DESIGN OF INDUSTRIAL AND SUPRA-FIRM ARCHITECTURES

GROWTH AND SUSTAINABILITY

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Abstract: The scope of organization design has expanded steadily from work-flow issues and job specifications to firm-level considerations and now to supra-firm industrial structures, where such issues as modularity and clustering loom large. Economic analysis has made little headway in analyzing how increasing returns may be generated through supra-firm structures such as networks and clusters, nor in the question of how their industrial architecture (modular vs. integral, open vs. closed) affects economic performance. The focus here is on the supra-firm industrial architectures that have arisen, either spontaneously through the evolution of capitalism or through purposeful design, involving both state and private actors. Striking cases such as the Chinese automotive industry, which started with the production of conventional automobiles and motorcycles and now encompasses both two-wheeled and four-wheeled electric vehicles, provide testimony to the power of some industrial configurations to outperform others. My analyses and arguments are placed in the global context of the urgent need to find ways to accelerate the uptake of green technologies (such as electric vehicles) in order to reduce emissions of greenhouse gases and at the same time promote the industrialization of countries still at lower levels of income and wealth.

Keywords: Industry architecture; organization design; modularity; industrial clusters; integrality; Chinese automotive industry; electric vehicles; electric two-wheeled vehicles

Use of electric two-wheeled vehicles is rising rapidly in China, making them the world's most significant form of electric-powered transport. The success of electric two-wheelers (E2W) is expected to have a big impact in driving down the cost of batteries and creating a ready market for four-wheeled vehicles, which is now getting under way in serious fashion in China. The growth in two-wheelers is phenomenal, even by the extraordinary standards of growth in China, rising from around 2 million units in 2002 to 14 million just four years later, with production and sales reaching 30 million vehicles by 2010. This is market expansion that calls for explanation beyond that of low costs.

There are several factors behind this market surge, among which the banning of conventional motorcycles in several municipal areas in China (on account of their noise and pollution) is significant. But the most important driving factor is the *modular industry structure* that has developed, allowing hundreds of new entrants to flock to the industry and assemble e-bicycles from modular components and standardized interfaces. These components, which constitute a few core platforms from which the e-bikes are created, are themselves adaptations of platforms developed by foreign firms. The Chinese E2W industry is a demonstration of the power of industry architecture, in this case a multi-level, quasi-open, modular structure where new firms can enter the industry relatively easily and produce new models at low cost, thereby accelerating the diffusion of new, green transport solutions (Weinert, Ogden, & Burke, 2008). The result is that China, which now has the world's highest carbon emissions from its intensive growth in fossil fuel usage, could become the world's cleanest transport sector (heavily involving private electric vehicles and public fast train systems), leapfrogging the rest of the world to this status through the aid of modular industry

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architecture. Environmentally speaking, this is good for China and for the world.

Time was when "organization design" referred to the design of the entities that populate the international business system – the firms and institutions making up the modern global economy. Organizational analysis emerged at the same time as the discipline of management appeared, coincident with the rise of large-scale production and marketing firms that transformed first the U.S. economy and then the European and Japanese economies, and has since spread worldwide (Fligstein, 1985; Franko, 1976). The concept and literature of organizational design emerged in the 1970s, with the realization that there were different approaches to capturing managerial and organizational efficiencies, even in what looked like standard-issue mass production firms. As "lean production," "mass customization," and "total quality management" came of age, along with notions of sociotechnical foundations of organization, so the prospects for organizational design broadened and brightened. Then the links with the wider economy were emphasized, as "industrial marketing and purchasing" and "supply chain management" emerged, so that the emphasis of organization design shifted from the firm itself to the organization within its network of inter-firm linkages.

Organization design still refers largely to possibilities inherent in the design and redesign of single firms or organizations. But there is now the inescapable added dimension of the organizational setting – or what could be termed, at a higher level of recursion, the issue of *supra-firm design*. It is this level that I address in this article.

CONCEPT OF SUPRA-FIRM DESIGN

The impetus for this development lies partly in the fact that some supra-firm designs clearly work better than others. Take the case of innovation networks, which could be manifested, for example, as R&D consortia. Here the issue of supra-firm design concerns the links between the collaborating firms, in terms of their R&D activities (where they might collaborate while remaining sturdy competitors in terms of products), and the design of these inter-firm linkages or routines. In Taiwan, for example, there was a rapid evolution of supra-organizational design of the country's R&D consortia that constituted an important institutional aspect of the government's "catch-up" strategy (Mathews, 2002a, 2003). Taiwan's consortia evolved from informal networks with minimal commitment to well-defined networks with substantial financial and technological commitment, from consortia with vague goals to organizational arrangements with precise goals. Improvements in the design of these supra-firm structures could be termed "economic learning" in contrast to organizational learning. The Taiwan R&D consortia provide an excellent example of design at the supra-firm level, where the emphasis is on collective improvement or learning. As such, it is central to national economic and industrial success.

Another case is provided by supply chain networks, where some companies have been able to generate enormous advantages by their ability to design a particular configuration of capabilities and activities along a supply chain and choosing where to insert themselves in such a configuration. Fine (2000, 2005) employs the term "supply chain design" to capture such strategic choices, where firms can draw advantages by localizing specialized capabilities in designated suppliers while emphasizing their own capabilities in branding and design. Here the processes of intermediation and disintermediation can follow each other sequentially.[1]

The impetus for supra-firm design as an analytic category in its own right derives also from an even more compelling development, namely that the current architecture of capitalist industry is non-sustainable (see Stern (2007) for a summary of the scientific evidence). It is leading to an over-reliance on fossil fuels, resulting in excessive combustion and emissions of greenhouse gases and to an over-reliance on a linear economic model where we take resources at one end from something called "nature" and dump wastes at the other end, again in "nature" – and never make the connection that these processes might be linked at a higher level of recursion. The burning of fossil fuels is leading to global warming or, more simply, to

1 Fine contrasts modular with closed product architectures and their linked supply chain organizational architectures. Voordijk, Meijboom, and De Haan (2006) provide an interesting test of the proposition that modular supply chains enhance the effect of modular product architectures, in the case of the construction industry, Mathews (1996) treats the same issues utilizing the terminology "holonic."

the fact that we are "cooking" the planet (Krugman, 2010).[2] The degradation and throwaway of resources cannot be allowed to continue if we want civilization to survive.

Concern over these issues started at the margins, in what was called the "environmental movement," but it has moved to the mainstream, and now with the rise of China and India, to the very center of concern. The environmental repercussions of conventional organization design (burning the fuels and wasting the resources) could be tolerated while they were practiced by a minority of the earth's inhabitants, but now that the Chinese and Indians have started to demand their share of industrial riches and have moved decisively to do so, then it seems that the design of fossil-fuelled industrial structures was not so effective after all. It cannot scale to a population of seven billion. Herein lays the extremely "inconvenient" truth facing industrial civilization (Gore, 2007).

Attention to supra-firm design – design at the industry level and higher – in such a way that diffusion of new low-carbon technologies might be accelerated is now emerging as a critical and indeed existential issue. Concern with the world of business that lies outside the firm has conventionally been the domain of economics – whether in its "micro" version at the level of individual actors or its "macro" version at the level of aggregates such as national income, taxes, and interest rates. But economics utilizes an outmoded framework of analysis that is mechanistic and equilibrium-based at the expense of consideration of the evolutionary dynamics and strategic interactions of firms within the real economy (Mathews, 2006a,b; 2010). The framework of conventional economics, with its linear thinking and refusal to take the ecological setting of industrial activity seriously (marginalizing it as externalities), is now an obstacle to redesigning the industries that have created the problem. Moreover, industrial economics in its conventional form is concerned with firms and markets and the price-guided competition they generate. But today the most interesting processes occur in the economic space *between* firms and markets – in networks, clusters, platforms, circular economy loops, and other supra-firm structures that are studied in strategic management but not (yet) in mainstream economics.

