

Machine Tools

A Case Study In Advanced Manufacturing

Ben Landau-Taylor and Oberon Dixon-Luinenburg

Abstract

Machine tools are essential in industrial metalworking and, as a type of capital equipment, machine tool consumption is a strong indicator of overall manufacturing capacity. Production is highly concentrated, with a small number of countries producing the vast majority of precision machine tools used in advanced manufacturing worldwide. The most important machine tool manufacturers are China, Germany, and Japan. China is unique in that its massive production is overwhelmingly for its own domestic manufacturing sector, whereas all other major manufacturers export a substantial fraction of their machine tools. The other major machine tool manufacturers are Italy, South Korea, the United States, Taiwan, and Switzerland; outside of these countries almost all precision machine tools must be imported.

Russia, the US, and the UK have all seen varying degrees of decline in machine tool production since their peaks, while several East Asian economies have built or massively expanded their machine tool industries over the same period and several European countries have maintained strong production.

This occurred because production of machine tools requires substantial societal infrastructure such as educated workers, significant capital investment, and a strong customer base, which companies in the fragmented machine tools market generally cannot create on their own. These things require deliberate state action to create and continued policy to sustain. All of the successful countries have maintained clear policies that help machine tool producers, while those that have declined, or failed to start significant production at all, have not. These policies have only been successfully implemented by states with strong coordination between elites in government, business, and finance.

The body of this report is comprised of two parts, first detailing the landscape of global machine tool production in the Landscape section, and then providing an analysis with wider applicability to advanced manufacturing and industrial capacity in the Analysis section.

Introduction

Machine tools manufacturing is an essential part of an industrial society and can serve as a bellwether for the industrial capacity of a nation. Machine tools exist fundamentally to serve and support manufacturing; a machine tool is in effect a machine to build more machines by manipulating an implement to shape metal in a controlled way. Products ranging from automobiles to airplanes, warships to medical devices, and mobile phones to mining equipment require the rate of production, machining quality and precision, and scalability of machine tools. Tens of billions of US dollars are spent annually on purchasing new machine tools, and the ripple effects in the economy are much larger.

We take a broad definition of machine tools¹ and trace their origin back to the Industrial Revolution in the mid to late 18th century England. These early machine tools were first developed for specific purposes by pioneers such as John Wilkinson, who created a precision boring tool that made James Watt's steam engine feasible. Later companies brought machine tools to market as core product lines, making them available to all manufacturing companies, including those without the scale to support building their own.

Major advances have transformed the capability of machine tools, such as a proliferation of tool types in the 18th and 19th centuries, the invention of computer numerical control (CNC) technology which automatically operates the tool according to a prewritten computer program, the development of non-conventional machining technologies, and ever-increasing automation since the 1960s. Two facts endure: 1) the necessity of machine tools for industrial manufacturing and 2) the vast and increasing disparity in production of quality machine tools between different states as summarized in Figure 1—a trend that is deeply tied to differences of industrial capacity, wealth, and power between countries.

Why is production so concentrated, and further, why is it concentrated where it is? Why have US companies lagged behind since the advent of CNCs while Japanese and German companies have excelled? Why are nations such as Russia, Brazil, and India unable to support a strong domestic machine tool industry while China has taken off exponentially since 1990? In this paper we endeavor to lay out the technical, sociological, and policy factors that determine the concentration of high-performance machine tool production and the implications for advanced manufacturing more broadly.

¹ [World Machine Tool Survey, Gardner Research, 2016](#)

>USD 10 billion
 USD 2-10 billion
 USD 0.5-2 billion
 USD 50-500 million

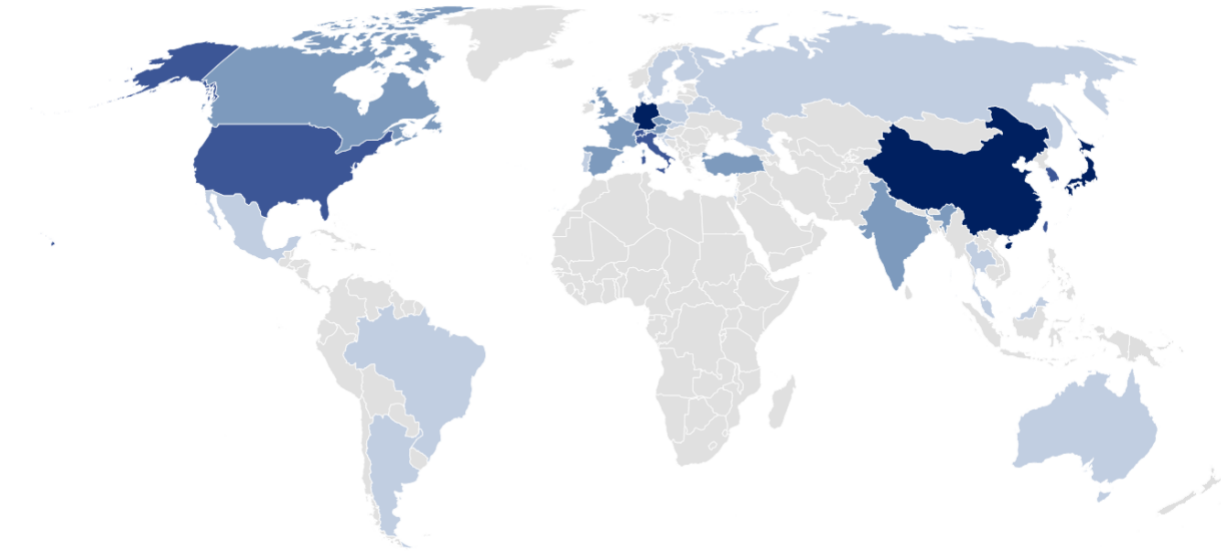


Figure 1: Global distribution of machine tool production in 2015

Landscape

Machine Tool Companies

Major Companies

Modern machine tool manufacturers vary widely in their corporate structure, product offerings, core markets, size, and degree of integration with the state. Machine tool producers often have limited vertical integration, and source much of their hardware and software from other companies. Most machine tool producers sell to large manufacturers and independent machine shops rather than using their machine tools to produce downstream goods.

