markets included models that were well suited to use in China and provided a market concept whose functions and resulting utility (positioned between automobiles and bicycles) could be quickly understood and accepted by Chinese consumers. Thus, G2WV designs developed outside China provided proven market concepts that readily served as the basis for the formation of a G2WV market in China.

By contrast, although E2WV product concepts provide personal transportation in functional forms very similar to G2WV designs (see **Figure 2**), E2WVs differed significantly from G2WVs in both their performance

Figure 2. E-Bike and E-Scooter versions of E2WVs
(Source: Yu, Hang, and Ma 2010)

characteristics and their costs. In the 1990s E2WVs were generally less powerful than even the least powerful G2WVs – typically 0.25 to 0.5kw for E2WVs compared to 3 to 6kw for G2WVs. The lower power of E2WVs limited their top speed to about 20km/hr and provided only modest climbing power in areas with hilly terrain. Moreover, E2WVs were initially powered by batteries that had to be recharged (usually at a user's home) after traveling only 30km or so, while G2WVs had travel ranges from 120 to 300km and could be quickly refueled at widely available service stations (Weinert et al., 2008). Given these limitations in functional utility, E2WVs did not prove to be a viable market concept in China's rural areas, where distances to be traveled typically exceeded the distance an E2WV could travel without recharging and in which little or no infrastructure for recharging existed outside a home.

On the other hand, the total purchase price and operating costs for E2WVs ranged from 50% to as little as 10% of the price and operating costs of G2WVs, depending on the relative power levels of the vehicles (Cherry, 2007). Moreover, the 30-kilometer operating range on a single battery recharge proved adequate for urban consumers, many of whom came to perceive E2WVs as a useful and desirable form of urban transport that was significantly less costly to operate than automobiles or G2WVs and more convenient than public transport (primarily buses). Thus, while initially not viable in rural areas, E2WVs quickly became an accepted and often preferred market concept for personal transportation among urban dwellers in China's rapidly growing cities. Finally, the lighter weight, lower power, resulting ease of handling, and affordability of E2WVs compared to G2WVs succeeded in attracting a new group of consumers – primarily women, seniors, and adolescents – who did not need or were uncomfortable with more powerful G2WVs.

2.2.2 Product Architectures

Although the E2WVs introduced in China resembled contemporary G2WV designs in their basic functional form, E2WVs differed significantly from G2WVs in their product architectures. The Japanese-designed G2WVs produced in China were based on mature product architectures that had been optimized for specific models by Honda, Suzuki, and Yamaha. The product architectures developed by the three Japanese firms were essentially *closed-system non-modular designs* (Sanchez, 2008) incorporating component designs that were specific to each company and model and using company-specific, often proprietary interfaces between components. Such designs left little need or opportunity for Chinese producers to develop alternative component designs or product configurations for the Japanese models that they produced under license or copied.

By contrast, the early E2WV designs developed domestically in China in 1995–1998 were largely based on pre-existing, industry-standard components (in other industries) for electric motors, batteries, battery chargers, controllers (to regulate vehicle speed), and various running gear components (most commonly, those used in bicycles). These components could also be connected through more or less standardized, non-proprietary kinds of interfaces to configure a working product design. The adoption of industry-standard components at an early stage in the evolution of E2WVs occurred in part because the Chinese government promulgated regulations that required E2WVs to use motors with a relatively narrow range of power levels (see further discussion below). As a result, early E2WV producers initially adopted a limited range of already-available, "off-the-shelf" direct-current (DC) electric motors within the allowed range of power levels. These motors were fitted with sprocket chain-drive gears, connected to chain drives mounted on rear wheels, and powered by rechargeable lead-acid batteries – all of which were also off-the-shelf, industry standard components widely used in bicycles or G2WVs. By basing the emergent E2WV architecture on standard kinds of components connected through standard interfaces, Chinese E2WV producers in essence created a *de facto* open-system modular product architecture as the basis for the emerging E2WV industry.

Because the emergent E2WV product architecture incorporated simple standard interfaces, E2WV producers could develop improved motors, batteries, controllers, and other components that conformed to the standard interfaces and thus could be introduced into the E2WV architecture with little or no modification required to other components. As we discuss in the next section, the *de facto* open-system modular architecture voluntarily adopted by Chinese E2WV producers provided a platform for rapid technological progress in improving the key components that largely determine the performance and cost characteristics of E2WVs.

2.2.3 Technological Progress

The G2WVs introduced in China in the 1990s had been extensively developed by Japanese producers and had achieved high performance levels on multiple dimensions by the time of their introduction into China. By contrast, the first E2WVs produced in China were largely Chinese inventions incorporating some basic components (primarily motors, batteries, and controllers) with significant potential for further technological development and performance improvement for E2WV use, particularly with regard to extending cruising range between charges and improving hill-climbing capability. Because the *de facto* open-system modular architecture used for E2WVs allowed improved versions of such components to "plug and play" in the standard E2WV architecture with little or no modifications to other components in the architecture (Sanchez, 1995; Sanderson and Uzumeri, 1996), E2WV producers and their component suppliers began to actively develop and introduce improved motors, batteries, and controllers that led to significant performance gains for E2WVs.