Moving forward, a new paradigm is called for, and one that suggests itself is the paradigm that has guided life through its millions of years of evolving more resilient and adaptable forms. This paradigm is the imitation of life and its processes, or *biomimesis*. Scholars such as Reap, Baumeister, and Bras (2005) outline an approach to the design of the industrial system as a whole, along biomimetic lines, in what they call "holistic biomimesis" – an approach that moves beyond the design of individual products and processes to consider the systemic and ecosystemic levels that are normally left out of industrial analysis and practice. They identify seven characteristics of ecosystems, drawing on the work of Benyus (1997), as formulating "conditions conducive to life." These conditions have the property that they have been tested by several billion years of evolutionary development – in other words, they are resilient.

In this article, I consider aspects of industry-level redesign of organizational architectures – modular-open architectures, industrial clusters, and eco-connections between firms – and demonstrate that each carries an overtone of biomimesis. In this way, industry design could help drive the transformation of industries that is needed if newly aspiring industrial powers like China and India are to accomplish their goals – most importantly, without degrading the planet.

REDESIGN OF INDUSTRIES AND ACCELERATION OF THE SHIFT TO GREEN TECHNOLOGIES

Industrial capitalism has revealed itself to be the most powerful transformative agent found in the world today. Its appearance in Britain in the second half of the 17th century, powered by access to fossil fuels, unleashed astonishing gains in productivity associated with rises in income, so that it was widely emulated. Polanyi (1944, 1957, 2001) aptly called this *The Great Transformation*, in the sense that nothing would be the same again. Capitalism was

2 See Paul Krugman, Who cooked the planet?, *New York Times*, July 25, 2010; available at: http://www.nytimes.com/2010/07/26/opinion/26krugman.html

indeed an amazing invention of humankind. Its appearance in cities led to demands for independence and liberties that today we take for granted in the West and which are now spreading worldwide. It ushered in the Industrial Revolution, which applied fossil fuels to production, along with new mechanical inventions, thus starting the world on a trajectory of industrialization and modernization that is bringing more and more of the world's people into its orbit.

The process of industrialization lifted close to one billion people in Western Europe, North America, and Japan out of the "Malthusian trap" that pinned income to population, and set them on a trajectory of rising per capita wealth. This created a "Great Divergence" between the West and "the Rest," accounting for the extreme disparities in wealth, income, and power that have characterized the modern world. In the 20th century, while serious efforts were made to industrialize in many parts of the world, it was only in East Asia that catch-up, or convergence, was achieved. Now in the 21st century these efforts have spread to China and India, and a "Great Convergence" is under way, reversing the trajectories of the past 200 years (Pomeranz, 2000; Wolf, 2011).[3]

However, if up to six billion people are to be raised to middle-income status by 2050, as envisaged by economists such as Spence (2011), then the model of industrialization has to scale sixfold. The industrial system fashioned over the past two centuries is now being stretched to accommodate the rise of new industrial powers such as China, India, and Brazil, and more of the emerging market countries after them. While the impact of the industrial system on its ecological setting – the environment – could be more or less ignored in the early phase of industrial expansion, now that it is filling the earth this is no longer a feasible option. The Western model cannot scale to accommodate the aspirations of China, India, and all the other peoples waiting in line for their turn to enjoy the fruits of industrialization. The urban congestion, pollution, waste generation, demands on fossil fuels, and the resource wars that would have to be fought to extend and defend oil supply lines are the consequences of extending the business-as-usual pathway and the reasons why the Western model cannot scale.

Rather than take the usual policy-oriented approach to these issues, I propose to examine the problem from the fresh vantage point of design – from the perspective of industrial and organizational architectures. Industries have grown within the setting of the capitalist mass production system with few constraints. Corporations are protected by limited liability, and on that basis they feel free to take resources as they wish, which in effect means plundering the earth's natural capital both as a source and a sink. This is one level of concern, which has to be addressed by the redesign of industries along "circular economy" lines where outputs from one process are fed as inputs into another process, in emulation of biological cycles (Mathews & Tan, 2011).

Another level of concern is raised by the need to identify the green technologies that can counter the tendencies to excessive resource throughput and carbon emissions, and to accelerate their uptake, in China and other countries where such technologies are most needed. This level of concern can be addressed through the redesign of industries along open-modular or quasi-open-modular lines, as opposed to the traditional closed-integral organizational architectures that dominated in the early years of industrial capitalism. There is now abundant evidence that diffusion of technologies is accelerated by open-modular industry architectures, as evidenced by the rapid uptake of new industries such as personal computers, video players, and cell phones by Taiwan, Korea, and now China, based on the modularization of these sectors. The same phenomenon is evident in new energy vehicles in China, including four-wheeled and two-wheeled electric vehicles, which promise to have an enormous impact in reducing that country's carbon emissions as well as urban pollution.

Wider concerns with social and economic inequalities have become a major destabilizing influence as industrial capitalism has globalized and brought new populations within sight of a middle-class income, provided their countries can master a new green development model that is not as resource-intensive as the earlier Western model that will not scale to accommodate a world of eight or nine billion aspirants. The architecture of industries based

3 See Martin Wolf, In the grip of a Great Convergence, Financial Times,January 4, 2011; available at: http://www.ft.com/cms/s/0/072c87e6-1841-11e0-88c9-00144feab49a.html#axzz1yx8OrRrZ

on isolated firms working to an anonymous market, along the model utilized in industrial economics, is giving way in these emerging countries to a more systematically pursued industrial clustering architecture, pioneered in China by Special Economic Zones (SEZ) and now diffusing to India and beyond. Within these SEZs, cities and towns are able to promote industrial clusters, on the model of the industrial districts pioneered in Europe and the United States in the 19th century, enabling firms to generate increasing returns as they multiply their interconnections and enable specialized firms to emerge as markets expand. There is again a clear biomimetic aspect to this, in the sense of the clustering of nerve cells to create ganglia in which resides intelligence – or, in the business analogue, "value-added."

MODULARITY AND ITS IMPACT ON TECHNOLOGY DIFFUSION

Modular systems have been with us for a long time. Design platforms emerged first in the military (which has driven the pace of technological change in multiple sectors) and then spread to the automotive sector, where modular platforms enabled companies to offer wide consumer choice based on a few core modules for the chassis, transmission, and engine. Modular design came to particular notice with the rise of consumer products like stereo sound systems and the personal computer with IBM-compatibility.[4] Firms like Dell were able to build a new business model out of the design of systems involving modularity, while in the semiconductor sector new IC foundry firms like TSMC, UMC, and Chartered, from Taiwan and Singapore, pioneered the strategy of *silicon modularity*, where chips are designed through the use and re-use of in-silicon system components, each one of which is IP-protected. Modularity and platforms emerged together, with each driving the other in a process now described in the business literature as co-evolution. In the canonical description given by Baldwin and Clark (2000), design rules for modularity encompass three categories: (1) *modular architecture*, which specifies what the modules do and how they fit together; (2) *interfaces*, which specify the rules of modular interconnection; and (3) *standards*, which test and prove a module's ability to fit within the overall system and enable one module to be compared with another within the system context. It is through the judicious understanding of the workings of these design rules that firms and systems designers are able to capture advantages from modularity not available in non-networked, integrated products. Gawer and Cusumano (2002, 2008) took these arguments further in their description of the emergence of platforms, both in their closed and open variants, as creating a new source of competitive advantage shared by many firms. Platforms, such as the Wintel platform in PCs, or the Apple platform that links the iPad, iPhone, and iPod, are in fact ubiquitous. The more an industry moves toward modularity, the greater is the likelihood that one firm will be able to initiate a new level of integration to bring components together into a platform. And as platforms emerge, the more pressure they place on the industry to modularize.