While some major companies report revenues in excess of 1 billion US dollars and employ tens of thousands of people, no single company controls even 5% of the global market and most companies employ less than a thousand people.² This is because machine tools are generally designed and marketed for very specific market niches and are highly customizable, negating many of the benefits of scale and ensuring that machine tool producers are smaller than many of their major customers. Even in a given market segment there will often be 10-30 machine tool models from various vendors available.

Some larger companies do practice more vertical integration as part of cost reduction and supply chain streamlining, but at least a few upstream suppliers remain essential for any high-end machine tool. In fact, there is significantly more market consolidation in certain machine tool components than in the production of machine tools themselves. Examples include motion controllers, servo motors, linear motion systems, and

² [World Machine Tool Survey, Gardner Research, 2016](#)

software for computer aided manufacturing kernels, machine controller simulators, and numerical control programming simulators. Companies that source these components internally or from lower-tier suppliers risk sacrificing standardization to the common platforms of the industry, top-level performance for specialized applications, and the fast development cycles that come when using an existing solution with strong support.³

As a capital investment, machine tools are typically bought for long-term use and require service and support contracts that must be continuously available for years or decades after the initial sale. Machine tool life cycle is on the order of 15 years and demand can swing wildly depending on macroeconomic trends and dynamics of target markets, so part of the industry's value as an economic indicator stems from the linkage between machine tool sales and cyclical investment in manufacturing. When money is cheap and consumer demand is strong, sales are good, but machine tool manufacturers take steps to ensure they can weather inevitable downturns. One strategy is to diversify across different market segments and geographical regions, such as targeting some products for the Asia markets and others for Europe, to smooth the peaks and troughs of cycles within a given market. Another is to optimize workforce, supply chains, and factories to facilitate expansion and contraction of costs, production volume, and product types in line with demand, termed volume and product flexibility in manufacturing systems literature.

Skilled labour is essential for machine tool production. Mechanical, electrical, and software engineering are required in the design process, experienced technicians are needed for assembly and testing, excellent supply chain and production management is required to stay on-schedule, and global technical sales and support teams are necessary to maintain customer relationships. Companies at the leading edge must continuously invest in R&D, which for the most specialized and advanced machine tools must include close relationships with key customers to ensure that R&D spending is targeted on projects that will bring real value.⁴

While pricing and margins vary wildly across the industry, a typical mid-sized machine tool manufacturer might sell a product for USD 200,000, spend USD 130,000 on components and labour, and take a net profit of 10-15% after costs of distribution, sales, R&D, and taxes.

Company Structure

A few examples of top producers from key regions with different strategies, structures, and types of leadership are provided below. These companies have been mostly successful in profitably bringing machine tool product lines to market and point to some of the effective strategies that are available.

Trumpf often tops the list of largest machine tool manufacturers by revenue, reaching USD 4 billion in 2018. Founded by Christian Trumpf and two partners in 1923 in Stuttgart, Germany, Trumpf is still family-owned and now has production facilities in 13 countries, including China, the US, and Italy. Nicola Leibinger-Kammüller has been president and chairwoman of the Managing Board since 2003, having come up through the company ranks starting in 1985. Succession appears to be handled relatively effectively within Trumpf, so it is likely that the 59-year-old Leibinger-Kammüller has plans for a smooth handoff. The company has done very well in recent years, achieving profits over 500 million US dollars in 2018 in part due to strong growth in laser machining systems, for which they can achieve significant vertical integration while facing relatively less

³ *The machine tool industry and the effects of technological change*, Heinrich Arnold, 2001

⁴ *Business model innovation paths and success in the machine tool industry*, Copani et al, 2010

competition than in other segments.⁵ Trumpf's long-term success is substantially due to following many conventional management practices of Mittlestand, a category of small- and medium-sized companies in Central Europe, and substantial early positioning in high-margin and high-growth areas.

Haas Automation is by far the largest machine tool manufacturer in the United States, with revenues of over USD 1 billion/year. Haas was founded in Oxnard, California in 1983 by the eccentric Gene Haas, who still owns and remains involved with the company today, while Rob Murray as General Manager plays a major role in day to day operations. Gene Haas is 66 years old, and it is unclear whether a successor is being prepared to run the company in the difficult business environment of the US. Haas makes a broad range of mid-tier vertical mills, machine centers, mold machines, and turning centers, with much more vertical integration in their manufacturing than is typical in the industry.

DMG Mori was formed from the union of two CNC manufacturers. Over the course of 2009 through 2015, the Japanese company Mori Seki acquired the German company DMG, which was itself formed from the merger of three German companies (Deckel, Maho, and Gildemeister) in 1993-1994. International mergers of this sort are rare, but this one seems to have gone smoothly. The chairman of the former DMG left the merged company in 2016, while most of DMG's mid-level leadership was retained, leaving DMG Mori's European operations in the hands of Germans with strong local knowledge. Product offerings of the combined DMG Mori include turning, milling, grinding, and laser machining systems as well as additive manufacturing systems. Revenue for the combined entity was about USD 3 billion in 2018.