In the 10 years between the introduction of the first E2WVs in China in 1998 and 2008, Chinese producers dramatically increased the performance characteristics of E2WVs (Weinart et al., 2008; Ruan et al., 2012). Battery capacities increased by 35% (with corresponding increases in cruising range between recharges) and battery lifetimes were extended by 160%. Battery technology advanced significantly with the development of longer lifetime lithium-ion (Li-ion) and nickel-metal hydride (Ni-MH) batteries for use in E2WVs. Motor efficiency improved by 60% and motor lifetimes improved 500%. By 2007, E2WVs were available with power as great as 1 to 1.5 kw and top speeds of 60–80 km/hr, thereby making E2WVs a viable market concept for suburban commuters in China's many large cities. In addition, regenerative braking systems that use the momentum of a moving vehicle to recharge its batteries were introduced by some producers into the E2WV product architecture.

These component technology improvements enabled significant increases in the size, power, speed, and range of E2WVs. The significant technological progress and resulting product performance improvements made by Chinese E2WV firms stimulated rapid growth not only in China's domestic market, but also in export markets. E2WVs developed and produced in China soon became established in a number of Asian countries as viable alternatives to Japanese and Taiwanese-produced or licensed G2WVs.

2.2.4 Government Regulation[6]

The introduction of G2WVs into the Chinese market in the 1990s was largely viewed favorably by the Chinese government for providing an affordable means of personal transport and for stimulating industrial development. Thus, the formation of the Chinese market for G2WVs was accompanied by little restrictive regulatory activity other than usual requirements for registering and licensing of individual vehicles.

By the time of the introduction of the earliest E2WVs in China in 1995–1998, however, the growing volume of bicycle, G2WV, automobile, and bus traffic in China's rapidly developing urban areas had created serious traffic congestion and environmental pollution problems. Because the early E2WVs moved more slowly than gas-powered vehicles, and because their low purchase price enabled ownership by many newcomers to urban areas who were not accustomed to the norms of city driving, E2WVs were viewed by many cities as impediments to the normal traffic flow of G2WVs, automobiles, and buses. As a result, in the late 1990s many Chinese cities began to ban the use of E2WVs on city streets (Steinfeld, 2004).

However, the mass migrations of people from rural areas seeking a better life in Chinese cities in the 1990s led to worsening levels of urban air pollution caused by emissions from gas- and diesel-powered vehicles of all types. As urban air quality deteriorated in Chinese cities, various levels of government in China began to view E2WVs more favorably as a desirable replacement for G2WVs in China's crowded cities.[7] In 1999 the Chinese central government overruled the bans against E2WVs adopted by city governments and issued National Standard GB1776-1999 promulgating the "General Technical Requirements for Electric Bicycles" (Yu, Hang, and Ma, 2010). The regulations limited E2WVs to 20km/hr in speed, 40kg in weight, and 0.24kw in motor power, and required E2WVs to be capable of being propelled by pedaling as well as by an electric motor.

These central government regulations effectively legitimized the large-scale use of E2WVs in Chinese cities and played a key role in inducing market entry and large-scale production of E2WVs by a number of Chinese firms. The general technical specifications promulgated in the National Standard for E2WVs essentially defined the functional characteristics of a new product concept that would become available to Chinese consumers, and thereby eliminated much commercial uncertainty as to what functions and performance levels the new E2WV product concept would offer to consumers. Moreover, although by 2007 Chinese producers had developed E2WVs that substantially exceeded the product specifications in the National Standard, the basic product specifications in the National Standard lent an important common focus to the early architectural and technological development of E2WVs by Chinese firms. In effect, the new National Standard resolved most of the technical uncertainty as to the kinds of component technologies and designs that could be used to provide the approved E2WV functions and performance levels, thereby encouraging investments in development of improved standard components and large-scale production systems.

2.2.5 Market Strategies

When introduced into China, G2WVs were both technologically mature and readily understood and accepted as a market concept. To serve the resulting demand for G2WVs, Chinese firms had only to put in place basic sales and service infrastructures in order to grow the market for G2WVs. Moreover, basic repairs and maintenance of G2WVs could often be performed by automobile or small engine mechanics throughout China, thereby substantially reducing the need to establish an infrastructure of trained and specialized G2WV mechanics.

By contrast, because the performance characteristics of E2WVs were significantly different from those of G2WVs (specifically, less power and more limited range), producers of E2WVs had to expend significant effort to communicate the attributes, suitable uses, and resulting benefits of E2WVs to potential customers. Moreover, because the early E2WV market included many producers of poorly designed and sometimes unsafe vehicles, producers of quality E2WVs had to develop sales and marketing capabilities that could distinguish their high quality products from those of less capable producers. Early involvement with customers also helped quality-minded E2WV producers identify the performance improvements (such as extended cruising range and longer lasting batteries) that were most desired by the market and thus most needed to establish E2WVs as a viable new market concept with mass appeal.