Simon (1962) provided the first modern discussion of these systems, and at the same time offered a plausible evolutionary account of their emergence in his famous fable of the two watchmakers. One watchmaker, Tempus, builds watches out of their constituent elements, while the other, Hora, builds his watches out of modular components containing ten elements each. Simon then discusses the relative difficulties the watchmakers face, particularly when encountering interruptions that disrupt the flow of work. Hora pulls ahead of Tempus rapidly because interruptions force Tempus to start each watch over again. Simon draws intriguing analogies from this case for the field of biological evolution, arguing that complex organisms arise precisely because of their modular, or cellular, structure.

4 See Langlois and Robertson (1995) for a general description of modular systems and application to the stereo and computer industries, while Chesbrough and Kusunoki (2001), Brusoni and Prencipe (2001), Langlois (2002, 2003), Schilling (2000), Chesbrough (2005), Baldwin and Woodard (2007, 2009), Campagnolo and Camuffo (2010), and Chesbrough and Prencipe (2008) provide overviews of the strategic and management issues involved. These concepts have been captured under a variety of names: Mathews (1996) termed them cases of "holonic" organizational architectures, while Miles, Snow, Mathews, Miles, and Coleman (1997) termed them "cellular" systems. All of these terms are getting at the same point, namely the building of systems out of re-usable and substitutable components that are themselves also systems, with their own systemic properties. Garud and Kumaraswamy (1995) go further and offer the beginnings of a theory as to why such systems offer advantages, introducing the concept of "economies of substitution."

The issue of industry design is brought out once we recognize that different organizational architectures are possible, and these lead to different business and economic outcomes. We are talking about inter-firm organizational architectures – the relations that firms have with each other, mediated through the character of the products they are engaged in producing. The key distinction to be made is between modular and integral architectures on the one hand, and open and closed architectures on the other. While there is no necessity for a modular product to be produced by modular industry architecture, there is obviously an "elective affinity" between the two approaches.[5] Japanese scholar Takahiro Fujimoto (1999, 2006) has done a service in clarifying the main issues. In the modular architecture, when talking of a product, there is a one-to-one correspondence between functional and structural elements. In the personal computer, for example, the function of processing is handled by the CPU, the function of input by the keyboard, the function of display by a flat panel display, and so on. In the integral architecture, there is many-to-many correspondence. In the automotive vehicle, for example, fuel efficiency is linked to the engine but also to the design of the body and suspension, while the suspension affects not just fuel efficiency but also the quality of the ride and the handling of the vehicle. On the other hand, there are open and closed systems or architectures. The Apple Macintosh worked with a closed system while the IBM PC moved toward an open system, based on the fact that IBM believed it was to its advantage to open the system up to components suppliers working to IBM standards. Fujimoto (1999, 2006) provides a threefold classification of product architectures arrayed in a 2x2 matrix, as shown in Figure 1.

	Integral	**Modular**
Closed	small cars motorcycle game software compact consumer electronics	mainframe computer machine tools LEGO (building-block toy)
Open		personal computer (PC) bicycle PC software internet

Fig. 1. Three basic types of product architecture: closed-integral, closed-modular, open-modular.
Source: Fujimoto (1999, 2006)

The three basic types of product architecture have a strong bearing on the organizational architecture of the industries producing such products. Industries generally start by producing products in closed-integral form (with a large company supplying the integral product, serviced by a supply chain in which there may be extensive vertical integration). Think of computers produced by IBM or PCs produced by Apple in the 1980s. Such architecture may evolve into a closed-modular form, as the lead firm seeks to economize in its own production through simplifying its product architecture, with a view to outsourcing the production of some of the lower-cost modular components. Think of IBM producing its System 360 computer along these lines, and then its IBM PC in the early 1980s. Such an architectural innovation, to use the terminology of Henderson and Clark (1990), frequently evolves into an open-modular

5 See, for example, Henderson and Clark (1990) and Sanchez and Mahoney (1996). The argument that organizational modularity corresponds to product modularity is known as the "mirroring hypothesis." Fine (2000) provides a strong argument as to why firms might want to align their product, process, and supply chain architectures. Sanchez and Mahoney (1996: 64) formulate the mirroring hypothesis as follows: "The [loosely coupled] standardized component interfaces in a modular product architecture provide a form of embedded coordination that greatly reduces the need for overt exercise of managerial authority to achieve coordination of development processes, thereby making possible the concurrent and autonomous development of components by loosely coupled organization structures." The converse argument is that increasing returns to modularity in design can be captured through inter-organizational integration, known as the "complementarity hypothesis." For an analysis in the setting of the Italian air-conditioning industry, see Cabigiosu and Camuffo (2011).

structure, where the lead firm no longer controls the process and has to strive for leadership along with complementary lead firms that supply key components to standardized interfaces. It is within the open-modular phase that platform leadership emerges as a key competitive construct (Gawer, 2009; Gawer & Cusumano, 2002, 2008) and strategies of imitation become significant (Ethiraj, Levinthal, & Roy, 2008). Likewise, the focus on modularity also brings attention back to the cases where integral architectures prove to be superior (Fixson & Park, 2008). The contrast between closed-integral and open-modular architectures is illustrated in Figure 2. In the open-modular case, there is a clear subdivision into sub-assemblies and sub-processes, with minimal interdependence between them. This is the key to their capacity to accelerate diffusion of new technologies.

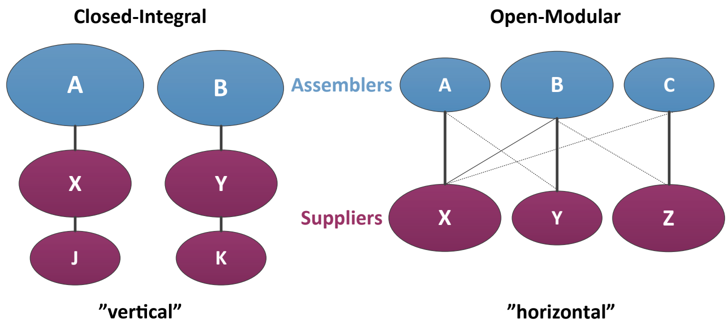

Fig. 2. Closed-integral vs. open-modular industry architectures.
Source: Weinert et al. (2008), Figure 3, adapted from Ge and Fujimoto (2004)

The impact of open-modular industry architecture on competitive dynamics has been the subject of recent analysis. It is generally agreed that the open-modular architecture favors rapid entry by newcomers, particularly from developing countries as the industry moves to low-cost regions. At the same time, the advanced suppliers of core components, such as Intel for the CPU in a PC, or Sanyo Electric for the optical pickup in a DVD player, can make the core component even more integral and hence enhance its competitive advantages. Meanwhile, the scope for upgrading on the part of the developing country firms is considered by some to be limited (e.g., Steinfeld, 2004), but China's ability to leapfrog its way into the global automotive industry, and toward advanced electric vehicles, would seem to cast doubt on this line of argument.[6]

High-technology companies that introduce technologically sophisticated integral products like computers, automobiles, or DVD players have a mixed response to modularization. On the one hand, modularization and standardized interfaces undoubtedly expand the market through cost reduction. But such processes also empower key component suppliers who can wrest control of the platform – as was done by Intel for the hardware and by Microsoft for the software of the IBM PC. And such processes can proceed to the point where latecomer assembly firms from newly industrializing countries can enter the industry, either as modular suppliers (e.g., of motherboards) or as assemblers, as in the case of Taiwanese firms producing the PC at very low cost from standardized modules and creating market opportunities for new firms such as Acer (Mathews & Snow, 1998). When new firms force their way into the industry through utilization of standardized modules, even while incumbent firms continue to compete on the basis of closed-modular or even closed-integral architectures, Fujimoto talks of an intermediate stage called "quasi-open-modular" architecture (Ge & Fujimoto, 2004). We shall discuss such a development in the Chinese two-wheeled electric vehicles case below.