FANUC is a group of publicly traded companies with operations around the world, originating as a subsidiary of Fujitsu in 1955 and spun off in 1972. Under the leadership of Seiueemon Inaba, FANUC captured half of the world market for numerical control by 1982 after partnering with US and German companies. FANUC has since maintained dominance in motion control systems and other essential components for precision machine tools under Seiueemon Inaba's leadership, with control gradually being handed off to his son Yoshiharu Inaba first as President in 2003 and ultimately as Chairman of the Board in 2016, while the 93-year-old Seiueemon maintains an honorary Chairman position. In recent years, FANUC has maintained profit margins over 20% almost every quarter and in 2017 had USD 5 billion in revenue, higher than almost all other companies involved in machine tool production. This is indicative of the dependency of machine tool makers on essential upstream suppliers who are more able to maintain monopoly positions than machine tool manufacturers themselves.⁶

Shenyang Machine Tool Company (SMTCL) is reportedly the largest Chinese machine tool manufacturer, with products including lathes, turning and milling machining centers, boring machining centers, and drilling machines. All of the products, especially those without numerical control, are primarily targeted at the domestic market. Founded in 1993 and headquartered in Shenyang, Liaoning Province, SMTCL acquired the German firm Schiess in 2004 and has since seen exponential growth in sales along with the growth of the Chinese manufacturing sector. SMTCL now manufactures tens of thousands of machine tools in both Germany and China and has reached revenues over USD 1 billion in good years. Xiyou Guan serves as Chairman and CEO, however, much of the internal power structure is unclear from publicly available information. SMTCL trades

⁵ *A Happy Family of 8,000, but for How Long?*, Carter Dougherty, *New York Times*, 2009

⁶ *The History of Fanuc*

on the Shenzhen stock exchange.^{7 8}

National Systems

Because of the key role they play in industrial production, and because of the key role industrial production plays in overall economic productivity, military capability, and political security, the way in which countries get machine tools is important. Much can be learned from a national-level analysis of the history of machine tool production in the broader context of industrialization, the policy priority that was placed on machine tools by countries that are now centers of advanced manufacturing, and specific dynamics internal to the industry. Figure 2 shows how consumption and production of machine tools is distributed in the world according to official numbers. Estimates are provided where official numbers are not available.

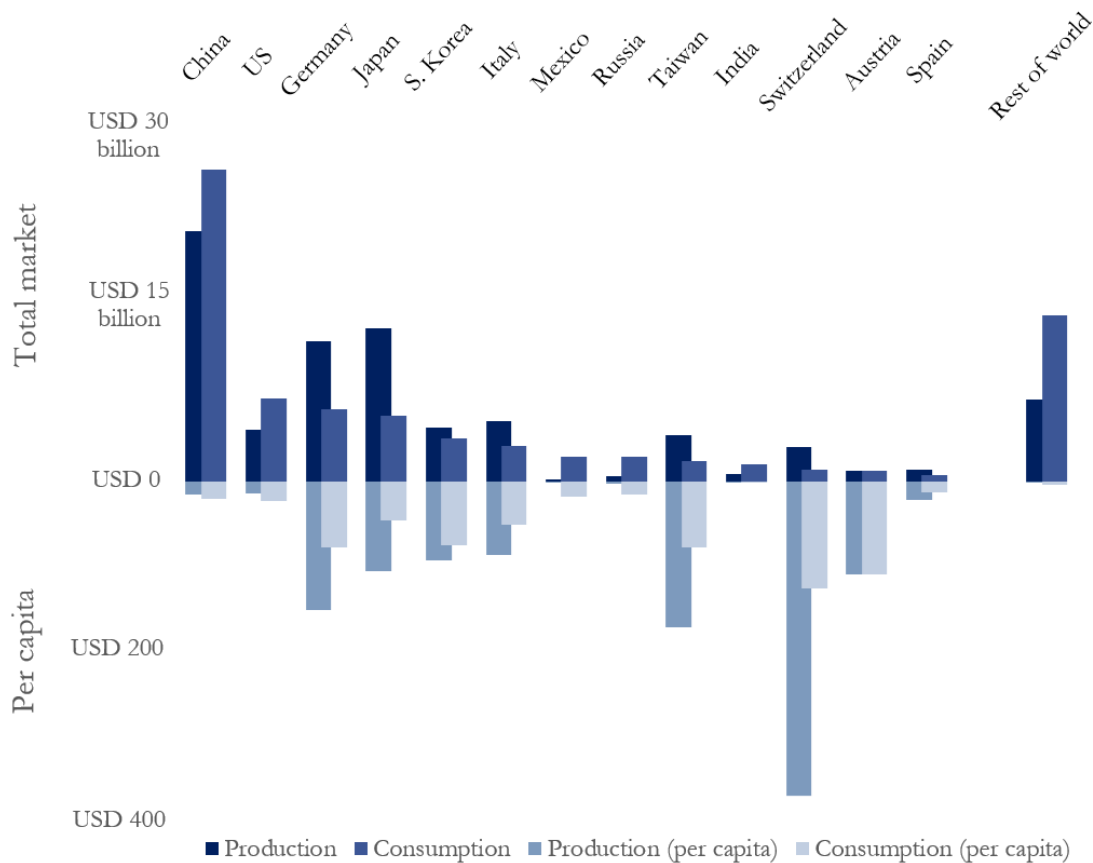


Figure 2: Machine tool industry by country, total dollar value and per capita⁹

Currently, machine tools consumption is dominated by China as its manufacturing capacity continues to rapidly expand—building new factories requires many more machine tools than maintaining or refurbishing existing ones. The United States is the second largest consumer, followed by Germany, Japan, South Korea, Italy, Mexico, Russia, Taiwan, and India. Not all national systems produce equivalent machine tools, with China

⁷ SMTCL Chairman Explains Strategy for Company's Future at IMTS 2012, *Business Wire*, 2012

⁸ *Business Success in China*, Hofer and Ebel, 2006, pg 251

⁹ *World Machine Tool Survey*, Gardner Research, 2016

producing the largest number and dollar value in machine tools but still producing far more lower-performance machine tools than any other major country and lagging in exports. Following China, Japan and Germany produce less but both produce machine tools of much higher quality. They are followed by Italy, South Korea, the United States, Taiwan, Switzerland, Spain, and Austria. Together, the top ten machine tool producers make up roughly 90% of production. Notably, there are some large consumers that do not produce very many machine tools domestically, such as Russia, Mexico, India, and Thailand.¹⁰

Having established the specifics of production concentration, what follows is a brief description of history and aspects of industrial policy and societal structure for several nations of past or present importance. The examination of countries with successful and unsuccessful domestic machine tool producers will show that a deliberate and well executed policy, set to promote knowledge transfer and high-value added manufacturing, is highly correlated with continuing leadership. We leave for the analysis section the establishment of causal mechanisms.

