Reinventing Mass Production: China's Specialization in Innovative Manufacturing

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Abstract: Based on more than one hundred firm-level interviews conducted between 2010 and 2012, this paper examines the political economy of China’s emergence as a global manufacturing powerhouse. Our argument is that China’s industrial growth trajectory cannot be fully explained by either factor the cost advantages associated with markets or the policy interventions associated with the developmental state. Instead, we argue that China’s rise stems from the development of unique capabilities in innovative manufacturing. We provide a typology for understanding the phenomenon of innovative manufacturing, and show how it has led to a complex distribution of risks and rewards, as well as multidirectional learning, across a variety of national contexts. Thus, through our analysis of Chinese industrial upgrading, we generate new frameworks for understanding national competitiveness and industrial catch-up in the contemporary global economy.
Introduction

While China has been growing steadily since the late 1970s, its centrality in global manufacturing has come about with remarkable rapidity. As recently as the year 2000, China still accounted for only 5.7 percent of global manufacturing output (by value), about a quarter of the United States’ (or Japan’s) share at the time. By 2011, China had heliected to the top position, achieving an unparalleled 19.8 percent share, just ahead of the United States’ previously world-leading 19.4 percent (UNIDO, IHS Global Insight study).

Many people feel this change is important. Few agree on exactly why. We know that more goods are physically fabricated and assembled in China today than anywhere else in the world. And we know that the goods themselves span an extraordinarily wide range of categories – everything from apparel and consumer electronics to wind turbines and solar panels. Because many of these goods are sold abroad – China in 2010 led the world with US$1.48 trillion in exports – Chinese manufacturing “prowess” can be felt across global markets. But what does leading the world in manufacturing output really mean? Is it really “prowess” that is involved, as opposed to just cheap labor? What sorts of skills, capabilities, and knowledge – if any – does substantial national presence in manufacturing represent? What sorts of advantages, commercial or otherwise, does it confer, and to whom?

While the answers are anything but self-evident, opinions abound, many expressed through polemical assertions about the viability of entire national economies, the legitimacy of industrial policy, and the morality of outsourcing. Adjudicating between the viewpoints becomes difficult, given that they are often premised on wildly
divergent assumptions about the very nature of manufacturing itself, the relationship between manufacturing (physical fabrication and assembly) and other production-related activities (such as new product definition and design), and the relationship between manufacturing and even more sweeping phenomena such as innovation. And for all the debate about the drivers and ramifications of China’s manufacturing rise, we hear precious little about the substance of the activity itself, the actual things going on within the firm.

Many observers begin from the perspective that global manufacturing concentrates in China because of the country’s extremely low factor costs (labor, land, etc.). Regardless of whether those observers feel the cost structure reflects natural market forces or aggressive governmental subsidies, their argument has two underlying premises: first, that manufacturing simply migrates to the lowest cost environment, and second, that the know-how required to actually do manufacturing is either trivial or easily acquired.

Nonetheless, some observers then go on to assert that precisely because of China’s position within manufacturing, the nation is developing proprietary know-how extending beyond manufacturing – ostensibly into everything from design capabilities to outright innovation, the development and commercialization of completely new products, processes, and services (U.S.-China Economic and Security Review Commission 2011). Knowledge, to the extent it is considered at all in this account, flows unidirectionally (into China), and then somehow transforms from the trivial – physical assembly – into the truly sublime, innovation.
Other observers, though, draw the opposite conclusion. They agree that manufacturing has moved to China (and other developing countries) because of cost advantages, but they argue it could do so only because of an information technology revolution that has permitted fabrication and assembly to be separated from much higher value R&D, product definition, design, branding, and marketing. In today’s world of globalized, highly deverticalized supply chains, China-based firms may be bending the metal and bolting together the parts, but those are no longer the production activities associated with true value creation, profitability, and proprietary know-how. Indeed, from this perspective, fabrication and assembly have never been as far removed from innovation as they are now (Kraemer et al. 2011; Steinfeld 2004).

For all their differences, neither account treats manufacturing – the bending of metal, the casting of parts, the assembly of finished products, etc. – as a locus for know-how or meaningful learning. Both see manufacturing as something easy to enter into, whether because of policy-induced or natural factor price advantages. And both see manufacturing as distinct from innovation, albeit with the first arguing that innovation grows from manufacturing, and the second that innovation and manufacturing are wholly disconnected. Neither, however, takes seriously the possibility of innovative manufacturing, the possibility of proprietary know-how and specialization becoming embedded in the fabrication and assembly process itself.

This paper places innovative manufacturing at the core of its argument. We believe that manufacturing, regardless of whatever exogenous forces may be contributing to it, must be studied at the level at which it actually takes place, the firm. Having conducted extensive interview-based research at this level, we find that a particular form
of innovative manufacturing is central to the Chinese growth story. China today is a national system – or more accurately, a collection of regional ecosystems – specialized in rapid scale-up and cost reduction. That is, China-based manufacturers have developed globally unparalleled skills in the simultaneous management of three variables: tempo, production volume, and cost. Nowhere else in the world – across such a wide variety of products – can production be scaled up so quickly, and with such dramatic reductions in unit cost. China, in essence, has become the *scale-up nation.*

Numerous other countries have low factor prices, substantial government inducements, and even large domestic markets. None has been able to expand manufacturing to the degree China has. Moreover, China has been able to expand manufacturing even in industries that are highly automated (thus having almost no low-cost labor component), and industries that appear nowhere on governmental priority lists (and thus are not showered by egregiously conspicuous subsidies). The point is not that basic factors costs or government support are irrelevant. Rather, it is that they are neither necessary nor sufficient to explain what has occurred in China, the development of a unique approach to a particular kind of manufacturing.