Modularization can enhance opportunities for outsourcing, in the pursuit of increasing returns from specialization. But outsourcing can also work against modularization, as when it is used solely for cost-cutting without regard to modular architecture. Outsourcing simply to

6 Insightful discussion of such issues is currently provided by scholars at the Manufacturing Management Research Center at the University of Tokyo, founded and directed by Takahiro Fujimoto. These scholars see modularity as both a means for latecomer countries to enter new industries, and in response, for integrality to be a viable strategy for Japanese, European, and American leaders, all within a dynamic setting. See Tatsumoto, Ogawa, and Fujimoto (2009) for a discussion of the impact of modularization on the computer industry and the platform strategy pursued by Intel.

capture static cost gains (e.g., by going to lower-wage assembly sites for test and assembly) can actually obstruct the pursuit of modularity (Starr, 2010). When outsourcing is combined with modularity (in a modular production network or MPN, based on manufacturing process outsourcing or MPO), the original equipment manufacturer (OEM) can shift the costs and capital investment risks onto the supply chain, where each supplier is responsible for one of the modules, and each module is allocated to at least one supplier. The suppliers, for their part, benefit from the demand created by the OEM; the supply chain provides such companies with an opportunity to specialize without having to try to cover the range of activities associated with a product.[7] When co-locating firms engage in complementary activities, clusters begin to make their presence felt.

INDUSTRIAL CLUSTERS

Firms in many industries cohere together in various kinds of networks, clusters, and development blocks. There are networks built on networks; indeed, the entire economy can be viewed as interconnected networks of networks (Castells, 2011). Networks grow and become clusters. Such interconnected firm aggregates are well recognized and indeed are becoming the object of increasing attention, due to the outstanding success of such high-tech clusters as Silicon Valley in the USA (Saxenian, 1996) and other science-driven clusters such as Research Triangle Park in North Carolina; the Hsinchu district in Taiwan where all the country's major IT and semiconductor activities are co-located (Mathews & Cho, 2000); and the Jutland region of Denmark (Andersen, 2011). It is widely recognized that the success of regions like Silicon Valley owes much to highly specialized complementarities arising between neighboring firms, something that cannot be accounted for in simple capital and labor terms in a production function.

Clusters and development blocks are the setting in which entrepreneurial and innovative activities can best be understood, as well as the more traditional activities of production of goods and services. This in itself is a powerful departure from earlier traditions that focused on firms acting as individual entities. In the years that have elapsed since Becattini (1990) first pointed out the salience of the Marshallian "industrial district" model to Italy's post-war economic development, and sparked research identifying, counting, and classifying the various kinds of firm concentrations found in Italy and throughout Europe (including famous districts such as the Prato textile district, the Sassuolo ceramic tiles district, and the Carpi knitwear district), the world of scholarship has come to a relatively advanced level of understanding as to what makes industrial clusters work. From the initial enthusiasm linked to the view of districts as being able to generate "flexible specialization" (Piore & Sabel, 1984) through their operations, as alternatives to large integrated firms, there has developed a nuanced understanding of how industrial districts survive and adapt to changing conditions, and how they combine small-firm features with large-firm guidance. The judgment of Harrison (1992) that such districts are not just "new wine in old bottles" remains valid.[8] At the end of

7 Miles and Snow (2007: 459–460) reviewed the field of supply chain management from an organizational perspective, considering the design of multi-firm network organizations, where they conclude that "Supply chain research, which originally focused narrowly on the efficient movement of goods among firms within an industry, now incorporates a substantial amount of organization theory." Further: "The emergence of the multi-firm network organization opened a whole new arena for strategic choice, and many firms became much stronger competitors by linking with specialist providers in an integrated supply chain." On modular production networks, see Sturgeon (2002, 2004).

8 The Florentine scholar Giacomo Becattini is generally regarded as the father figure of Italian industrial district studies, from his 1990 article and earlier work in Italian. His research has been complemented by other notable Italian scholars such as Sebastiano Brusco (1982), who studied the Emilian model, and many others. Harrison (1992) provides an excellent overview that summarizes findings for the 20th century, while Bresnahan, Gambardella, and Saxenian (2001) summarize their studies of emergent "Silicon Valleys" in places such as Ireland, Israel, and Taiwan, identifying five "deep regularities" associated with all such developments: (1) access to highly skilled technical labor; (2) access to managerial labor; (3) institutional forms favoring new firm formation and firm building; (4) connections to markets; and (5) a combination of cooperation with competition. Dahmén (1989) utilized the idea of development blocks, or groups of complementary firms spanning different industries, in his study of the industrialization of Sweden.

the 1990s, Porter (1998, 2000) added his voice to those analyzing and advocating clusters.[9] But the industrial district phenomenon is now seen to encompass not just the advanced world but even more significantly the developing world such as in India, Pakistan, and countries in East Asia.[10] Most notably, the phenomenon can be regarded as the driving factor in China's resurgence as an industrial power, particularly in the setting of the Special Economic Zones (SEZs).

Research on the industrial cluster phenomenon in advanced countries in Europe, North America, and Japan, while developing in varied and important ways such as through investigating the evolution of Marshallian industrial districts and markets-as-networks, has demonstrably failed to diffuse into the disciplines of economics and strategic management, or even organization theory and entrepreneurship studies. Clusters and other supra-firm phenomena such as platforms (Gawer, 2009) and open-modular systems remain on the margins of scholarship despite their real-world significance. It is the rise of industrial clusters in China, and no doubt in India as well, spurred by the creation of Special Economic Zones, which is going to change the situation drastically. My contention is that the success of these emerging industrial giants of the 21st century cannot be understood without reference to the industrial cluster phenomenon that is embedded within them, housed within such institutional settings as SEZs. All the intellectual machinery developed to understand the rise of clusters in the advanced world is now going to have to be applied in order to make sense of this same phenomenon in the developing world, but in a new context defined by globalization and the emergence of global production networks and global value chains (Yeung, 2009). Insights generated through the study of emergent industrial clusters in China and India, and their interaction with global firms and the global value chains that they have been creating, will in turn have repercussions on our understanding as to how such clusters work in the developed world and how they can be created in the developing world – and so the process of mutual scholarly influence will proceed, in a "circular and cumulative causation" pattern that emulates the processes identified for economies more generally.[11]

Industrial clusters are thus widely recognized today to be powerful engines of wealth generation. They may be depicted as microcosms of the economy at large, full of interesting and challenging detail that is passed over by mainstream economics and even by much of strategic management research. How firms enlarge their strategic options through forging connections with one another and in enhancing and deepening the inter-firm knowledge flows that result remains the focus of attention. Firms that form part of a network have access to many more resources than would be available to them individually, and such firms can contract with third parties to accomplish many more activities than would otherwise be under their control, thus expanding the market that is available for their products or services. As the market expands, so the scope for specialization and intermediation grows (exactly as foretold by Adam Smith and earlier by Italian political-economic theorists such as Antonio Serra and Giovanni Botero).[12] This generates a series of positive feedback loops that can be described

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9 Michael Porter opened the way to his cluster studies with the identification of a role for "related and supporting industries" in his 1990 framework for analyzing national competitive advantage. But he focused on clusters themselves, particularly at the state level in the U.S. Porter's work has raised public and policy awareness of the significance of industrial clusters.

10 Wei (2009) provides an informative account of the emergence of the Wenzhou model of a footwear cluster in China, while Zhou and Xin (2003) illuminate the ZGC cluster in Beijing. Barbieri, Tommaso, and Huang (2010), Fan and Scott (2003), and Zhu (2009) are examples from a burgeoning literature on Chinese industrial clusters. On the development of Special Economic Zones as an outgrowth of the earlier experiences with Export Processing Zones and Free Trade Zones, first in China and then in India since 2001, see Aggarwal, Hoppe, and Walkinhorst (2009) and Aggarwal (2012). Yusuf, Nabeshima, and Yamashita (2008) provide a useful overview of the extent to which clusters have been "designed" to promote industry development in Asia.

11 The phrase "circular and cumulative causation" was first used by the Swedish development economist Gunnar Myrdal in his 1960 book Asian Drama, and was taken up by the Cambridge economist Nicholas Kaldor as a way of encapsulating real development processes in real economies. See Toner (2000) for a comprehensive discussion.