United Kingdom: Machine tools were first invented in their modern form in 18th century England. English manufacturers maintained a strong position in the world market, such as it was, until the early 20th century. By the time of the First World War, British production had been superseded by the German Empire and the United States, both of which had fostered their domestic capabilities utilizing British technology. After the Second World War, British machine tool makers suffered decades of decline as policymakers focused on other priorities.

Today the United Kingdom is a hub of finance and other high-value services but is largely deindustrialized, with production and consumption of machine tools per capita vastly less than Germany, Japan, or even the United States and China. The UK no longer makes the top ten on any important metric, whether of production or consumption, absolute or per capita.

United States: After building up a strong domestic industry through the 19th century, protected by tariffs and turning a blind eye to intellectual property theft, the US after the Second World War held an extraordinarily dominant position. Numerical control (NC), and then computer numerical control (CNC), were invented in the US in the post-war years at a time when there was substantial state investment in developing advanced technologies in the context of the Cold War. However, with the rise of commercialized CNC machine tools in the 1970s along with relatively open trade with West Germany and Japan, US manufacturers lost market share not only in worldwide export markets but in the domestic market as well. There were not any clear steps taken to specifically undermine US machine tool makers, but there was no interest in supporting them either; in the political climate of the 1980s and 90s, it was politically infeasible to substantially restrict trade with Cold War allies or provide direct aid to struggling US manufacturers.

Despite projections of a possible recovery, US machine tool manufacturing has still not recovered since 1990, and few major players in the world market are US-based.¹¹ As a part of a larger disillusionment with the economic policies of the country, especially since the 2008 crisis and in light of the rise of China, US policymakers and intellectuals have in recent years begun to more deeply question the consensus views on free trade and ostensibly non-interventionist industrial policy. However, the nature of US corporate governance,

10 *World Machine Tool Survey*, Gardner Research, 2016

11 *The post-1990 rebirth of the US machine tool industry: a temporary recovery?*, Kalafsky et al, 2006

intellectual property law, labour representation, public R&D expenditure, and direct subsidies remain mostly unchanged.

Germany: An industrial economy, including machine tool production, was developed under the Kingdom of Prussia and then the unified German Empire in the 19th century. English laws limited sale of machine tools to German manufacturers. However, these were circumvented and through deliberate industrial policy Germany built up a strong domestic industry and overtook British production in the early 1900s. After the setbacks of the intervening decades, post-war West Germany engaged in ambitious reconstruction in an attempt to both rebuild the parts of German industry which had worked so well before the Second World War and to eliminate structural instabilities.¹² The magnitude of West German and then just German economic planning was and continues to be understated due to reliance on US support and, later, exports to the US market. However, the financial system, targeted subsidies, and public research institutes all continue to be leveraged to establish German companies' ability to produce high-value goods for the European and world market.

The re-unification of Germany in 1990, the building up of the European Common Market and then the European Union, and continuing industrial policy have helped Germany remain, alongside Japan, one of the top exporters of machine tools. German policymakers continue to prioritize the country's position in high value-added manufacturing through public R&D expenditure, trade agreements negotiated via the EU, a robust publicly funded education system with a focus on manufacturing, and a bank-based financial system regulated in such a way that long term relationships between banks and companies are incentivized, creating a suitable environment for capital-intensive manufacturing with incremental innovation.¹³ Germany's increasing integration with the rest of Europe includes substantial operations by numerous German machine tool companies in other European countries such as Italy, France, and Poland.

Russia: Tsarist Russia began attempts at industrialization in the late 19th century, working with German and English companies and engineers in attempts to gain the necessary knowledge and technology. In the run-up to the First World War some progress was made but hampered by German advances and political instability. After the Russian Revolution, machine tools were one of the key targets of Soviet planners, and by the Second World War the Soviet Union was able to produce vast quantities of relatively low quality machine tools to support the war effort.¹⁴ Soviet machine tool production continued to rise through the 1970s and eclipsed US production. However, Soviet technology was still backwards relative to that of the US and its allies and Soviet manufacturing techniques were highly inefficient.¹⁵

Within the centrally planned economy of the Soviet Union and with the Iron Curtain preventing Western competition, this inefficiency contributed in its own small way to economic stagnation but did not prevent military demand from propping up a complete industrial supply chain. However, beginning with the perestroika of the 1980s and accelerating with the dissolution of the Soviet Union in 1991, the better and cheaper Western machine tools became available while supply chains within the former Soviet republics were badly disrupted.¹⁶

12 *Currency and Economic Reform: West Germany after World War II*, pg.374-404, Stopler and Roskamp, 1979

13 *Changes in Germany's Bank-Based Financial System: A Varieties of Capitalism Perspective*, Sigurt Vitols, 2004

14 *A Comparison of the US and Soviet Industrial Bases*, Central Intelligence Agency, 1989

15 *From Tsarism to the New Economic Policy: Continuity and Change in the Economy of the USSR*, R.W. Davies, 1990

16 *Disorganization*, Blanchard, Olivier, and Kremer, 1997

Production dropped precipitously across the region and in the Russian core.