Something about the Chinese ecosystem is not only making manufacturing stick, but also drawing in ever more sophisticated kinds of manufacturing from outside. We argue that that “something” is different from just low cost. In terms of pure input prices, China is not necessarily the cheapest place to produce for a number of products. It is, however, the place where production can be ramped up to high volume the most rapidly (which for many producers is critical given the time value of money and the desirability of getting to market quickly). It is furthermore the place where innovative steps are now
consistently being taken to squeeze costs out of high volume operations. In essence, firms in the Chinese ecosystem have developed unique skills for either marching down existing industrial experience curves with extraordinary rapidity, or in many cases, redefining those curves entirely (see Figure 1).

This type of specialization is by no means unidimensional. Indeed, through the course of the paper, we will provide a taxonomy for classifying different variants of knowledge-intensive scale up. Beyond doubt, however, is that China has emerged as the global locus for every one of these variants. Production processes that as recently as a decade ago appeared fully mature and impervious to further cost reductions or technological improvements have in recent years been revolutionized with their migration to China. The traditional distinction between mature and immature industries has largely collapsed. We believe that this complex, multi-dimensional phenomenon constitutes a new form of national competitiveness and industrial catch-up, one that should not simply be filed away under the broad label “process innovation.”

Our research suggests that residing at the heart of China’s competitive specialization is the accumulation of firm-specific know-how, usually by means of extensive, multidirectional inter-firm learning. In essence, this is a phenomenon involving the development of unique capabilities by a wide variety of firms, operating in a wide range of different sectors, and based across a variety of different local ecosystems, all within China. Furthermore, across all these examples can be found an international dimension to the learning, thus underscoring the globalized nature of China’s particular brand of innovative manufacturing.
But whether purely domestic or globalized, this form of specialization – in all its variants – has already exerted far-reaching influence on not just manufacturing, but the full range of production activities worldwide. Undoubtedly, some global incumbents, particularly those unable or unwilling to adapt, have been driven from the market. At the same time, however, Chinese-style scale-up has substantially lowered barriers to entry to other kinds of global innovators, many of whom are today not just outsourcing activities or transferring knowledge to China, but are in fact learning from the Chinese and substantially changing their own behavior as a result.

Scale-Up Across Diverse Industrial Sectors

Before examining Chinese scale-up in detail, we will provide a very general sense of its contours across three decidedly different sectors: wind turbines, solar photovoltaics (PV), and consumer electronics. These sectors vary across several dimensions: degree of governmental support, extent to which they sell into a domestic market, degree to which they rely on low cost labor, and degree of geographic concentration within China. All are highly competitive with tens and often hundreds of entrants. While some state-owned firms can be found in these sectors, the sectors on the whole are dominated by private and/or foreign-invested firms, a characteristic of Chinese manufacturing in general.

Our first example, wind turbine manufacturing, received obvious and extensive central governmental support. In the mid-2000s, Beijing identified wind energy as a national priority, created a massive national market through technology portfolio standards for power generating companies, and pushed knowledge-transfer from overseas firms through localization requirements. As indicated by Figure 2, the domestic market
boomed. Given local content requirements and the physical characteristics of the products themselves – wind turbines are generally too bulky to ship – essentially all of the production represented by that curve took place in China, some by multinationals, some by domestic private firms, and some by domestic state firms. As indicated by Figures 3 and 4, prices plummeted with increased Chinese localization.

In other sectors, comparable or even more dramatic ramp-up and cost reduction occurred in the absence of central governmental support or a meaningful domestic market. A good example here is crystalline silicon (c-Si) solar photovoltaic panel production. China in the mid- to late-2000s went from producing almost no solar PV cells and modules to being by far and away the world leader (see Figure 5). Because in solar the Chinese government until very recently refused to enact portfolio standards or feed-in-tariffs, China-based PV producers had no domestic market. They instead exported virtually their entire output to countries like Germany that had precisely these sorts of demand-inducing regulatory interventions.

With the ramp-up of Chinese solar PV production came historically unprecedented reductions in solar cell and module prices. Traditional c-Si solar PV fabrication is based on a process invented in the late 1950s in the United States. For decades, it had been considered a fully mature technology, one in which major price reductions seemed unlikely. Thus, solar panels remained niche products, too expensive to compete with electricity generated on the grid, and thus appropriate for only very remote, off-grid applications. But that is now beginning to change. As indicated by Figure 6, solar PV module prices were at approximately $2.75/watt in early 2009. By early 2012, with China-based producers having multiplied global production capacity to accommodate
rapidly growing markets (see Figure 7), the prices had fallen to roughly $1.10. In some respects, we are now witnessing with China-based production the c-Si solar PV industry’s version of Moore’s Law.

Worth noting is that in the Chinese PV industry, virtually all the firms are privately-owned (the largest among them all listed on overseas exchanges), and they are spread across a number of (primarily coastal) locales. This is an industry that has neither received much central support, attracted much state-ownership, nor concentrated in any particular locale.