12 Adam Smith's *Wealth of Nations* (1776) needs no introduction. Italian scholars who anticipated his ideas and elaborated on the role of urban clusters more forcefully must certainly include Antonio Serra (*Breve Trattato delle cause che possono far abbondare li regni d'oro e d'argento dove non sono minere*, 1613: Brief treatise on the causes that can increase wealth in terms of gold and silver where there are no mines) and before him Giovanni Botero (*Delle cause della grandezza delle citta*, 1590: Causes of the greatness of cities). On the significance of their ideas for a long-lost tradition of political economy, but highly relevant to the study of clusters, see Reinert (1999).

as a chain reaction, resulting in the cumulative and circular causation of enhanced production capacities in clusters. Such feedback loops give a spring or bounce to a network that surpasses whatever is available to a firm on its own. The network can reconfigure itself as needed, with inter-firm relations being activated, de-activated, and re-activated as circumstances warrant, leading to a shuffling and reshuffling of the resources embodied in the collective organization. This gives rise to the evolutionary dynamics that generate knowledge spillovers, common resource pools, and interconnections that can then be translated into synergies and systemic returns – better known in economics as increasing returns (Arthur, 1989).

The reshuffling of resources within the cluster may be characterized as an analogue to the reshuffling of the genome of a biological species through Darwinian experimentation and selection, and the shifting activity networks in the cluster that are made possible by this resource reshuffling as the phenotypical expression of these changes in genotype. With due regard to the limitations of biological analogies in the business world, it strikes me that this is a fruitful way to view industrial clusters and to gain insight into the sources of their advantages over the single, isolated firm.[13] Resource dynamics between firms as characterized in this way recalls the principle of biomimesis as the paradigm needed to guide the design of industrial architecture and symbiosis.

CLUSTERING AND MODULARITY

It is not just developing countries like China that utilize modular architectures and clusters to accelerate their market entry and growth. The same strategy can be seen in the case of new market entrants in the developed world – such as Micro Compact Car (MCC), the Mercedes-Swatch joint venture producing the Smart car in Europe. Here it was a case of Swatch bringing its design expertise and the German automaker its production capabilities together in a joint venture created in 1994, and with a new plant built in Hambach, Germany. A cluster of suppliers (known as "system partners") surrounded the MCC plant. Each built one of the modules, such as cockpit, rear axle, or doors, and these modules were then assembled into the final product by the same companies placing their employees in the MCC plant, utilizing a degree of product and process modularization unknown in the automotive industry at the time (Takeishi & Fujimoto, 2001). This was as clear a case of organizational design at the industry level that one is likely to find.

There is no mystery to this process. A comparable process unfolded in Europe in the 1980s with the rise of IKEA as a modular furniture producer and retailer. Prior to IKEA's architectural innovation, the furniture industry was completely closed and integral, with firms supplying their own branded products in vertically integrated fashion. But because the founder of IKEA, Ingvar Kamprad, found himself locked out of the industry by incumbents, he followed a different course and had producers supply modular products exclusively to his own outlet, thus bypassing the closed-integral architecture of the industry. By 2001, IKEA was a global force in furniture retailing and production, with sales of 10.4 billion Euro (US$9.6 billion), a total of 143 company-owned stores in 22 countries, plus another 20 franchised stores and a value constellation of over 2,000 suppliers providing intermediate modular products that IKEA put together in its famous self-assembly kits. How large is the "suction power" of this vast network in the final consumer market? In 2001, there were over 255 million visitors to IKEA stores, and they utilized 110 million catalogs in making purchases. The huge purchasing power assembled by IKEA is what drives the strategizing by the supplier firms, to enroll themselves in the IKEA network. What drives the strategizing by IKEA itself is the platform leadership that enables it to extend its range beyond what any company on its own could expect to accomplish. (I am using the phrase platform leadership in the sense given by Gawer & Cusumano (2002), namely strategizing around the attraction and capture of as many complementary firms as needed to create an industry platform out of a given technology or organizational form.)

This process, where quasi-open modularity is used to accelerate entry into a global business,

13 Nelson and Winter (1982) characterize intra-firm routines as the economic-level analogue of the replicators of a biological system. But the problem is that this notion of routines as replicators does not admit of an easy identification of genotype and phenotype, which is fundamental to the biological conception, whereas to take the argument to the cluster level admits of such an analogue in terms of cluster resources and activities.

driven by the power of a large and growing market to reward specialization, can be found in one industry after another. The process has been studied and documented in the computer, semiconductor, and IT industries; the electronic consumer products industry; the household appliance sector; the furniture sector; and the automotive sector including the two-wheeled vehicles sector, particularly the electric versions of these products. In each case, the process involves a closed-integral product architecture being challenged by a quasi-open modular structure (an architectural innovation, to adopt the terminology of Henderson & Clark (1990)), whereby some firms make the strategic innovation of entering the market as "integrators," based on having a supply of key components from existing industry participants. The new entrants provide an expanded market for the components producers, who are compelled to supply this fresh demand or see new competitors do so. But as they supply the demand, they contribute to the expansion of the market and its further modularization (Jacobides, 2005; Langlois, 2002; Sanchez & Mahoney, 1996). Market expansion creates opportunities for specialized intermediary suppliers to be created, thus driving the process of modularization further. This is exactly the process of market growth and specialization ("division of labor"), reinforcing each other through mutual interaction in a process of circular and cumulative causation, that is expounded by the Smith-Young-Kaldor framework to be discussed below. Modularization is the engine of industry expansion.

The extra twist that I wish to add to this description is how latecomer firms in China and elsewhere in the developing world can make use of these trends toward open modularity (or quasi-open modularity) to facilitate their entry into the industry and accelerate the market expansion through rapid cost reduction. While comparative advantages in terms of low labor costs play an important role, at least in the early stages, it is the competitive advantages created by the approach to industry design, involving clusters and modular networks, that really drive the industries forward. As Wang (2008: 516) puts it, "Architectural innovation is contributing to the Chinese 'catching up' process in terms of industrial development." He argues that local firms opt for a low-cost, low-price strategy as a means of gaining entry, and depending on first-tier and second-tier components suppliers is an optimal way to achieve this. Firms pursue an imitation strategy, engaging in mass production of copied components which come to be standardized at the industry level.

To what extent can we describe this development of a particular kind of industrial organizational architecture (IOA) as the product of design? As an inter-organizational phenomenon, such a quasi-open-modular IOA is clearly beyond the control of any single organization. Yet once it is recognized as a means of promoting latecomer entry into an industry, and accelerating the uptake of green technology, then such industry architecture can be "designed" through national innovation policies that are created to favor such an outcome. And this is precisely what we observe in the case of the Chinese automotive industry and in particular its rapid adoption of electric vehicles, where we see clearly the power of modularity as a principle of design of industrial organizational architecture.

CHINA'S AUTOMOTIVE INDUSTRY AND ELECTRIC VEHICLES

As a latecomer to the automotive industry, China was concerned to promote technology transfer as fast as possible. This it did through a variety of well-known and recognized strategies – foreign direct investment by major Japanese, European, and American producers, with incentives being offered in terms of accessing the Chinese market, in return for commitments to transfer technology and build local supply chains. Modularity undoubtedly played an important role, just as modularity and standardization played an important role in the development of the U.S. automotive industry.[14] The result has been a rapid build-up in China's share of global production, as shown in Figure 3.

14 On the role of modularity and vertical integration vs. "deintegration" in the U.S. automotive industry, see Argyres and Bigelow (2010).