Russia continues to see machine tools as essential for its defence industry, but, due to the vastly superior quality of foreign machine tools from the US, Europe, and Japan, defence companies prefer to buy from abroad. In combination with sanctions and the weakness of Russian currency, this is a major impediment to Russia's rearmament plans. The Russian government has invested in R&D, education, and offered indirect subsidies and even tried to ban foreign-made machine tools, all to no avail. With the World Trade Organization limiting the tariffs that can be applied without ramifications and domestic defence companies' unwillingness to use lower quality Russian machine tools, there is no sign that Russia will be able to cut off its dependence on foreign machine tools in the foreseeable future.¹⁷

Japan: The first substantial attempts at establishing a machine tool industry in Japan began after the Meiji Restoration in 1868. Meiji Japan rapidly transitioned from a feudal society to a Westernized industrial one through deliberate replication of Western ideas of governance and methods of industrial production, sending emissaries to many European nations to learn from them. The revitalization of Japanese society enabled them to break the bonds of domination by European powers experienced by many other Asian nations and create a colonial empire of their own. However, by the Second World War Japanese industry was still far behind that of the US and Western Europe. After 1945 the Japanese government was restructured under US occupation and major reforms were made to re-industrialize the country under the leadership of keiretsu, large conglomerates with different units holding significant shares in one another. After the advent of CNC machine tools and with licensing agreements with US companies, Japan began to play a major role in the world machine tools market and overtook first the US and then West German production in the 1980s.

After 1995 Japan experienced a significant slowdown in nominal economic growth that continues to this day. However, improvements in industrial technologies, including CNC machine tools, continued with aggressive expansion into the Chinese market as China liberalized trade and became the largest consumer of machine tools. Japan still maintains relatively closed markets with deeply interlinked companies and financial institutions, along with policies and an economic structure designed to support high-value manufacturing.

China: China under Mao starting in 1949 engaged in a massive technology transfer from the Soviet Union as part of a plan to reinforce the security of the communist world against the threats of the US and its allies.¹⁸ This involved thousands of engineers and technicians traveling between the two countries and the construction of many large factories in China with the aim of overcoming the country's technological backwardness. After the Sino-Soviet split of the 1950s-1960s, China continued modernization policies but faced widespread poverty, production inefficiency, and economic stagnation until, under Deng Xiaoping beginning in 1978, reforms were undertaken to create a "socialist market economy" more open to global trade. This included normalized diplomatic relations with the US in 1979, permanent normal trade relations in 2000, and China's inclusion in the World Trade Organization in 2001.

Chinese machine tool production and manufacturing output has grown exponentially since 1990, with real GDP growing over tenfold by 2015 and machine tool production and consumption rising to the highest in the entire world. After the partial liberalization of the Chinese economy there still remains massive state planning

¹⁷ [The Russian machine tool industry: Prospects for a turnaround?](#), Tomas Malmlöf, 2019

¹⁸ [Technology Transfer from the Soviet Union to the People's Republic of China: 1949-1966](#), Zhang et al, 2006

through state-owned enterprises, public banks, import and export controls, mandated technology transfers for foreign direct investment, currency manipulation, and other broad and targeted policies to support the strategic development of industries.

Taiwan and South Korea: Both former colonial possessions of the Japanese Empire, Taiwan (governed by the ejected leadership of the Republic of China) and South Korea (under a dictatorship backed by the US following the Korean War) rapidly industrialized in the 1950s and 1960s. With pressure, support, and attempts at control by the US, major land reform and export-focused industrial policy were instituted following the Japanese model. These policies were much more successful than nearby attempts in Malaysia and the Philippines, and Taiwan and South Korea were both able to become highly industrialized by the 1990s. Both now export large quantities of machine tools to China and maintain strong industrial policy as well as powerful private conglomerates with deep ties to the state.¹⁹

Brazil: Industrialization began in Brazil in the late 19th century, but significant domestic production of machine tools did not start until the 1930s. Local producers were often immigrants from Europe and copied the design of foreign machines, creating machine tools to serve local needs not well served by imports—especially during the Second World War when machinery from the industrial core was being used for the war effort. The central government did not make significant attempts to facilitate technology transfer and development of machine tools until after 1945, but even then the industrial policy was often contradictory in its aims and inconsistent over time as Brazil experienced various political changes. To the extent to which import restrictions benefitted machine tool producers, it was predominantly for the lower end. Foreign producers of high end machine tools actually benefited from policies in some cases.²⁰

By 1990 the Brazilian machine tool sector had attracted substantial foreign investment but was uncompetitive and had limited technological prowess. After 1990 there was substantial liberalization and reduction in industrial policy, but instead of creating an efficient and competitive industry there was a consolidation of machine tool manufacturers and increased reliance on foreign components. The result is a modern machine tool sector in Brazil that includes some relatively competitive firms, a few of which are domestic but many of which are foreign, and then many uncompetitive domestic companies serving specific niches and small manufacturers that barely manage to subsist. Overall production and R&D expenditure is low and Brazil imports the majority of its machine tools.^{21 22}

Global Dynamics

Concentration of machine tool production has increased substantially since 1990 as multilateral trade, multinational companies, and global value chains have grown in significance.²³ Enormous volumes of machine tools cross borders,²⁴ with China's imports driving much of the entire world's production and the United States

19 [How Asia Works](#), Joe Studwell, 2013

20 [The Brazilian Machine Tool Industry: Patterns of Technological Transfer and the Role of the Government](#), International Development Research Centre, 1982

21 [The development state in Brazil: comparative and historical perspectives](#), Ben Schneider, 2015

22 [The heterogeneity of the machine tool industry in Brazil](#), Guerrero et al, 2017

23 [Examining the Global Machine Tool Industry: Transitions or Continuity?](#) Kalafsky, 2016

24 [World Machine Tool Survey](#), Gardner Research, 2016

importing well over half of the machine tools used domestically. In total, about 40% of machine tools used around the world are imported, with this number being much higher for high performance machine tools.