Regional concentration (in Guangdong) is, however, characteristic of a third example, consumer electronics fabrication and assembly. As shown in Figure 8, notebook PC and mobile phone production has scaled rapidly in China since the mid-2000s. It is blockbuster products like the Apple iPod, iPhone, and iPad, though, that perhaps best exemplify the phenomenon. Apple designs, brands, and markets such products, but as many people now understand, it is multinationals like Foxconn that handle all the fabrication and assembly in their China-based factories. Firms like Foxconn, Quanta, Delta and others like it are known for their ability in any given product line to scale-up rapidly, accommodate late-stage design changes, take on additional design responsibilities shed by customers, and all the while continue meeting downward price pressures induced by their largest customers like Apple. And meanwhile, they perform these tasks simultaneously for not just Apple, but the full array of global brand leaders.

These sectors are remarkably different. Common across them, however, are unique firm-level capacities for scale-up, capacities that can be understood in terms of the four variants discussed below.
Taxonomy of Firm-Level Specialization in Scale-Up

Knowledge-intensive scale-up comes in a variety of forms, each of which involves distinct types of capabilities and distinct patterns of inter-firm learning. In our research, we have identified four such patterns, each of which is described below with firm-level examples.

Backward design and the reengineering of somebody else’s existing product

This pattern, to a greater degree than any other we discuss, in many ways resembles traditional processes of reverse engineering. By creating versions of existing products that are simpler to manufacture at scale, new Chinese entrants in many sectors have been able to outcompete established incumbents by undercutting them on the basis of price, and gaining domestic or global market share at their expense. However, among Chinese firms, this cost advantage, rather than resulting from cheaper inputs and larger scale production as held by conventional views about reverse engineering, often stems from a distinct process of backward design that subjects product attributes to the demands of a particular cost curve. Product alternatives are weighed, but cost curves ultimately drive product selection even if this necessitates sacrifices in quality and performance. What results from this process is a product that resembles the original archetype, but, by way of simplified componentry, cheaper materials, and better manufacturability, can be scaled at low cost and incredible speed. The relationships and interactions within which such processes of backward design occur are varied, in some cases creating highly competitive environments that allow for little but the thinnest of margins (other firms
duplicate the new designs), and in other cases permitting Chinese firms to command significant value.

The wind turbine sector illustrates this diversity well. In one instance, a Chinese firm acquired from a German counterpart a license for the production of a key wind turbine subsystem, the generator. The problem for the German designer of the generator, was that due to engineering constraints, the model was not compatible with the most cost-effective fan available. In this case, though, the Chinese licensee was able to redesign the original generator to accommodate the cheaper fan, eventually re-licensing this innovation back to the European firm (Interviews 051711 and 082611). The backward design capabilities of the Chinese firm permitted it to realize a product alternative that the German firm had considered, but had dismissed as unworkable. Interestingly, once the alternative was demonstrated to be feasible, the German firm was willing to pay for this proprietary information through reverse licensing. The iterated, multidirectional pattern of learning is noteworthy.

While in this example the Chinese firm was able to contribute production knowledge within a formal contractual relationship, in many other cases Chinese firms have used backward design skills to develop cheaper, mid-level products that compete directly with the product archetypes and their originator firms (Ge and Fujimoto, 2004; Thun and Brandt, 2010). Particularly in the Chinese domestic market, many established multinationals have been unable – and to some extent unwilling – to engage in such processes of cost-driven design, and have lost market share to cheaper alternatives as a result.
In the wind energy sector, where rapidly expanding domestic markets for turbines attracted established foreign manufacturers and their key suppliers to China, domestic firms have been able with great rapidity to develop competing products at much lower cost. By sourcing important components from foreign suppliers, licensing technology, and, in some cases, by buying smaller foreign competitors, Chinese wind turbine suppliers have been able to access technology relatively easily (Lewis, 2007). Yet instead of producing these designs as they are, Chinese firms employed backward design strategies to resort to cheaper materials, better manufacturability, and, where possible, simplified components from domestic suppliers. As a result, market prices for turbines have dropped from 7500 RMB/watt to 3500 RMB/watt in just three years (Chinese Wind Energy Association 2011), leaving many foreign players unable to compete despite fully localized production (Interview 083011).

The speed at which they have been able to engage in backward design has provided Chinese turbine manufacturers a competitive advantage even in instances where foreign firms have attempted to replicate this strategy. To reduce cost and increase competitiveness, a European turbine manufacturer followed the Chinese example and developed a cheaper, mid-level product for the Chinese market, utilizing materials, components, and suppliers equivalent to those used by the Chinese competition. Although the firm was able to develop a product for a similar price, by the time it had completed the backward design process and established a local supply chain, the product was obsolete. By that point, the Chinese market had already moved on to larger turbine sizes (Interviews 083011, 111711). In part, the European firm was slowed in its product development by lengthy negotiation and approval processes involving its European
headquarters. Yet, the speed advantage of its Chinese competitors also emanates from a more general willingness on the part of the Chinese to agree to a target price (one that often seems unrealistically low to outsiders), and then scramble improvisationally to figure out the feasibility and design details. In this case, the Chinese firms emphasize speed and cost at the expense of process and procedure.

Whether the ability to sell turbines at competitive prices in the Chinese market requires quality shortcuts that will affect their long-term reliability, and whether – even after cost-driven design changes – Chinese wind turbine manufacturers are able to earn margins that make this industry desirable for themselves and their foreign counterparts, remain questions open to debate. What seems clear is that on the relatively level playing field of fully localized production and domestic demand, Chinese firms have in rapid succession been able to engineer wind turbines that cost as little as 75 percent of the least expensive 4500 RMB/watt models offered by their foreign competitors (Interview 083011).