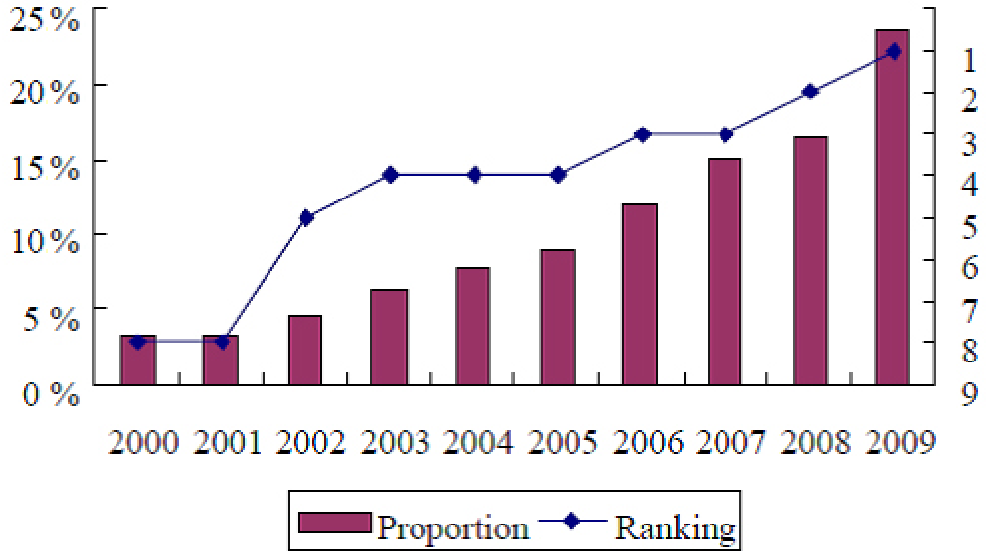

Fig. 3. Global production share and ranking of Chinese automotive firms, 2000–2009.
Source: Wang and Xiao (2011), Figure 1.

The production data on their own tell a fascinating story – that China has invaded the global automotive industry in the space of a decade – and is now set to leapfrog the entire industry to dominate in electric vehicles, both two-wheeled and four-wheeled varieties. Key to this success is modularity. By 2010, China had arrived as the world's largest producer, accounting for 23 percent of global production, up from less than two percent at the beginning of the decade. This extraordinary accomplishment calls for sustained analysis. Many of the Chinese firms had developed beyond mere joint venture partners and were competitive in producing new models of their own. Contributors to this rapid arrival were cost and modularity; in particular, Chinese firms adopted and adapted the platforms that leading foreign producers had created, and which they were induced to transfer to their Chinese partners. There are dozens of these platforms, and Chinese firms have adopted and adapted them all, using them to launch their rapid rise as a global producer. Combined with this adoption of modularity as a driver of international competitive advantage, the Chinese have also promoted clustering in certain key industrial zones such as Shanghai and Guangdong. The two phenomena, modularization and clustering, both reflecting inter-firm industrial dynamics, reinforce each other in synergistic fashion.

While the state-owned firms such as SAIC, FAW, and others have largely remained dependent on their foreign (joint venture) partners (at least in the domain of internal combustion engines), the newer "independent" companies such as Chery, Geely, Great Wall, and BYD have moved ahead rapidly, introducing their own new models with their own brands, by taking advantage of the growing modularity of the industry and the availability of standardized components for the chosen platforms. Some commentators see mere copying in these companies' rise – for example, the Chery QQ being based on the Daewoo Matiz, or the Great Wall Peri based on the Fiat Panda, or the Chinese "jeeps" (high-mobility multi-purpose wheeled vehicles HMMPWVs for military use) built by Dongfeng Motor being based on components from AM General (formerly American Motors). But the key to their success is their capacity to drive the process of modularization from quasi-open modular to fully open modular, in a process that resembles what Tatsumoto et al. (2009) call the modular "separation effect."

Geely's transformation is emblematic of this gap effect. Founded in 1986 as a manufacturer of refrigerators, Geely moved into production of motorcycles in 1994 and then into vehicle production in 1998. At that time its vehicles had to be classified as "vans" to avoid certification issues, but Geely received state approval to manufacture automobiles in 2001. At that time there were upward of 120 producers in China (official and unofficial), and government policy favored the big state-owned corporations like FAW and SAIC that were locked into joint ventures with foreign partners. Geely began by mixing and matching existing components.

Its first independent model was the *Haoqing*, based on the Charade, produced in China by FAW, the result of technology transfer from Toyota's affiliate, Daihatsu. No fewer than 70 percent of the components utilized were interchangeable with the Charade – 60 percent supplied directly from FAW and a further 10 percent based on copied standardized units.[15] The next model, the *Maple*, introduced in 2002, was based on interchangeable parts from two foreign models already produced in China, the Citroen ZX and again the Charade. This represented an "architectural leap" for Geely, which in itself helped to drive the industry to a quasi-open modular architecture. Subsequently, Geely has produced engines that can fit within several extant platforms, while Geely's cars can accommodate engines bought from other manufacturers, all based on standardized interfaces. Complementing the quasi-open modularity of its product, Geely has designed a modular supply chain, outsourcing the majority of components to suppliers with whom it works closely and has long-term relations. In this way, Geely was able to build on its links with suppliers for its motorcycle business, incorporating suppliers who also supply to the big foreign companies such as VW, Toyota, Nissan, and GM. As Wang and Kimble (2010b: 18) state: "Having Geely as the customer helps those suppliers realize economies of scale because of the higher production volume."

The same argument can be made with regard to other successful Chinese independent producers such as Chery Automobile. Chery is a small state-owned company based in Wuhu, 200 km west of Shanghai, founded in 1997, that built its first prototype self-badged car in 1999, and has since expanded rapidly, becoming China's largest vehicle exporter by 2007. The first prototype was based on a chassis licensed from Volkswagen. The key to its rapid insertion in the international industry is its preparedness to tap into the international supply base created by an increasingly modular automotive industry. This style of development has been aptly called "compressed development" and modularity, particularly its open version, would seem to drive it fastest.[16]

The proportion of Chinese cars featuring quasi-open modular product architecture has now reached probably 30 percent of total production in China – a proportion that is growing and which is having a much greater influence than the closed-integral architecture traditionally employed by the automotive majors. Component suppliers themselves are helping to drive this process, merely by responding to the growing demand. For example, Mitsubishi now sells engines to at least 21 carmakers in China, while the engine management system module produced by Delphi (formerly linked to GM) can be utilized with any Mitsubishi engine. In the same way, makers of DRAMs in the semiconductor industry were driven to make their modular parts standardized and consistent with Intel's CPU chipsets, thereby accelerating the rate of market expansion (Tatsumoto et al., 2009).

Electric Vehicles

Most recently, China has formulated strategies designed to leapfrog the world's automotive giants and become the leading producer of electric vehicles (EVs). Originally, China focused its New Energy Vehicles on alternative fuels, particularly diesel, and then on electric hybrids that run on both their gasoline engine and their electric motors, powered by their on-board batteries and recharging systems (such as regenerative braking). But with the 12th Five-Year Plan (covering the years 2011–2015), China is clearly focused on pure electric vehicles (i.e., on battery-powered EVs) and plug-in hybrid electric vehicles (PHEVs), which are seen as the next wave for zero-emission vehicles. They are also much simpler in design and construction, since there is either no internal combustion engine or it is operated in ancillary mode only. Chinese automotive firms are leaping (indeed leapfrogging) to adopt these new forms of

15 This section is based on Wang (2008) and Wang and Kimble (2010a, 2010b, 2011).

16 On compressed development, and for further discussion of the Chery case, see Whittaker, Zhu, Sturgeon, Tsai, and Okita (2010). Sturgeon and Van Biesenbroeck (2010: 13) describe Chery as follows: "Chery Automobile, a small, state-controlled company based in Wuhu, China, has been able to develop and market a line of Chery brand vehicles within a remarkably short time by tapping the expertise of first-tier global suppliers with operations both in China and in the West. Chery obtains a full range of inputs from the global supply base, from parts to production equipment to design and system integration expertise." They then qualify the point, stating that "Since learning is relatively shallow, the sustainability of Chery's approach will need to be proven over the long term." Their analysis does not move to the point where Chery and other Chinese vehicle producers have leapfrogged to the new paradigm of the electric vehicle.