Control over machine tool production is even more concentrated than geographic location of factories. Many Japanese, German, and Chinese companies will establish plants in other countries, such as Trumpf, based in Germany, with operations in 12 countries including China, the US, France, and Italy. These companies, even if they are legally separated into subsidiaries, cannot be seen as wholly separate from the parent company and the state in which that parent company was founded. As such, some fraction of German “imports”, especially from the rest of the EU, are imports from German companies run by Germans but operating elsewhere, be it for reasons of cost, political advantages with local stakeholders, or lead time for certain components. Similarly, some fraction of Chinese domestic production is in fact run by joint enterprises with foreign multinationals and is not best seen as wholly Chinese, especially as attempts at forced technology transfer are not always successful. Given the international nature of these companies and supply chains, raw statistics on import and export numbers do not give the full picture.

Part of the reason for the current shape of multinationals and global trade is the so-called liberal world order, which is deeply tied to the concept of the industrial core. Every major producer of machine tools with the exception of China is part of what can be termed the American alliance, and without decades of preferential trade with the US, China would not be where it is today. Several countries outside of the core have tried to create domestic machine tool production capacity with little success, for example Brazil²⁵, India²⁶, Iran^{27 28}, and Russia²⁹. In countries that are described as ‘developing’, accumulation of capital to invest in industrial capacity is often a limiting factor and foreign direct investment is leveraged as a way to use capital and know-how from rich countries. However, the track record is poor for foreign direct investment without other substantial actions by the state in enabling machine tool production.

While such investment has sometimes been used as a tool by developing countries, the empirical evidence^{30 31} suggests that in order to build a robust industrial base a state must first establish near-complete sovereignty, self-reliance, and internal coordination, as with China or the Soviet Union, or be allied with a strong power which has done so, as with West Germany, Japan, South Korea, or various Soviet satellite states before 1990. This phenomenon must be explained. We will investigate the causal mechanics in the Analysis section.

25 [The heterogeneity of the machine tool industry in Brazil, Guerrero et al, 2017](#)

26 [Industrial Policy and Performance since 1980: Which Way Now? R Nagaraj, 2003](#)

27 [Iran's Economy: A Survey of Its Decline, Central Intelligence Agency, 1991](#)

28 [Iran: The Struggle for a New Traditional Islamic Economy, Rosser and Rosser, 2018](#)

29 [The Russian machine tool industry: Prospects for a turnaround?, Tomas Malmlöf, 2019](#)

30 [States and economic growth: Capacity and constraints, Johnson and Koyama, 2016](#)

31 [How Asia Works, Joe Studwell, 2013](#)

Analysis

Traditions of Knowledge

A *tradition of knowledge* is a body of knowledge that has been successfully worked on by multiple generations of people.³² After robust machine tool makers were established in England, the successful development of a machine tool industry elsewhere always required importing much of the relevant tradition of knowledge from where they already flourished, as we saw previously in the discussion of national systems. These traditions involve not just technical knowledge of how the machines work, but the whole process of design and production from sourcing of materials to running a factory and developing machine tools with an understanding of their end use. Without these essential concepts and their successful implementation through a transfer of deeply implicit knowledge, only the most crude machine tools can be made without extraordinary expense.

In the post-1990 era, these traditions lie in large part in the hands of private firms. A substantial body of work exists fleshing out the knowledge-based theory of the firm in the strategic management literature, generated primarily by American academics studying business management and administration. This framework conceives of the technical core of a company comprising embedded routines and social structures with tacit knowledge emerging from these complex patterns rather than being encapsulated in the minds of individual skilled engineers or technicians.³³ What this means is that even having experts or being given technical documentation is not necessarily sufficient to reproduce the innovative capacity of a firm that produces, for example, advanced machine tools.

The premise is borne out by the successes and failures of technology transfers ranging from that between the USSR and China to modern corporate mergers and acquisitions. For example, when Chinese plants tried to create Russian industrial products with only blueprints, they tended to fail more frequently than when they copied the entire production process with the help of Russian technicians³⁴, and when management structure is changed in an acquired high tech firm there can be substantial productivity losses even when the same individuals stay on in their same nominal roles³⁵.

Existing as they must within specific social structures and within the context of a national economy, the traditions of knowledge that power machine tool production can be built up or hollowed out by the surrounding conditions. An initial successful push to create endogenous production does not then create an eternal engine that chugs on irrespective of subsequent policy decisions or economic forces, let alone one that creates machine tool of superior quality suitable for export markets. Market forces help keep German and Japanese companies efficient and serving specific customer needs but are not the sole reason why these companies can maintain their strength relative to producers in other nations.

China today showcases the difficulty of transitioning from mass-producing low- to mid-tier machine tools for domestic use to producing cutting edge precision machine tools—the nation is still heavily dependent on

32 *On the Loss and Preservation of Knowledge*, Samo Burja, 2018

33 *A Knowledge-Based Theory of the Firm-The Problem-Solving Perspective*, Nickerson et al, 2004

34 *Technology Transfer from the Soviet Union to the People's Republic of China: 1949-1966*, Zhang et al, 2006

35 *Acquisition Integration and Productivity Losses in the Technical Core: Disruption of Inventors in Acquired Companies*, Paruchuri, 2006

imports from overseas for its most advanced capital equipment. Because much of Chinese consumption is still on the low end and the state is reticent to block the import of capital equipment needed for ambitious growth plans, domestic producers are not well positioned to enter the high-end market. Copying existing technologies also becomes much more difficult on the leading edge and the most innovative products require a different organizational culture and structure to produce.

Russia shows what can happen if the context in which a tradition exists is disrupted: Soviet machine tool production was a powerhouse but it evaporated after the opening of markets; the splintering of the Warsaw Pact led to factories shutting down or being repurposed and workers losing their jobs in the face of superior Western imports.

In the United States as well the traditions of knowledge in machine tool production have decayed, albeit more gradually, since their height in the mid-twentieth century. Today even the expertise required to operate the best machine tools is scarce in the US labour market, limiting efforts by American machine tool producers to partner with their users in developing new tools.