Making somebody else’s (new-to-the-world) product design come true

The ability of Chinese firms to move complicated products down the experience (learning) curve is also manifested in a different type of interaction with foreign firms, one characterized more by mutual gains and multidirectional learning than what is generally associated with backward design. In this second variant, the Chinese firm’s knowledge about production, scaling, and reengineering is marshaled to make a foreign partner’s product design commercially viable. Basically, the foreign firm provides the design, and the Chinese firm figures out how to make it at a competitive price.
The reasons for foreign firms to enter such relationships are as varied as the contractual details that regulate the interaction. The foreign firm may have no manufacturing capabilities at all, it may be unable to manufacture the product at a commercially viable price, or it may be deterred by the capital and tooling costs of commercializing a new technology. What these cases have in common, however, is their reliance on the production know-how of Chinese firms to replace, redesign, and substitute parts until the product can be manufactured at a commercially viable price. Rather than licensing or selling outdated technologies to Chinese firms for local manufacturing, as has been common in many developing economies including China (Vernon 1966), these instances of foreign-Chinese cooperation bring new-to-the-world innovation specifically to China because that is where the knowledge exists to complete the commercialization process, particularly with respect to higher volume products.

Again, an example from the Chinese wind energy sector illustrates the broader phenomenon. In 2009, a Chinese wind turbine producer acquired a 10-year exclusive license for the manufacturing of a groundbreaking, new-to-the-world wind turbine from a European engineering firm. The turbine employs a fundamentally different design concept offering greater reliability and versatility in both offshore and onshore applications. What on the surface resembles a standard licensing transaction – the kind that has occurred countless times in the course of China’s economic development – upon closer examination reveals a much more complicated, multidirectional pattern of learning.

Although the European firm developed the turbine design concept, the redesign for manufacturability and cost reduction occurred during small batch production on the
site of the Chinese manufacturer roughly two years after the initial contract was signed. The European design house specifically selected the Chinese partner among multiple potential licensees for this particular technology, choosing largely on the basis of manufacturing capabilities that would ensure reliability for the product and commercial viability for the project as a whole. Engineers employed by the Chinese firm made design changes to simplify tooling and assembly processes, and, in cooperation with other local firms, reduced costs by localizing sourcing and by introducing substitute materials. Additional design adjustments were then made during the process of scale-up to accommodate requirements for mass manufacturing.

The Chinese engineering team acknowledged the learning benefits from this cooperation, yet, interestingly, so too did the European partner. The European firm, without any manufacturing capacity of its own, placed great emphasis on being part of small batch production and subsequent scale up in order to maintain and improve its own design (and design-for-manufacturability) capabilities. This was especially important in the case of this particular turbine concept, as its novel componentry required all the components to be produced in-house. For the Europeans, learning from Chinese partners to improve design-for-manufacturing came to be understood as imperative for maintaining competitiveness and innovative capacity (Interviews 011311, 052011, 082911).

Hence, the licensing agreement between the two firms is merely the legal manifestation of a much more deep-seated process of cooperation, in which both sides chose each other for particular capabilities and the potential for knowledge transfer. To the Chinese firm, the new design offered a commercial advantage in a highly competitive
market environment. To the European firm, the Chinese licensee provided rich
production experience and extensive capabilities for translating complex designs into
cost-competitive products. The ability of Chinese firms to contribute critical knowledge
to the commercialization of new-to-the-world innovation suggests a more pivotal role for
China in the global division of labor than simply being the world’s preferred
manufacturing location due to the availability of cheap inputs. It also challenges,
however, ideas about the feasibility of separating advanced innovation and production,
showing how closely linked seemingly disconnected activities are.

Rapidly-scaled new-to-the-world product innovation

The Chinese ability to move products rapidly down the experience curve is not
applied exclusively to designs originally developed by foreigners, as was the case in the
previous two examples. In some instances, Chinese firms use these capabilities to
commercialize their own in-house new-to-the-world product innovation. That is, because
these firms have particular knowledge surrounding scaled-up manufacturing, they are
able to see commercial potential in nascent technologies – or even basic science – that
may be available in the public domain, but have lain dormant because others deemed
them too costly or risky to develop. In general, production knowledge and manufacturing
capabilities play a particularly critical role when a) manufacturability is a key constraint
in bringing an idea or concept to market, and b) when scaling has to take place in a
particularly short timeframe in order to take advantage of opportunities in fast-moving
market environments. Thus, although the new-to-the-world product in these cases is not
primarily the result of process innovation, manufacturing capabilities are important to make it commercially viable.

A case involving a Chinese solar PV manufacturer exemplifies this situation (Interview 082611). Like many innovations in the solar industry, where the conversion efficiencies of light to electricity for different processes are easily calculated but are hard to approximate in practice, this particular innovation developed by the Chinese solar manufacturer was based on a commonly known theoretical principle that had not yet been made to work in a commercial solar application. The Chinese firm, like many of its competitors in China and abroad, was researching ways to commercialize this principle, as it offered a way to produce higher efficiency solar panels.

The firm’s R&D center discovered a material produced by a third party vendor that allowed the firm to run the process in the laboratory. The desired efficiency level was achieved after several months of trials. A key challenge, however, was to utilize existing production equipment to manufacture cells based on this new principle, and to do so very rapidly. Due to different material requirements, the new product was more expensive than traditional solar cells. At the time, the extremely high price of silicon – the main raw material for solar cells – justified the additional expense to produce a higher efficiency cell, as it created a product that generated more electricity for every unit of silicon used in production. Speed was of the essence, however, since competitors researching the same technology – the Chinese patent office had denied patent protection since the technology is based on a commonly known principle – and the possibility of a drop in silicon prices threatened over time to erode the competitive advantage the firm could derive from its invention (Interview 082611).
Through collaboration between the R&D team and production engineers, the firm was able to utilize existing production equipment to manufacture the new product, and within months had four production lines churning out new, higher efficiency cells. Precisely because the firm found ways to use existing production lines to rapidly scale a new product, the initial invention became commercially viable in a very short period of time. Speed permitted the firm to capture the value of its innovative know-how. By the time competitors developed a similar product, silicon prices had already dropped so far that the original firm decided to reconvert its production to a traditional product since the cost increase to achieve higher efficiency was no longer justifiable (Interview 080811, 081011).