EVs and PHEVs, building their own models from platforms adapted from those already developed in the automotive industry generally. The progress registered so far is impressive.

The FAW group (formerly First Auto Works), now one of China's largest automotive producers (more than 1 million units annually) has already built two new EV production facilities, in Changchun and Dalian city. The newly launched vehicles, including the Besturn 50 plug-in hybrid electric vehicle (PHEV) and Besturn 70 electric vehicle (EV), were independently developed by FAW Group. The company asserts that it will invest a total of 10 billion yuan to develop eight kinds of new energy vehicle product platforms, leading to 13 new energy passenger cars and three commercial vehicles during the Twelfth Five-Year Plan period.[17] FAW now appears to be thoroughly emancipated from its earlier dependence on Mazda.

The private producer Geely has introduced its electric vehicle, the Nanoq (meaning "polar bear" in Greenland), to be supplied in Europe through a joint venture with the Danish company Lynx. The joint venture will utilize batteries supplied by Lynx GT (described below). Other producers such as Changan, Chery, and SAIC are introducing their own models, based on modular platforms that speed up the process of development. They are rapidly building modular supply chains in the form of clusters to support their EV production activities. The key module in the case of EVs is the battery itself, and here there has been super-charged activity by Chinese firms linking themselves to European and American firms. The support provided by the government-owned banks channeling investment into the sector means that the electric vehicle industry is growing fast, with modular organizational architecture driving the development.

The exception to this trend is BYD, one of the spectacular success stories of the EV sector. A major lithium-ion battery producer for the cellular phone and consumer goods sector, founded in 1995, it elected to enter the automotive industry by acquiring an existing automotive producer. By 2008, BYD was able to produce its first hybrid electric (or dual mode) vehicle, the F3DM, which started shipping in early 2010, then a four-wheel drive S6DM (with dual motors controlling the front wheels and a 75kW electric motor the back wheels). In 2010, it launched a pure EV, the e6, a five-seater sedan with a 75kW electric motor and the BYD proprietary Fe lithium-ion battery. BYD is working with taxi operators and municipal governments in China to grow the market for its EVs, and in 2010 formed a joint venture with the German firm Daimler to produce EVs for China under the joint venture's own brand. BYD follows a quite different strategy from other Chinese automotive producers in seeking to control its entire value chain through vertical integration. BYD even produces its own charging stations, giving it a unique systemic perspective on the entire EV industry.

China is also paying close attention to the building of the infrastructure needed to support electric vehicles. It shows marked originality in the fact that the Chinese overseas oil company CNOOC (China National Offshore Oil Corporation) is investing in the acquisition of domestic petrol stations with a view to turning them into EV charging centers – in competition with the domestic oil firms Sinopec and CNPC. Likewise, the electric power grid companies, State Grid (SGCC) and China Southern Power Grid (CSG), are looking to build charging networks and integrating them into their planned smart grid developments. Again, JVs are being utilized to accelerate technology diffusion. In 2011, Better Place, the American-Israeli company producing EV's battery charging and switching stations, announced an agreement with CSG envisaging the opening of battery switch stations by the end of the year.

Under China's 12th Five-Year Plan, electric vehicles (called "New Energy Vehicles") are designated as one of the seven strategic industries to be promoted through a range of tax breaks, subsidies, and technology promotion. Under the Plan, an interim target of 1 million vehicles is set for 2015, with a longer-term goal of reaching 100 million vehicles (cars and commercial vehicles) by 2020. One can agree with Wang and Kimble (2011) that this is indeed a national leapfrogging strategy.[18]

17 See "FAW's New Energy Vehicle Launches August 23, 2011" at: http://www.faw.com/faw_online/news/dzjy_jybj/jyzb/20110829133200038.htm

18 Sources on China's EV initiatives include Weinert et al. (2008) and Wang and Kimble (2010a,b; 2011) as well as Wang and Xiao (2011).

Two-Wheeled Electric Vehicles

The most spectacular effect of modularity is seen in the case of two-wheeled EVs, or electric "motor" bicycles (E2Ws). Here the impact of modularity is linked to market promotion via local municipalities banning the use of internal combustion engine motorcycles in cities on account of the noise and fumes they emit. The result has been a marked rise in production and sales of Chinese electric two-wheeled vehicles, which by 2007 had reached a level approaching 15 million units produced per year and far exceeding production of all passenger vehicles (see Figure 4). By 2010, production was estimated to reach 30 million units. Here is an industry that cries out for close study from an organizational perspective.

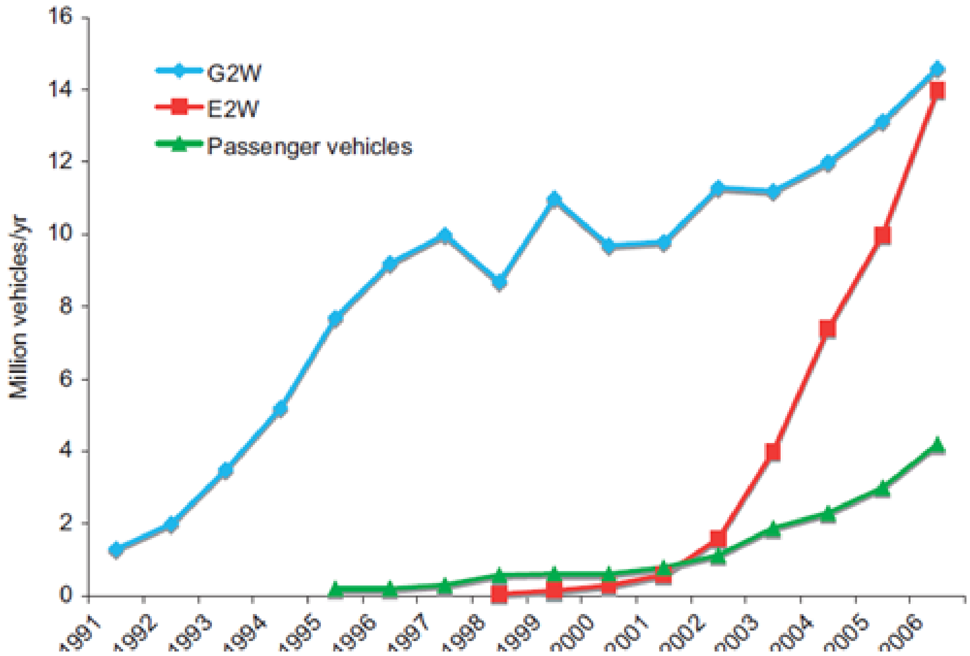

Fig. 4. Growth of electric two-wheeled vehicles in China, 2000–2007.
Source: Weinert et al. (2008).

Just like the bicycle industry before it, the e-bicycle industry is highly modular, with key components like batteries supplied by just a few critical suppliers. In terms of the Fujimoto classification, the E2W industry in China is quasi-open modular (Ge & Fujimoto, 2004). The e-bicycles are assembled from just a few components, which because of high levels of demand have become rapidly standardized. Each final producer can work with multiple component suppliers, while each module producer can sell to multiple assemblers. Batteries come from firms such as Protanium, the lithium-ion battery producer. And again, just as the bicycle industry has demonstrated some cyclicality in its "reverse integration," moving from extreme modularity to closer integration (via the Japanese firm Shimano), so the E2W industry in China is also showing the two trends at work. While the industry becomes more fragmented and modularized, at the same time a leading company, Xinri, is building a distinctive competitive advantage through vertical integration, now covering every step in the E2W value chain except batteries, and emerging as China's largest supplier. Xinri's base is in Wuxi, where a vast modular supply cluster is developing to power the E2W sector.[19]

ROLE OF SUPRA-FIRM STRUCTURES IN INDUSTRY GROWTH AND STABILITY: AN ANALYTIC FRAMEWORK

Let me draw the threads of this discussion together by focusing on the key drivers of the expansion of clusters and modular systems within the wider economy. There is a rich "heterodox" economics tradition that organization and strategy theorists have yet to tap into in explaining the growth and diffusion of the modular and open inter-organizational

19 See the company's website at: http://english.xinri.com/

architectures discussed so far. Let me mention just three: (1) Allyn Young, in his 1928 Address to the British Association for the Advancement of Science, on the theme of specialization (division of labor) and increasing returns; (2) Alfred Marshall, in his notion of firms within clusters generating increasing returns through external economies; and (3) David Ricardo, in his idea that two countries can specialize and improve their economic position by the resultant "gains from trade."