E2WV producers who tried to sell their products through established G2WV dealers also came to realize that G2WV dealers were less motivated to sell lower-priced E2WVs than higher-priced G2WVs. As a result, the producers of E2WVs that eventually gained major market positions in China did so by setting up their own E2WV sales channels. In addition, E2WV producers also had to establish networks of service and repair facilities to support their products, since a suitable infrastructure of such capabilities did not already exist in China. In effect, successfully establishing and serving a market for E2WVs in China required E2WV producers to become directly and broadly involved in providing E2WV sales and service support to their customers.

In this regard, the case of Jinhua Luyuan Electric Vehicle Co., Ltd. is instructive (Dan, Hang, and Ma, 2011). In 1997, its second year of production of E2WVs, Luyuan published its own magazine to promote the benefits of E2WVs (low operating cost and reduced urban pollution, among others). After facing irate customers and nearly going bankrupt when batteries from a supplier proved defective, Luyuan both led an E2WV producer campaign for stricter national standards for E2WV batteries and began its own development program for E2WV batteries. As Luyuan began to develop more reliable, longer-lived batteries, it launched a program that let customers trade in their old batteries and finance the purchase of Luyuan's improved batteries. To support customers who could not find repair and service facilities (or whose batteries were depleted before reaching home), Luyuan instituted a 24/7 customer hot line with mobile road service crews to assist customers in distress.

Undertaking such service and support activities that resulted in significant engagements with customers before and after sales proved to be a key reason for Luyuan's rapid success in establishing a viable E2WV market presence in China. Moreover, E2WV firms like Luyuan that realized the need for after-sales support of customers eventually gained more than just a growing share of the new E2WV market. They also gained an understanding of the business benefits to be derived from actively building long-term relationships with customers and from providing customer service and support as an integral part of their business strategy. The customer-oriented capabilities that Luyuan and some other firms developed in establishing the market for E2WVs in China served them well not only in rapidly growing the E2WV market in China, but also in developing a large export market for Chinese-produced E2WVs in Asia.

In fundamental respects, while many producers in the early stages of G2WV market formation were focused on cost reduction through improving production efficiencies and on constantly introducing new models as the drivers of their business strategies, many of China's E2WV firms adopted the kind of customer-oriented business strategies and developed the kinds of customer support capabilities that are now recognized as essential to competitive success in developed economies. As the Luyuan case suggests, adopting customer-oriented strategies and developing the kinds of customer-support capabilities that are usually essential for market success in developed economies may also be the keys to success in the formation of new product markets based on new product concepts in developing economies, too.

2.2.6 Industry Structures

Research into the influence of product architectures on inter-firm relationships in an industry's development and production processes suggests that both firm structures and industry structures will "mirror" the structure of the product architecture(s) on which the industry is based (Sanchez and Mahoney, 1996; Sanchez, 2000a, 2008; Baldwin and Clark, 2000). This research suggests that industries based on competing *proprietary closed-system, non-modular, tightly-integrated product architectures*[8] are likely to be populated by extensively vertically-integrated assembler firms that develop and produce all or most of the components each uses in its products, and/or that maintain "quasi-integrated" relationships with a few suppliers with whom the firm has close, long-term working relationships for developing and producing components, often secured through long-term supply contracts or cross holdings of shares (Williamson, 1981). Thus, product markets based on proprietary closed-system, non-modular, tightly-integrated product architectures tend to spawn industry structures dominated by a few large firms with their own base of quasi-integrated component and service suppliers.

By contrast, use of open-system modular product architectures in a product market is likely to give rise to a *modular industry structure* in which potentially large numbers of supplier firms can develop and produce components and supporting services that "plug and play" in a common modular architecture used by potentially large numbers of assembler firms to readily configure product variations to serve many kinds of customer needs and preferences (Sanchez, 2000b, 2002b, 2008). Essential technical coordination among the participants in a modular industry is achieved when industry participants adhere to standard interface specifications that enable many firms to develop and produce components that will plug and play in the modular product architecture that is the basis for a product market (Sanchez and Mahoney, 1996). Modular product architectures thereby provide an *information structure* that facilitates the formation of industry structures and processes in which large numbers of suppliers and assemblers can develop, produce, assemble, sell, and service modular components and modular product variations (Sanchez and Mahoney, 1996; Sanchez, 2002a, 2002b, 2008).

The development trajectories of the G2WV and E2WV markets in China largely reflect these suggested influences of product architectures on industry architectures. The Chinese G2WV market, which was initially based on proprietary closed-system, non-modular, tightly-integrated product architectures licensed or copied from Japanese manufacturers, first evolved into a strongly vertical industry structure characterized by tightly-coupled vertical relationships between assembler and supplier firms dedicated to production of specific G2WV models. Only after the modularization of G2WV architectures by private firms did the Chinese G2WV industry begin a process of vertical disaggregation that stimulated the development of a base of geographically distributed, independent component suppliers and the emergence of multiple assembler firms serving local, regional, and national markets.