*Product Platform for Technology Co-Development and Absorption*

Lastly, the presence of both production scale and considerable know-how in vast Chinese manufacturing operations has provided a platform for a variety of international innovators to rapidly integrate their technology into a product. In many cases, the Chinese manufacturer produces a product that then incorporates an outside innovator’s technology as a component. The external innovator, however, is more than just a high-end component vendor who sells a product at arms-length to the Chinese customer. In many cases the vendor actually commercializes the technology in cooperation with the Chinese customer. The vendor brings to the table knowledge about a particular technology that may have applications to a product the Chinese manufacturer has already scaled up. The Chinese manufacturer brings to the table knowledge about production, knowledge about how the component technology might be applied at scale, and
knowledge about how the original product will be improved as a result. Between the two parties involved, a component technology can be simultaneously commercialized and applied to an existing product at high production volumes.

In such cases, the interaction between global innovators and Chinese firms is not a simple commercial transaction, but instead a process of co-development that defines the very application of the technology itself (Herrigel 2010). Particularly for technologies with multiple applications – such as a liquid nanomaterial that may have potential uses in flat panel displays, solar panels, or LED lighting – integration into an extant, mass-manufactured product transforms the technology from a principle into a component with commercial value (Interview 101311). The new technology, therefore, has an instant market, since the Chinese co-developer becomes a high volume customer. This type of technology absorption entails contributions of knowledge from both the original innovator and the Chinese manufacturing firm, again resulting in a process of multidirectional learning. Yet in contrast to cases in which Chinese manufacturing capabilities make possible the commercialization of complex designs, in the cases of technology absorption described here, the Chinese product platform often determines the fundamental features – and markets – of the new technologies being fed in by outsiders.

A fairly typical case involves the cooperation of US-based Innovalight with the Chinese solar cell manufacturer JA Solar. A silicon valley start-up founded in 2002, Innovalight developed a nanomaterial with a number of potential applications in products ranging from integrated circuits and displays to solar PV. With Department of Energy funding and support from the National Renewable Energy Laboratory (NREL), the firm developed an understanding of how the nanomaterial, a silicon ink, might be applied in
the solar photovoltaic industry, concluding that it could potentially increase the efficiency of solar cells by 7 percent (Scanlon 2011). Yet, while Innovalight and NREL could together determine how the material might improve a single solar cell, neither had experience in large-scale manufacturing. Presumably, neither had the know-how required for applying the material in a cost-effective manner in high-volume solar PV production. Outside investors certainly seemed to doubt Innovalight’s know-how in this area, for the firm was unable to raise the capital needed to build a solar PV production facility (Wang 2011).

In 2009, short of funds and nearly out of business, the company changed strategy, focusing on licensing its technology to solar manufacturers rather than building a production business itself. The same year, Innovalight found a partner in the Chinese cell manufacturer JA Solar. Looking for a way to gain an edge over its competitors, JA Solar was willing to invest in the collaborative development of a technology that could substantially improve the efficiency – and, thus, market appeal – of its main product. The idea would be to use the nanomaterial as a component, essentially applying it to a cell in order to improve the cell’s efficiency. After a year of joint research and development, the two firms announced the successful production of high-efficiency solar cells using Innovalight’s silicon ink technology. As a result, the two firms in 2010 signed a three-year agreement for the supply of silicon ink, as well as a strategic agreement for the joint development of high-efficiency cells (JA Solar 2010).

For JA Solar, the collaboration with Innovalight resulted in the ability to utilize foreign technologies for the production of a new line of high-efficiency solar cells. For Innovalight, JA Solar’s manufacturing capabilities offered a type of expertise it could not
gain from the collaboration with NREL. The process of joint development with JA Solar for the first time verified Innovalight’s silicon ink technology as a product that can contribute value in solar PV. Established as a legitimate player in the solar industry, Innovalight subsequently began licensing its technology to other solar manufacturers.

With its record of successes, Innovalight in 2011 was acquired by Dupont, and integrated into the global conglomerate’s solar division. Dupont aims to be a global leader in the provision of high-value componentry to the solar industry. Innovalight’s silicon ink will be coupled with other Dupont innovations in metal pastes and solar cell backing films. In January 2012, Dupont signed a $100 million supply deal with Chinese solar PV manufacturer Yingli (Stuart 2012).

While it is unclear whether JA Solar will be able to translate its cooperation with Innovalight into a long-term competitive advantage – particularly in light of the fact that Innovalight began licensing the product to JA’s competitor’s as well – it is evident that JA’s manufacturing capabilities played a critical role in developing silicon ink technology as a viable product in the solar industry. Through a global process of multidirectional learning and mutual risk-taking, Chinese production knowledge provided a platform for the commercialization of American innovation.

Scale-Up in the Broader Conceptual Context

In each of the four categories discussed above, we witness in China-based manufacturing either rapid movement down an existing experience curve or the origination of an entirely new curve. Sometimes, new curves emerge in ostensibly
mature industries previously believed to be immune to such changes. How do these outcomes relate to broader concepts in public policy and academic debates?