What follows is a discussion of industrial policy and other societal forces affecting the evolution of traditions of knowledge relevant to machine tool production.

Industrial Policies and Structural Factors

The laws, policies, economic structure, and culture in a country are all deeply important in supporting high-end machine tool manufacturing. These will impact the type of companies that exist, the way in which they run their operations, and the way they interact with local and global markets.

Industrial policy can mean many things, from the building of essential infrastructure to minor interventions in the market to systematic planning of vast sectors of a national economy. An examination of the history of machine tool production shows the fingerprints of industrial policy at all times and in all places where machine tool production was pursued as a goal of the state, ranging from simple tariff protection in the US in the 19th century to strong planning in financial markets in post-war West Germany, from export discipline in South Korea in the second half of the 20th century to state ownership, 5-year plans, and vast infusions of capital in present-day China. All of the countries that play a prominent role in global machine tool production have robust systems of industrial policy. However, these policies are not always framed or conceived as such by policymakers and differ significantly in both extent and priorities.³⁶

A perennial criticism of industrial policy is the distortion of market forces, and examples of this in practice are easy to find in both largely successful industrial policy programs, as in Japan or Germany, as well as less successful ones, as in Brazil or Thailand. Often the nature of industrial policy will depend not only on the coordination and competence of the state but on situation-dependent trade-offs, beliefs about the type of planned economic activities that are beneficial, and economic relationships with other countries.

Japan, Germany, and a number of other countries in the industrial core have explicitly or implicitly prioritized high value-added manufacturing for export, through methods such as direct state investment in R&D, public

³⁶ *Development and Industrial Policy in Practice: Issues and Country Experiences*, Jesus Felipe, 2015

education focused on manufacturing, various forms of protectionism, and incentivizing businesses to export high-value goods. China has taken a more heavy-handed approach to industrial policy even post-1990, often directly contradicting WTO rules as opposed to playing around the edges as other countries usually do. US and UK policymakers, on the other hand, have largely attempted to deregulate their economies and have not acted to support domestic manufacturing except in what are seen as essential strategic industries, such as defence. These differences in policy priorities and conceptions of industrial policy are a major determinant of the ability to make machine tools and the continuation of associated traditions of knowledge.

In many countries, an important factor in industrial policy is access to capital. Policies can be designed to encourage domestic capital accumulation or, alternatively, foreign direct investment can be encouraged to bolster growth. However, while countries such as Ireland and China have leveraged foreign direct investment to substantial gain, in countries such as Brazil and Malaysia the effects of foreign direct investment are much more ambiguous. Often in order to encourage foreign investment the state must limit its industrial interventions, and the way foreign companies operate within a developing market does not always create knowledge transfers and local capabilities in the ways that are required to build up advanced manufacturing.³⁷ Thus, investors spend money in a country and economic activity takes place, often resulting in substantial profits, but local traditions of knowledge are not created.

State support of manufacturing can extend into the legal system and economic structure. For example, when the German system was rebuilt after the Second World War it was deliberately structured so as to create a specific type of manufacturing economy, not just through normal economic policy also but through legal requirements for companies and the place of organized labour and community interests in economic decision making. Labour unions remain to this day a powerful force within German corporate governance.

The US system also changed substantially from 1930-1950, but the type of economic activity incentivized within the US was different, with more focus on military technology and certain kinds of radical innovations that allowed for impressive achievements in spaceflight and information technology. Within the US, corporate governance, financial regulation, labour laws, and other structural elements deprioritized manufacturing of goods such as machine tools and withered the traditions of knowledge which supported them while advancing other interests. Machine tool makers gradually became uncompetitive with foreign competition while simultaneously domestic customers, such as the automotive industry, experienced a decline of their own market share to companies based in Europe and East Asia.

In contrast, while the planned economies of Russia and then China were able to create the apparatus of large-scale production of machine tools, the incentives upon producers did not lead to the same efficiency and sophistication seen in leading market economies; traditions of knowledge were created but did not grow in the same ways. The reforms of the Chinese economy have made Chinese producers able to at least improve efficiency and volume of production but the Russian traditions barely exist at all at this point; there is no money to be made as a machine tool maker in modern day Russia operating with dysfunctional institutions and competing with foreign imports.

In conclusion, some important elements for a strong machine tool sector are robust industrial policy, including

³⁷ *The Effects of Foreign Direct Investment on the Host Country's Economic Growth: Theory and Empirical Evidence*, Rosa Forte, 2013

support of upstream and downstream industries; incentives to innovation and efficiency, typically mediated through a market; access to capital, including incentives for allocation to long-term capital-intensive endeavors; and forms of corporate government that are conciliatory to organized labour and incentivize long-term in their planning. Germany and Japan enact all of these and maintain strong production, as do most of the other major producers to varying degrees. Periphery countries often fail at all of the requirements, including countries like Russia which were once much more significant.

China and the US both only partially satisfy the criteria. China has been able to avoid giving power to labour through an authoritarian state willing to crush labour actions but, while it is not clear exactly how centrally planned their economy still is, Chinese producers are still far from the most innovative or efficient. In the United States, industrial policy has been relatively minimal through the period of decline in machine tool production, the extraordinary amount of capital available to invest typically flows to investments with a quicker and higher return, corporate executives are incentivized to think long term, and labour unions as constituted have often had a negative effect on the efficiency of manufacturing firms.

Beyond the clearly delineated factors there is the nebulous world of culture. How much people care about making money over other priorities, how easily people accept strong-handed government action, and how willing people are to sacrifice for some perceived greater good all vary across communities and nations. Industrial policy as practiced in China, or indeed their way of dealing with organized labour or consumer disputes, could not be implemented in Japan, let alone the US. The policy and structural reform that can support a robust advanced manufacturing sector is dependent not just on more tangible factors like levels of national and regional development, geography, and global market conditions, but also by what the stakeholders in the state are willing to accept.