By contrast, the E2WV market, which began on the basis of a *de facto* open-system, modular architecture incorporating many industry standard components, soon gave rise to a decentralized modular industry architecture with over 1300 E2WV assemblers and hundreds of motor, battery, and controller component suppliers selling to assemblers throughout China (Weinert et al., 2008). Competition among component suppliers to sell their industry standard components to the growing numbers of E2WV assemblers encouraged investments in developing better and lower-cost components, thereby accelerating technological progress and E2WV market growth. Component suppliers who developed the most attractive components were also able to achieve significant scale economies that further lowered the costs of both components and final products, thereby further stimulating the growth of the E2WV market in China and the development of export markets.

3. LESSONS FOR TECHNOLOGY AND ECONOMIC DEVELOPMENT POLICY

We now draw on our analyses of the influences of modular product architectures in the formation and evolution of the G2WV and E2WV markets in China to propose some important implications for technology and economic development policy. We suggest some important ways in which encouraging and supporting the use of open-system modular product architectures may be an effective instrument of technology and economic development policy for accelerating technological progress, for helping domestic firms to build long-term customer relationships and thereby achieve greater success in export markets, and for promoting more innovative and geographically distributed industrial development.

3.1 Modularity in Accelerating Technological Progress

Some early research into modularity investigated historical cases in which modular product architectures were used in a mature stage of a product's technological and market development. On the basis of such studies, and in particular the observed prevalence of standardized interfaces in the modular product architectures studied, some researchers conjectured that use of modular architectures was only possible in technologically mature products (e.g., Baldwin and Clark, 2000).

Other researchers, however, have suggested that the observed use of modular architectures in such studies was less a consequence of technological maturity and more the result of some firms realizing that use of modular product architectures can confer significant strategic advantages, including enabling rapid technological upgrading of products, increased product variety, shortened development times, and reduced development and product costs (Garud and Kumaraswamy, 1993; Sanchez and Mahoney, 1996; Sanchez, 1995, 1999; Sanchez and Collins, 2001). As Sanchez (2000a, 2002c, 2008) has observed, product markets with the highest rates of sustained technology development and innovation are commonly those based on modular product architectures.

Moreover, today innovative new product concepts are increasingly "born modular" as firms adopt open-system modular architectures at the inception of a new product market as the basis for distributed, autonomous technology development (at the component level) that can significantly accelerate the rate of overall technology development in a new industry (Sanchez, 2008).

The formation of the E2WV market in China was based on a *de facto* open-system modular E2WV architecture resulting from the widespread adoption of "off-the-shelf," industry standard components joined together through simple, standard interfaces – interfaces that readily allowed the substitution of improved component variations into the architecture. The ease with which improved components could be introduced into the E2WV architecture invited the rapid and widespread development of more efficient motors, longer-lived batteries with greater power densities, and more accurate and efficient microprocessor-based controllers. These component-level improvements enabled the rapid introduction of higher-performing products into the market, often at lower costs than prior-generation, lower-performing products.

We therefore suggest that new product markets founded on open-system, modular product architectures may be able to achieve higher rates of technological progress – leading to more rapid improvements in product performance and higher rates of market growth – than product markets founded on closed-system, non-modular product architectures, *ceteris paribus*.

3.2 Modularity in Building Long-Term Customer Relationships

Research into the possible influences of modular product architectures on firms' marketing strategies has suggested that modular product architectures may be used as platforms for building and maintaining customer relationships (Sudharshan and Sanchez, 1998; Sanchez, 1999, 2008). For example, firms using modular architectures may involve individual customers in "mass customizing" a product configured to meet their individual preferences. Firms may also offer component upgrades for previously sold products to help customers upgrade the performance of their products as technologically improved components become available. Although both modular and non-modular durable goods that need service and repairs over a long period of time present opportunities for long-term engagements with customers, the possibilities for mass customization and ongoing upgrading made possible by modular products offer firms significant new opportunities for building closer and longer-term customer relationships. Moreover, these opportunities are likely to increase substantially when use of open-system modular product architectures encourages component producers to develop many component variations for mass customization and improved components for upgrading products.

We therefore suggest that when firms can use open-system modular product architectures to offer their customers more product variations and to upgrade previously sold products (as Luyuan did in the E2WV market in China), some firms may use their modular product architectures as platforms for developing close, long-term customer relationships. We further suggest that those firms are more likely to develop significant customer-oriented capabilities they can use in competing effectively against both domestic competitors and more experienced multinational companies in their home market.

We also suggest that such firms will be able to enter more export markets successfully, and will be more successful in the markets they do enter, than firms that do not have access to open-system modular product architectures, *ceteris paribus*.

3.3 Modularity in Developing Export Markets

The ability to quickly and inexpensively configure new product variations by introducing new component variations into modular architectures may reduce the time and cost required to develop new product variations suitable for use conditions encountered in other countries. To the extent that export markets require product adaptations that can be met by mixing and matching different component variations in a modular product architecture, firms using modular product architectures may more easily enter export markets by configuring modular product variations that can meet the demands and conditions of targeted export markets.

We therefore suggest that firms using products based on open-system modular architectures will be more likely to enter export markets – and will do so sooner, more widely, and more successfully – than firms using closed-system, non-modular product architectures, *ceteris paribus*.