At the policy level, our findings challenge the view that China’s rise in manufacturing stems primarily from exogenous shifts in factor prices. This view, frequently expressed in critiques of the Chinese government’s management of exchange rate values (Bergsten 2010), assumes a world in which experience (learning) curves are essentially fixed for any given industry, vary little among firms within industries (that is, reflect little about firm-specific knowledge or skills), and shift primarily due to factor price difference (See Figure 9). We acknowledge that in many national contexts, production-related activities – including manufacturing – are frequently rewarded with subsidies and regulatory protection. This has certainly been true in China, though to varying degrees depending on the sector. This has also been true in a general sense in the United States. Conceptually, however, we argue against the notion that exogenous distortions can easily explain – let alone be treated as proxies for – knowledge creation within the firm. That is, we do not feel that experience curves can simply be shifted up and down exogenously. A price subsidy may permit a newcomer to enter the game. What that subsidy will not guarantee is that the firm will then continue to march smoothly down the experience curve. That takes firm-specific learning and know-how. What subsidies certainly do not guarantee is that a firm will be able to effectively define a new experience curve. That takes an arguably even higher order of learning and innovation. And last but not least, subsidies cannot explain the unprecedented tempo at which both of these phenomena now unfold in China-based firms.
Given our emphasis on learning and the development of firm-specific know-how in a late industrializer context, our perspective bears certain affinities with the developmental state literature, particularly the work of Amsden (Amsden 1989; 2001). Like Amsden, we argue that late development – or at least several critical cases of late development – entail not invention or new product innovation, but instead knowledge generation on the shop floor. That is, we find that at least in China, particular kinds of knowledge-based specialization have developed within the firm, and often directly on the shop floor. What we witness is not just mimicry of global best practice, but in fact a redefinition of that global standard. There is, in a sense, movement from imitation to (process) innovation (Kim 1997).

There are differences, however, between Chinese-style scale-up and the type of learning described by Amsden, Kim, and others. In China, subsidies abound, but they come from a variety of different levels of government, and they are applied seemingly haphazardly and indiscriminately across industrial sectors. Thus, in contrast to what took place earlier in South Korea, it becomes difficult in China to discern any particular strategy on the part of the state, and even more challenging to draw links between the subsidies and the learning that occurs within the firm. In part, that challenge stems from the fact that this learning is not taking place in oligopolistic contexts – ones with just a few large-scale corporate participants – but instead in sectors with intense competition, myriad entrants, and considerable churning. Few of these entrants are state-owned, and even fewer could be described as “national champions.” Many are relatively anonymous. Almost all, however, are deeply embedded in global production networks, cross-border commercial partnerships, and international knowledge flows.
But that leads to a more important point. The type of learning described by Amsden occurred in an era dominated globally by vertically-integrated companies producing goods with essentially integral product architectures (Ge and Fujimoto 2004; Ulrich, 1995). That is, the products themselves – automobiles, for example – embodied a level of complexity requiring tight geographical and managerial linkages between design, component sourcing, and assembly. These activities happened, in a sense, under one roof. Thus, capability building entailed one vertically-integrated firm – the new entrant – learning from another vertically-integrated firm, the global incumbent. The new entrant, then, innovated by using that learning to develop better management of the relationship between various pieces of the production process. Broadly speaking, lean production is precisely this type of innovation (Cusumano 1989; Womack et al. 2007).

What we are describing, however, is taking place in a much more networked form of production, one in which product architectures are more modular, inter-firm production relationships are more extensive, and firm-level specialization in particular production activities is much more pronounced. Indeed, that the firms themselves often specialize in just a subset of all the tasks needed to bring a product to market means that those firms -- virtually by definition – must be networked with other enterprises that can “complete the package,” so to speak. In contrast to some of the literature (Kraemer et al. 2011; Steinfeld 2004; Sturgeon 2002), we argue neither that modular production architectures have completely separated design and assembly, nor that knowledge-intensive value creation remains concentrated in the former, and relatively absent in the latter. Our data suggest that China-based assemblers in many cases remain tightly linked to design partners, often through multidirectional communication and learning.
Moreover, the know-how that these assemblers contribute is valuable enough to induce partners and competitors from advanced industrial nations to try to learn it. That is, the learning in some instances is now happening in reverse (as in the case of multinational wind turbine manufacturers producing in the China market), and in other cases multidirectionally across partnerships (as in the case of China-based solar PV manufacturers and their overseas component suppliers).

Our particular emphasis on scaling – the simultaneous management of tempo, volume, and cost – is related to, but also somewhat different from what other scholars have recently observed in the Chinese context. We certainly agree with the idea that China, for all its regional differences, should now be understood as a national commercial ecosystem, and one with important capabilities in process innovation (Breznitz and Murphee 2011). While in the past, particular regions clearly did emphasize specialization in particular industrial sectors (Segal 2003; Segal and Thun 2001), our data suggest that such distinctions have become far more ambiguous today with the proliferation of diversified manufacturing all along the nation’s coast and well into the interior. Perhaps more important, we are skeptical of assertions by previous scholars that firm-level learning in China should be understood as stemming primarily from broad characteristics of the Chinese political system (Breznitz and Murphee 2011) or specific aspects of local state industrial policy (Segal 2003; Segal and Thun 2001; Thun 2006). While we have not yet developed a full explanation for the origins of the learning we have observed, we believe that the phenomenon is more rooted in the creativity of individual entrepreneurs and the multidirectional flows of knowledge across networks than it is in the hierarchies of the political order.
On the political front, though, it is worth noting that the entrepreneurial specialization observable in China today bears similarities to what unfolded in Taiwan in the 1970s and eighties: a focus on manufacturing assembly, highly networked business operations, extensive reverse engineering, rapid scaling, and rapid technology absorption. It is certainly possible that this approach to production developed in Taiwan and on mainland China entirely separately, albeit for similar reasons – political uncertainty, governmental preferences for state-owned firms as opposed to entrepreneurs, etc. (Wu 2005). It could be equally true that Taiwanese firms, through their now extensive operations on the mainland, have actively transplanted this model.