It was Young (1928) who boldly posed the issue of increasing returns as the central question to be addressed in economic analysis of the modern industrial system. In place of seeing the genesis of increasing returns as a marginal issue, to be dealt with alongside externalities as something quaint and uncommon, Young grasped that increasing returns are central to the way that mass-production industries go about building the market for their products. On the strength of the expanded market, they are able to invest in specialized capital equipment, and as the market further expands they are able to make use of specialized value chains of intermediate suppliers, sometimes aggregated together in industrial clusters. Young insisted that it is not factor questions and supply-side issues that need to be addressed in accounting for increasing returns but growth of markets (i.e., growth in demand). This demand-side emphasis is a singular characteristic of Young's framework, an emphasis that mainstream economics has ignored. Young insisted that firms in modern mass-production industries first address the market and take active steps to build the market prior to making definitive investments in production. The other feature of such firms' investment behavior, which again did not escape the notice of Young, is their preparedness to sink large sums into investment in large-scale production systems that would be completely unwarranted by the current state of demand. Such investments are made with an eye on growing the market through cost reduction as fast as possible. Cost reductions are based on prior investments in specialized capital equipment provided by specialist suppliers whose existence is made possible by the breadth of the market as well as in internal efficiencies that are under the firm's direct control. It is the efficiency gains on the part of external suppliers that generate Marshall's "external economies."[20]

To translate into the language of modularity, Young's account makes sense of why modular production systems may outperform closed, integral systems (up to a point) because the appearance of specialized stable intermediaries enables final producers to reap productivity gains (increasing returns) while the productivity improvements of the stable intermediaries (modular suppliers in a value chain) drive expansion of the market. As the market expands, it creates opportunities for even more specialized intermediaries to appear, and as they improve productivity, they enable the market to further expand, and so on – in a process of circular and cumulative causation that is best described as a chain reaction. This is why modular industrial systems will outperform any other industrial architecture, if they are allowed to express themselves and if they are initiated by deliberate, entrepreneurial acts of industrial design and by supportive government policies.

Indeed, there is an opportunity here to adapt Ricardo's 19th-century doctrine of comparative advantage, as formulated between countries.[21] Ricardo's doctrine is that two countries, A and B, will improve their position (income) by trading goods in which they specialize (i.e., where they possess a comparative advantage). Now transpose this argument to the case of two firms in a value chain. Firms A and B will improve their joint productivity by sourcing from each other's specialization. Here surely lies the origin of economists' general category of "increasing returns." The gains from trade are real and can be observed at the firm level.

As firms increase their level of specialization, and play the role of specialized suppliers of intermediate products, they create multiple opportunities to enhance their joint productivity through multiple inter-firm interactions. This is precisely what Marshall (1890) was pointing to in his rather vague formulation of "external economies" – that is, the savings reaped by firms from their interaction with neighboring firms as these neighboring firms improve their productivity through specialization. Thus, the most obvious case of Ricardo's gains from trade would be Marshall's external economies reaped by firms in an industrial cluster through their interactions. In both cases, modularity and clustering, we observe firms benefiting from

20 See Marshall's original exposition in his *Principles of Economics* (1890).

21 See Ricardo's original exposition in his *Principles of Political Economy and Taxation* (1821).

systemic gains arising from inter-firm activities that would not be available to a firm acting on its own. And, as asserted by Young, it is market expansion that triggers the appearance of these specialized suppliers of intermediates, and their appearance then drives further expansion which triggers further specialization, and so on. What this process generates is economic expansion and increasing returns.

Some strategic management and organizational scholars have linked gains from trade with the inter-organizational architecture of value chains.[22] There is clearly scope here to derive gains from trade at the inter-firm level as a strategic consequence of different forms of inter-organizational industry architecture, and to link such phenomena to the wider picture created by Ricardo's comparative advantage, Marshall's external economies, and Young's increasing returns and division of labor. In this way, we can fashion the theoretical framework that explains why firms organize themselves into value chains and allow modularization (through specialized componentry) to appear, and what drives the entire process.[23]

CONCLUSION

In this article, I have sought to demonstrate the power and salience of supra-firm structures in the design of industries, in particular the role played by modularity (and degrees of modular openness) in accounting for the success and failure of industries so created. The emphasis has been on the role played by modularity in accelerating the uptake of new technologies and enhancing opportunities for firms to break into established markets or create new ones. The utility of such a framework is demonstrated by examining the case of China's entry into industries such as automobiles, and into newly emerging sectors such as two-wheeled and four-wheeled electric vehicles. Here conventional explanations of China's successes, which focus on costs and government coordination and macroeconomic manipulation, can account for only part of the success. The less obvious but arguably more important features have to do with the power of modularity and its influence on the speed of diffusion of new product forms and patterns of industrial organization. Clusters, networks, and modularity are the all-important organizational features essential to understanding these recent market upheavals.

The capacity of modular organizational systems to accelerate diffusion of new technologies and facilitate market entry, and the "designability" of such industrial structures, have an immediate and important bearing on the greening of the industrial model being adopted by China and India. The issue of global warming is addressed by a variety of scientific disciplines working within a conventional policy framework. Mitigation of carbon emissions is ritually called for in public statements, but how this is to be achieved without blocking the industrialization efforts of new industrial giants such as China, India, and Brazil has not been satisfactorily resolved. Promotion of renewable energies, through market expansion programs and cost reduction strategies, are widely supported but meet stiff political and economic resistance from fossil fuel lobbies who see their interests threatened.

The promotion of specific kinds of supra-firm organizational architectures, such as clusters and quasi-open-modular structures, provide the missing ingredient, both in development strategies as well as in market-entry strategies by advanced firms. It is the close attention paid to such matters in China that helps explain the country's remarkable rise as a manufacturing power over the course of the past decade and as a source of much of the green technology that is diffusing around the world.

The introduction of new inter-organizational industrial architectures along the lines discussed here – designing open-modular architectures wherever feasible, promoting clustering and inter-firm linkages to turn wastes into inputs – promises to provide a new avenue for bringing industrial capitalism into alignment with its ecological setting and providing industry with a biomimetic paradigm to guide its growth and sustainability. Such

22 Jacobides and Winter (2005), for example, contrast two industries – the U.S. mortgage banking industry (prior to the bursting of the subprime lending bubble) and the Swiss watch industry – in terms of their fluctuating degrees of modularity. In the process they discuss how firms benefit from sourcing components to specialized suppliers, capturing gains from trade. Jacobides and Hitt (2005) provide a similar reference to gains from trade where this is interpreted in terms of firms with different capabilities along a value chain either complementing each other or integrating their operations.

23 Aspects of this issue have been tackled in the theoretical economics literature, notably by Yang and Borland (1991), where they investigate increasing returns to specialization in a dynamic general equilibrium model.

organizational design approaches to climate change mitigation do not appear to have registered as yet with global policy bodies. It is surely time to widen the frame of thinking and to give organizational and strategy scholars an opportunity to make a real contribution to redesigning the capitalist economic processes that give the global industrial system such vibrancy and wealth-generating potential. The susceptibility of particular industries to modular redesign, and their capacity to support rapid diffusion of new technologies, especially low-carbon, clean technologies, is a critical public issue where scholarship and policy development will have to move together in unison.

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