3.4 Modularity in Promoting Industrial Development

As our comparison of the different industry architectures spawned by G2WV and E2WV markets in China suggests, the development of new product markets is likely to lead to quite different kinds of industry structures in new industries based on closed-system non-modular architectures *versus* open-system modular product architectures.

In many respects, use of closed-system non-modular product architectures as the basis for industrial development is consistent with traditional industrial policies favoring the development of "national champions." The development of the post-war Japanese and Korean economies, for example, was significantly driven by the growth and success in both domestic and export markets of favored, vertically integrated *keiretsu* firms in Japan and *chaebol* firms in Korea, each of which typically produced their own sets of closed-system non-modular products (Johnson, 1982; Amsden, 1992).

Open-system modular product architectures, on the other hand, may be used to pursue alternative industrial development policies encouraging development of more geographically-distributed "network" types of industry structures (Steinfeld, 2004; Zhu and Shi, 2010). Our analysis of the G2WV and E2WV markets in China suggests that several advantages may be realized when industrial and economic development policies favor use of open-system modular architectures as the basis for the formation of new industries. These development advantages include the creation of industry structures that are relatively open to new entry by small to medium-sized firms, that provide a high level of (embedded) technical coordination among the entrants to a new industry, that sustain high levels of innovation and accelerated rates of technological progress, and that enable the wide geographic distribution of economic development.

We therefore suggest that industrial development policies favoring the use of open-system modular architectures will result in industries that are more effective in encouraging entrepreneurial activity, more innovative, and more geographically distributed than industrial development policies favoring closed-system non-modular product architectures controlled by a few vertically integrated firms.

4. IMPLICATIONS FOR COMPETENCE-BASED STRATEGIC MANAGEMENT

The preceding discussion has suggested a number of ways in which the use of open-system modular architectures is likely to change the dynamics and trajectories of technology and economic development in an industry. As suggested in the previous section, open-system modular architectures may be used as a policy instrument to promote industrial development, especially in the context of developing economies. Alternatively, especially in developed economies, open-system modular architectures are increasingly emerging voluntarily among firms interested in establishing open-system modular architectures as the basis for an industry's products.

Sanchez (2008) analyzed the greatly differing influences of closed-system non-modular product architectures *versus* open-system modular architectures on the competitive and cooperative dynamics driving the evolution of product markets. In his study, Sanchez suggests how the objectives and priorities of strategic managers will differ in each stage of the Product Life Cycle (Leavitt, 1965), depending on whether a firm is using closed-system non-modular architectures or open-system modular architectures. We now draw on that study and on the analyses presented in this paper to suggest in summary form some fundamental implications of the use of open-system modular architectures in an industry for the theory and practice of competence-based strategic management at each stage of the Product Life Cycle (Sanchez and Heene, 2000; Sanchez and Collins, 2001).

4.1 Embryonic Stage

A firm that adopts a closed-system non-modular architecture for its products is essentially committing to a "go-it-alone" strategy in which it will have to create its own proprietary product architecture, components, and interfaces in competing against other industry players. Entering a new product market with such an architecture usually entails high risk, since a firm must develop its own product (and sometimes its own technologies) and then hope that its product will be among those whose functions, features, and performance levels will be successful in competing against competitors' product offers.

By contrast, adopting an open-system modular architecture that uses industry-standard components and interfaces is a commitment to undertaking a cooperative strategy in which a firm may collaborate with many other firms in defining a new product architecture and in defining industry standard components and interfaces.[9] In contrast to management priorities in a go-it-alone strategy, a key strategic management priority in open-system modular markets is therefore establishing and maintaining collaborative product and market development relationships with other firms. Because collaborations require mutually beneficial exchanges of knowledge and effort, strategic managers must also be able to identify and nurture the organizational capabilities that will make their firm a desirable partner for industry collaborations. Rather than making "bet the company" commitments to specific optimized product designs, strategic managers must be able to lead their firms in exploring new markets through "real-time market research" (Sanchez and Sudharshan, 1993) in which a wide range of new and upgraded product variations may be configured from industry standard components.

4.2 Rapid Growth Stage

For a firm using a proprietary, closed-system non-modular architecture, the strategic priority in the Rapid Growth Stage of the Product Life Cycle is deciding whether to (i) commit to major investments in ramping up production and marketing based on its own product architecture, (ii) to switch to another firm's product architecture that may be more promising (if licenses to use the architecture are available), or (iii) to exit the new industry. To the extent that the process architecture a firm must invest in to support its proprietary product architecture is specific to its proprietary product architecture, a firm may experience a form of "lock in" to its process architecture and related assets that limits its ability to change or modify its product architecture in the future. Thus, strategic management at the beginning of a Rapid Growth Stage is often a "bet the company" exercise in which committing to the wrong product architecture can be very consequential.

By contrast, in open-system modular markets, much of the investment in production and service assets needed to develop a new product market is distributed among many players, both component specialists and assemblers, thereby reducing the need for any individual firm to invest in specific-use assets in order to be a player in the new industry (Sanchez, 2003). Instead, the priority for strategic managers is strengthening the relationships between the firm and suppliers of components used to differentiate its products and to keep its product costs competitive through use of industry standard components.