In terms of the actual learning itself, some of the specialization we describe fits previous accounts of what Chinese firms do. Our first variant of scaling, particularly in its emphasis on redesign through reverse engineering, has been deeply informed by the work of Ge and Fujimoto (2004). Furthermore, output from this kind of specialization – mid-market goods that perform slightly less well than top-tier counterparts, but are much less expensive – fits completely with what Thun and Brandt describe (Thun and Brandt 2010). However, Ge and Fujimoto on the one hand and Thun and Brandt on the other are primarily emphasizing product-specific attributes, design and market segmentation. We feel these aspects are critical, but incomplete. They cannot be fully understood if removed from the context of speed and volume. Even just with reverse engineering, what is arguably unique in the Chinese case today is how quickly this can be done, and how quickly the new designs can be brought up to full production volume. It is that sublime knowledge surrounding speed, as opposed to just new product definition (mid-market or otherwise) that overseas firms are now trying to learn from their Chinese partners and
competitors. Indeed, that is one relatively new motivation for overseas firms to set up manufacturing operations in China, often by acquiring a local producer (Interview 030312). Acquisition becomes a vector for learning.

It is the issue of speed – the tempo of scale-up – that links the different types of learning in our typology. Reverse engineering is an important, but by no means predominant, part of Chinese manufacturing know-how. Quite different from reverse engineering is our fourth category of technology absorption. The account there is about non-hierarchical production networks in which knowledge – and technology – is co-developed (Herrigel 2010) between firms rooted in very different kinds of industrial sectors. They learn from each other, create value for their individual inputs through that learning process, and then deliver a single product to the customer. This is not simply the story of globalized – and often quite hierarchical – supply chains. Nor is it a story of manufacturers purchasing and rapidly integrating mature technologies through one-way learning. Rather, it is a story of multiple players sharing knowledge and risk in order to commercialize emergent technology. Moreover, it is a story of multiple players participating in movement down – or even outright redefinition of – an industrial learning curve, one not so long ago thought to have been quite flat. Thus, through its specialization in scale-up, the Chinese ecosystem can be understood as part of a broader pattern of industrial co-development (Herrigel 2010), one that is not simply shifting existing value from one global locale to another, but instead creating new value where none had existed before.
Conclusion

As we have argued in this paper, the Chinese business ecosystem today has developed specialized expertise and distinct patterns of multidirectional learning in production scale-up. This, in essence, amounts to a system-wide phenomenon of innovative manufacturing.

We do not feel that Chinese-style innovative manufacturing is a necessary byproduct of China’s existing political order. One cannot draw a direct, deterministic connection between a Chinese version of the developmental state and the particular type of industrial specialization that has arisen in the Chinese ecosystem. Indeed, in contrast to some of its East Asian neighbors, the Chinese state, for all its developmental ambitions, has struggled with organizational complexity, extensive decentralization, skewed incentive structures, and conflicting priorities. Despite its extensive presence in the Chinese economy, the state has not consistently generated strategic, centralized responses to the challenges associated with late development.

That said, the phenomenon described in this paper is neither devoid of state involvement, nor disconnected from state developmental policy. For example, China’s national push to develop a competitive wind industry has relied on demand-side regulation to stimulate market development and local content requirements to transfer global technologies to local supply chains. These policies not only attracted foreign firms to China, but have also provided the context within which Chinese firms have pursued backward design to become globally competitive. At the same time, other sectors – such as solar PV – were not granted such policy support until very late in the game (Beijing began stimulating the domestic demand side only in 2011), well after production volumes
had reached world-leading levels and firms had already developed specialization in scale-up. Still other sectors designated as “pillar industries” by the Chinese government have neither received consistent policy support, nor developed identifiable specialization in any domain. Understanding this variation on both the governmental and business sides is an aim for future research.

At the local level, in contrast, government support has been far more consistent, but essentially indiscriminate and haphazard across industrial sectors. Whether through the provision of subsidies, tax breaks, financing, or – perhaps most important – guidance through the bureaucratic jungle that issues construction permits and other kinds of licenses, local governments have been a critical enabler of the firm-level abilities to manage speed, scale, and cost. But, as noted, this support has been quite unsystematic and ad hoc, focused as much on local development and business promotion as anything else. Partly as a result, the support has been directed as frequently to foreign firms as domestic ones. This is clearly evident in consumer electronics production. The Chinese economy’s single largest exporter today is the Taiwanese-owned electronics manufacturer Foxconn (Duhigg and Barboza, 2012). All in all, this certainly amounts to a pattern of government behavior different from the strategic, longer-term focus associated with the traditional developmental state.

Whereas the archetypical developmental state – namely that of South Korea – structured growth through rule-setting, regulation, and strategic intervention, the Chinese government has participated in the economy in a far more experimental, almost mercurial fashion. Policies are often rolled out informally and allowed to develop organically with shifts in producer practices on the ground. Only after practices disseminate and prove
successful are the policies then formally announced and institutionalized. Hence, both the state that is making policy and the producers being affected by policy become accustomed to highly flexible and improvisational operations. Improvisation becomes the norm. So too does interaction with extensive networks, both to facilitate information flows under ambiguous conditions, and to spread risk by creating options for different paths that can be taken at a moment’s notice.

At the firm level, these characteristics of the policy environment have at least two consequences. First, China-based producers learn to behave in an extremely flexible, highly networked manner. Learning and operating through continually evolving networks becomes routine. Second, given the fluidity of the situation, the boundaries between competition and cooperation become extremely ambiguous. All the sectors discussed in this paper are extremely competitive. Numerous entrants compete bitterly for business, and all recognize that any given type of specialization – while necessary to secure profit – should always be considered fleeting. Firms cooperate extensively in networks, but so too do they compete. Thus, they end up in a mode of almost continual improvisational specialization, all within the general category of innovative manufacturing.

Crucial to recognize about this environment of improvisational networking and intense competition is that it is not populated exclusively by domestic firms. Chinese innovative manufacturing relies in elemental ways on the contributions of outsiders. Sometimes these outsiders are physically present in China, and sometimes they interact with Chinese counterparts from afar. Regardless, overseas firms are critical sources of technology and knowledge. What we hope to have illustrated in this paper, however, is that this is not a case of one-sided “technology transfer” or unidirectional knowledge
flow. Rather, it is a more complex phenomenon involving multidirectional learning, one in which Chinese firms contribute indispensable know-how and capabilities for the commercialization of innovation.

It is not always clear who captures the most value in these interactions. Risk and reward in these relationships are frequently spread in complicated ways, particularly given that many of the relationships are not clearly hierarchical. This is not simply the world of the traditional supply chain in which a lead firm, commanding the bulk of the revenue, drives the behavior of subordinate suppliers or subcontractors (Gereffi, Humphrey, and Sturgeon, 2005; Nolan, 2012). But what is clear is that some foreign firms have benefited – and have learned – by engaging a Chinese developmental style that prioritizes speed and flexibility over rules and procedures. Moreover, it seems apparent that across a number of industrial sectors, firms globally will soon either have to work closely with Chinese counterparts or learn ways to mimic their know-how in order to successfully commercialize technology.

As an ecosystem, China has clearly done well in many respects. It has achieved sustained growth despite haphazard policy approaches on the part of the state. It has avoided the main pitfall associated with participation in modular production, the possibility of getting eternally stuck in the lowest skill, lowest value pieces of global supply chains. The ecosystem, as we have argued, has become the locus for considerable innovation, and as a result, has steadily attracted higher value production activities and higher status overseas commercial partners. Some of those partners today clearly feel that in order to maintain their own competitiveness and knowledge-based assets, they have to be in China.
Yet, despite these favorable outcomes, the Chinese ecosystem’s particular brand of specialization bears considerable costs and risks. The processes described in this paper have entailed enormous investments in manufacturing capacity, fixed assets basically. Particularly in cases where significant innovation cannot so clearly be extracted from the manufacturing process itself, such as in electronics, China’s ability to benefit from large-scale manufacturing hinges on its ability to pull related, higher-value added activities into these ecosystems of scale. Additionally, Chinese firms have placed large bets on sectors such as wind and solar in which demand, almost regardless of any cost savings achieved by producers, depends ultimately on market stimulation by regulatory actors. Whether those regulatory actors are overseas or in China, they hold in their hands the fate of these industries. And, in numerous industrial sectors, the rapid expansion of manufacturing has created the risk of overcapacity, potentially imposing financial losses to investors in a process of industry consolidation.

Solutions to the world’s most pressing problems – including climate change – inevitably involve technological innovation. Ways have to be found to make existing technologies cheaper and completely new technologies commercially viable. The Chinese business ecosystem today is providing unprecedented options for both avenues. Given its focus on scaled manufacturing, however, it is also bearing much of the financial and environmental risk for these options. For all the global political wrangling surrounding China’s rise in manufacturing, many of the gains have been internationalized, while the risks have remained decidedly local in nature. Given the centrality of Chinese manufacturing in the global innovation system, the management of these risks constitutes a sustainability issue not just for China, but for us all.
Figures

Figure 1: Industry-Specific Experience Curves and Chinese Specialization in Scale-Up
Figure 2. Cumulative Installed Wind Power Capacity, 1980-2009

Figure 3. Price Declines for Installed Wind Power

Figure 4. Percent Domestic Content in Chinese Wind Turbines


Figure 5. Annual Solar PV Production by Country, 1995-2010
Figure 6. Price Declines in Solar PV Production

![Graph showing Crystalline PV Module and Polysilicon Prices](image)

Source: IMS Research - www.PVMarketResearch.com

Figure 7. The Rise of Chinese Production in Solar PV

- Between 2000 and 2010 global shipments grew 53% (CAGR)
- U.S. market share slipped from 30% to 7% (30% CAGR)
- China/Taiwan grew from <2% to 54% (115% CAGR)

![Graph showing U.S. and China & Taiwan Market Share of Global Shipments of PV Cells/Modules](image)

Source: NREL 2011
Figure 8. China, Production of Mobile Phones and Notebook PCs (in millions)

Source: Chinese Bureau of Statistics
The Mercantilist Perspective: Experience Curves Shifting in Response to Exogenous Price Distortions

- Market-based worldwide industry experience curve
- Learning curve in distorted price environment

Cost per unit vs. Production Volume
References