4.3 Shake-Out Stage

For firms using closed-system non-modular architectures, the strategic priority in the Shake-Out Stage is increasing market share to increase the scale of production and distribution and thereby to obtain production and distribution cost advantages. Firms will then seek to use price-based competition to drive other firms out of the market and/or to acquire firms operating at smaller scale.

For firms using open-system modular architectures, a strategic priority in the Shake-Out Stage will be developing the design, branding, distribution, and marketing capabilities needed to differentiate their products effectively from those of competitors in the market place. In addition to achieving large-scale operations in the production and distribution of proprietary products, product differentiation and marketing will be critical firm capabilities. Firms may seek growth through mergers and acquisitions with other firms that can bring market domination through product differentiation advantages, as well as through increased scale.

4.4 Maturity Stage

Contrary to some interpretations of the Product Life Cycle, Sanchez (2008) characterizes the Maturity Stage as a period of active market segmentation as consumers' experience with a product concept leads them to imagine versions of products that could provide even greater utility in their specific use context. The challenge for all firms in this stage is to understand how consumer preferences are evolving and segmenting, and then to provide product variations that have been well differentiated to suit the emerging preferences of different groups of consumers (i.e., new market segments).

For firms using closed-system non-modular designs, the strategic decisions to be made during the Maturity Stage are essentially a replaying at smaller scale of the decisions the firm had to make during the Embryonic Stage: Which proprietary product architectures or variations of architectures shall the firm commit to in order to serve any emerging market segments it has identified? Once again, to the extent that the firm is using proprietary product and process architectures that have little value outside the firm, the firm's strategic managers will face high-risk decisions to invest in serving specific new market segments.

For firms using open-system modular architectures, the emergence of significant market segments with specific kinds of preferences offers opportunities for firms to review their architectures for opportunities to create new architectures with greater scope for product variety and upgrading, as well evaluating possibilities for cost savings through introducing integrated component designs that combine functions that have become standard in products for a given market segment. Creating new open-system modular architectures incorporating some modular components as well as newly integrated component designs may enable both performance improvements and cost reductions that enhance the appeal of a firm's products in specific market segments.

4.5 Decline or Renewal

The Maturity Stage of a product market may last for decades, but eventually most product markets will enter a stage of Renewal or Decline. In Renewal, a product market goes through a period of renewed growth that may be caused by change in underlying market demand or by technological changes in the product that offer greater performance for price and thereby stimulate more demand. In Decline, a product market may be regulated out of existence (products found to be hazardous may simply be banned), or substitute products may come along that simply attract a product market's current customers to it.

For firms using closed-system non-modular architectures, opportunities for Renewal are likely to depend on the firm's own ability to develop technological improvements that significantly change the performance-to-price ratio offered by its products or that address major regulatory issues successfully. Again, the "go-it-alone" strategy inherent in a proprietary product and process architecture increases the cost and potential risk of any strategic decision to seek renewal of demand for a firm's products. By contrast, in open-system modular markets, the higher rate of technology improvement and greater cost reductions typically realized when many firms are working on those goals often results in extended periods of Renewal as prices fall and performance rises across the industry.

When a product market enters a final period of Decline, any closed-system, non-modular proprietary architectures whose integrated component designs have been fine-tuned to serve the preferences of specific market segments are unlikely to have much "real options value" (Myers, 1979; Myers and Majd, 1990; Sanchez, 1995) to be reconfigured and redeployed to other markets. In such cases, firms may tend to stay in a declining market for extended periods of time as they try to recoup as much as they can of the sunk costs invested in their proprietary architectures before finally exiting a market. Firms that use open-system modular architectures, by contrast, are likely to exit declining markets more quickly – both because they are likely to have lower sunk costs in their open-system modular architectures, and because their open-system modular architectures may have greater flexibility to be adapted to other markets' requirements.

5. IMPLICATIONS FOR FURTHER RESEARCH

Although architecture concepts in general and modularity concepts in particular are now firmly established in management theories of competitive strategy and innovation, there has been relatively little penetration of these concepts into technology and economic development policy discussions. We now draw on the open-system modular architecture perspective and derived propositions advanced in this paper to suggest possibilities for further research of considerable relevance to technology and economic development policy. Although a comprehensive statement of the theoretical and practical implications of modular architectures for industrial and economic development policy is beyond the intended scope of this paper, we next suggest some implications of our architectural perspective and propositions for further research into three widely-used policy instruments for stimulating technology and economic development: industrial clusters, bottom-of-the-pyramid innovation, and frugal engineering.

5.1 Industrial Clusters

The creation of industrial clusters has long been a staple of economic development policy (Porter, 2000; Romanelli and Khessin, 2005). Industrial clusters have demonstrated that some development advantages may be conferred by the concentration of economic activity in a given region. These potential advantages include achieving greater scale (and thus lower costs) in production of intermediate and final products, economies in transporting intermediate goods from suppliers to nearby final producers, improved communication and coordination among co-located firms, greater potential for "cross fertilization" of knowledge among proximate firms, and the creation of pools of skilled workers to fuel growth of both established firms and start-ups.

However, industrial clusters may also have some important drawbacks, especially in the context of developing economies. These potential drawbacks include inducing dislocations of workers who must relocate to the region of a cluster, substantial costs of undertaking large-scale infrastructure development projects, potential urban crowding and accompanying increases in costs of living and wages, and exposure to swings in global economic cycles that may disproportionately affect the economy of a region that is largely based on a single industry.

New industries based on open-system modular product architectures may offer new possibilities for achieving many of the potential advantages of industrial clusters without incurring the drawbacks noted above. Perhaps most fundamentally, as noted previously, the standardized interfaces in an open-system modular architecture provide an *information structure* that enables embedded coordination of geographically distributed component development, production, and assembly activities (Sanchez and Mahoney, 1996; Sanchez, 2002b, 2008). Thus, use of open-system modular architectures in industries may provide a new means to achieve essential technical coordination across geographically dispersed development, production, and assembly activities.

When geographically distributed new product development and production activities can be coordinated through open-system modular architectures, dislocations of workers and new infrastructure development costs may be avoided or reduced. Economic development may become more evenly distributed geographically throughout an economy.[10] At the same time, use of standard components in open-system modular architectures may enable achievement of significant economies of scale and learning in component production.[11] If the interfaces between modular components are made simple so as to require only basic tools and skills for assembly of products, assembly operations may also be geographically dispersed, possibly reducing transport costs and time between dispersed component producers and assemblers. Open-system modular architectures may also help to stimulate development of a more skilled and mobile workforce when workers learn skills that can be applied widely in the assembly, maintenance, and repair of open-system modular product architectures in use in an economy (Sanchez, 2002b).

In effect, use of open-system modular architectures to achieve technical coordination of new development, production, and assembly activities may offer many of the economic development advantages of industrial clusters – and some new advantages specific to open-system modular architectures – without the economic costs and risks that may result from geographic concentration of development activities. Further research is needed to clarify the extent to which "modular production networks" like those used in China's G2WV and E2WV markets today may offer an attractive alternative to industrial clusters as a means of promoting economic development (Sanchez and Mahoney, 1996; Sturgeon, 2002).

5.2 "Bottom-of-the-Pyramid" Innovation

Traditional models of economic development and international trade portray innovations as originating in technologically advanced countries and migrating to less developed economies only on a limited basis or only after they have started to become obsolete in developed economies (Vernon, 1966, 1972). More recently, as more developing economies join the global rising tide of technological and production capabilities, research has noted an increasing incidence of "bottom-of-the-pyramid" innovation (Brown and Hegel, 2005; Anderson and Markides, 2007; Prahalad, 2010). In this phenomenon, indigenous firms in developing countries may create new products appropriate to the use requirements and economic means of consumers in their own and similar countries – and increasingly may be able to do so without the involvement of firms from developed economies. Bottom-of-the-pyramid innovation processes typically create much simpler, more robust, and more affordable designs than those developed by firms in developed economies, whose product strategies often emphasize adding new features and frequent changes of style that may increase product costs.

As incomes in developing economies rise and the demand for basic, affordable versions of many kinds of consumer products increases, there appear to be some significant advantages in adopting product designs based on simple, robust, modular architectures that incorporate common "industry standard" components, including those that may have originally been developed for use in other industries. The rapid development of the E2WV market in China is a case in point. The use of a simple, robust modular architecture originally based on standard components "borrowed" from other industries helped Chinese firms to quickly configure affordable E2WV variations adapted to various use conditions and consumer preferences in China and in export markets. These modular innovations helped Chinese companies achieve a commanding lead in the global market for E2WVs (Weinert et al., 2008). Use of already available, proven industry standard components results in lower product and maintenance costs (because of economies realized through large-scale production of reliable industry standard components) and reduced requirements for development of new skills to service and repair new kinds of products.

The configurability, technological evolvability, and affordability of simple open-system modular architectures appear to make such architectures an attractive design methodology for bottom-of-the-pyramid innovation processes. Further research is needed to identify the extent to which bottom-of-the-pyramid innovators are aware of and could take advantage of the potential benefits of open-system modular product architectures, as well as to clarify the potential role of government policy in disseminating and stimulating use of open-system modular architectures in bottom-of-the-pyramid innovation processes.

5.3 Frugal Engineering

Engineering design as taught in many universities and widely practiced in firms in developed economies is essentially an optimization exercise in which designers seek (i) to maximize product performance subject to a cost constraint, or (ii) to minimize cost subject to a performance constraint (Sanchez, 2000b, Suh, 1998). Broadly speaking, design and development strategies of firms serving developed economies typically seek to gain competitive advantage in their markets by creating higher performing products. Engineering design in such firms is therefore usually focused on maximizing performance (including adding more features) subject to specified cost constraints. On the other hand, the needs of developing economies are likely to be better served by engineering design focused on achieving very low costs while meeting basic to moderate performance requirements.

Recent research has noted the importance of developing *frugal engineering* capabilities focused on serving the needs of developing economies for simple, affordable product designs (Seghal, Dehoff, and Pannee, 2010). Although modular architectures may also be used to create very complex designs, our analysis of Chinese E2WVs suggests that simple forms of open-system modular architectures may be especially appropriate for achieving the objectives of frugal engineering. Further research into design methodologies for defining "simplest possible" sets of components and "simple and robust" modular interfaces between components could help to clarify the potential contributions of open-system modular architectures to frugal engineering.

6. CONCLUSIONS

In this paper we have developed and applied an architectural perspective in analyzing the development trajectories of G2WV and E2WV markets in China. These analyses have suggested some potential contributions of open-system modular product architectures to technology and economic development. These analyses, in turn, have suggested ways in which open-system modular architectures may become an important technology policy instrument for stimulating new market formation and associated industrial development in developing economies. We have suggested that simple open-system modular product architectures can contribute significantly to new product market formation and industrial development by providing platforms for accelerating technological development, improving firm capabilities in building long-term customer relationships, facilitating development of export markets, and enabling a wider geographic distribution of economic development within countries.

We have also suggested how the primary strategic management concerns of firms differ in the five stages of the Product Life Cycle, depending on whether a firm is using closed-system non-modular architectures or open-system modular architectures.

We then suggested three directions for further research into the potential contributions of modular architectures as a policy instrument for stimulating economic development. We have suggested that further research may help to clarify the potential for modular production networks to offer a viable and attractive alternative to industrial clusters as a policy instrument for stimulating economic development. We have also called for research into the potential contributions of modular architectures to bottom-of-the-pyramid innovation processes and frugal engineering methodologies for serving the needs of consumers in developing economies.

It is our hope that this discussion will suggest new avenues for both public-sector and private-sector research into the potential uses of open-system modular architectures in firm strategies and as policy instruments for stimulating new patterns and dynamics of industrial development that can bring new kinds of benefits to developing economies.

NOTES

1. A product architecture defines (i) the way in which a product design is decomposed into *functional components* and (ii) the ways in which the *interfaces* between the functional components are specified to enable the components to work together as a system (Sanchez and Mahoney, 1996).
2. A product architecture becomes *modular* when the interfaces between functional components in a product design are specified to allow the introduction of a range of component variations into the architecture without having to make changes in the designs of other components in the system, thereby enabling the fast and low-cost configuration of product variations and the ready introduction of technologically improved components (Sanchez and Mahoney, 1996; Sanchez, 1999).
3. A modular product architecture becomes an *open system* when firms that want to use the modular architecture to create products have both the competences and/or the legal right to create or use the modular component designs and interface specifications used in the modular product architecture (Sanchez, 2008).
4. Our description of the evolution of the Chinese G2WV industry draws extensively on research by Ge and Fujimoto (2004) and Steinfeld (2004). Our architectural perspective on the factors affecting the evolution of the Chinese G2WV industry leads us to some interpretations of the evolutionary dynamics in China's G2WV markets that differ in some respects from the interpretations of these authors, but that are nevertheless compatible with these authors' findings.
5. Our description of the evolution of the Chinese E2WV industry draws largely on research into that industry by Weinert, Ma, and Cherry (2007); Cherry (2007); Weinert, Ogden, Sperling, and Burke (2008); Yu, Hang, and Ma (2010); and Ruan, Hang, Wang, and Ma (2012). Once again, we note that our architectural perspective leads to some interpretations of the evolution of the Chinese E2WV market that differ in some respects from the interpretations of these authors, but that are essentially consistent with their findings.
6. For a more detailed discussion of the influences of regulations at the national, provincial, and city government levels on E2WV market evolution, see Ruan et al. (2012).

7. For example, in 1996 Shanghai prohibited the sale and registration of all two-stroke, gas-powered motorcycles. This ban encouraged the rapid entry of Shanghai Cranes and other local companies into the E2WV industry (Ruan et al., 2012).

8. A *proprietary closed-system* product architecture is one whose component technologies, designs, and/or interfaces are the intellectual property of a given firm and are therefore unavailable for use by other firms. A *non-modular* product architecture is one in which the interfaces between components do not allow the introduction of component variations into the architecture unless significant redesigns of other components are undertaken. A *tightly-integrated* product architecture is one that has been optimized to meet specific cost or performance goals and therefore cannot be readily adapted technically to other purposes by simply changing the components used in the product architecture (Sanchez, 2008).

9. Sanchez (2008) suggests that in industries using open-system modular architectures, the traditional Embryonic Stage may be preceded by a "Precompetitive Cooperation and Collaboration Stage" in which firms work together to define and develop the technological basis for the industry's new product and process architectures.

10. For example, by 2007 E2WV production in China was distributed among the six major production centers of (in order of importance): Zhejiang, Tianjian, Jiangsu, Shanghai, Shandong, and Sichaun, with more than 600 assembler and component supplier firms located in the two largest centers (Ruan et al., 2012).

11. For example, in the 10 years between 1998 and 2008, manufacturing costs for E2WVs fell to nearly 20% of the original price of the first E2WVs sold in China – in large part due to growing economies of scale and economies of learning realized by firms in producing standard components for the E2WV modular architecture (Ruan et al., 2012).

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