Power Centers

When we discuss power in the production of machine tools, what matters is who controls what machine tools get made, where they can be sold, and where the profits go. Much of this power lies, on the first level of analysis, in the market. Some upstream suppliers have more power through controlling essential technologies for precision machine tools, but overall there are few monopolies or oligopolies in the machine tool market, so decisions of price and access are decentralized. If we set aside the power that is held by individual machine tool makers and suppliers, there remains the more fundamental question of who decides the parameters within which the market is allowed to operate.

In this domain, there are several nexuses of power for a national system: internal state actors, which include legislators, executive agencies, or courts; domestic capital, including public and private banks as well as other investors; and foreign interests, such as investors seeking to engage in direct investment and governments or intergovernmental organizations seeking to affect domestic policy. These actors play a greater role in shaping global machine tool production than any single machine tool producer and often even than all producers combined.

The case of legislative and executive actions within a state or sub-sovereign entity is straightforward. Industrial policy is enacted on this level and structural reforms will typically stem from these levels as well. Coordination

of actors within a state is not a given—in fact, poor coordination is the norm³⁸—but effective coordination as with Germany or Japan in the post-war years or China in recent decades demonstrates that the state can exert economic power far beyond what any private company can do. For example, West Germany was able to direct massive amounts of capital (some from the US-backed Marshall Plan) to developing industrial capacity in the 1950s, and China today can leverage access to its markets for transfers of critical technologies. In some countries, for example the US, courts also play a major role in determining state and international policy.

Financial institutions hold power through their ability to control the flow of capital, determining who gets loans and who gets investment. Banks are always highly regulated by necessity, but they are differently regulated in different jurisdictions, and some states have large amounts of capital under the management of public banks which operate under different incentives than private banks. For example, American investment and commercial banks are all private and are generally not allowed to hold equity in companies to which they also loan money. Germany, on the other hand, has both public and private banks that can simultaneously hold debt and equity with multiple companies across an industry.³⁹

German banks have both the incentive and leeway to influence things like supplier choice, encouraging their debtors to buy from other German companies in which they also have a stake, and generally exerting a sort of soft industrial policy. American banks cannot play this role, and while some American firms do maintain complex ownership structures this does not occur to the same extent as in Germany. Japan and Germany are also considered to be bank-based financial systems in contrast to the more market-based system of the United States and United Kingdom, in which there are more non-bank investors. There is disagreement as to which of these two approaches works better in the long term, and how substantial some differences really are, but it is very clearly the case that the way capital is controlled within a jurisdiction has a major impact on the dynamics of capital intensive industries such as machine tools.⁴⁰

Foreign interests often exert their influence in ways that are quite subtle. When courting foreign direct investment as an infusion of capital and know-how, it is common to find concessions that are offered to investors to incentivize them and a race-to-the-bottom effect can occur.⁴¹ The influence of foreign states can encompass a vast range, and the actions of intergovernmental organizations such as the WTO and EU tends to be an extension of influence from key stakeholder nations. Since 1990, the United States has often used the WTO or its own State Department to lower barriers to entry in many markets, which is good for US businesses and some domestic interests in developing countries but antithetical to many active forms of industrial policy.⁴² Pressures to alter economic policy are one of the mainstays in international relations, and some countries are much less equipped than others to resist these pressures. A well run state will work effectively with leading companies, banks, and foreign powers without being cowed by them; the other power centers are thus extensions of statecraft more so than independent powers unto themselves.

Among the states and other powers that hold sway, there is wide disparity in the coordination within and

38 [Functional Institutions are the Exception](#), Samo Burja, 2018

39 [Should Banks own Equity? A Corporate Finance Perspective](#), Jan Mahrt-Smith, 2000

40 [Bank-Based or Market-Based Financial Systems: Which Is Better](#), Ross Levine, 2000

41 [The Effects of Foreign Direct Investment on the Host Country's Economic Growth: Theory and Empirical Evidence](#), Rosa Forte, 2013

42 [Development and Industrial Policy in Practice: Issues and Country Experiences](#), Jesus Felipe, 2015

between different players as well as the resources they can bring to bear. The global market as a whole exists within a hegemonic liberal world order under the leadership of the United States, but coordination of state, financial, and intergovernmental organizations within this system is quite weak. The United States itself on the national level does not have strong coordination to maintain domestic machine tool production and instead imports from its allies. Other countries with significant production capacity in machine tools maintain that capacity in part due to the ability to coordinate domestic stakeholders in order to maintain favourable conditions that support domestic industry, generally while also maintaining access to both US and Chinese markets. In Western Europe and East Asia a large part of the privileged position held by US allies stems from Cold War policies of containment, to which end US policymakers allowed or actively pushed sound industrial policy within their sphere of influence to counter the threat of Soviet expansion. However, state leadership in these regions still played the largest role in creating the conditions for successful industrial expansion.

Other than China, few countries outside the American sphere of influence have been able to coordinate well enough to develop robust machine tool production that survives liberalization. Foreign direct investment has been a major tool of development and does not tend to support advanced manufacturing in institutionally weak countries. Part of the difficulty can be attributed to the openness of the global machine tool market—most countries can access the machine tools they need without producing them domestically, and so marshalling the political will to create domestic capacity is challenging. Without a strong domestic market, the advanced technological capability required to compete is also difficult to sustain without access to global markets—access which is generally contingent on agreeing to WTO rules limiting the very industrial policies necessary to develop the technology. Countries wishing to forge their own path economically or militarily have strong incentives to build domestic machine tool production, but even in countries such as Russia or Iran where this need is clearly very strong, efforts have yielded very little success.

Conclusion

We began by asking why machine tool production is so concentrated in specific countries, such as Germany and Japan; why former leaders in production such as the UK and US have experienced such decline since 1945; and why some countries, such as China, have successfully spun up massive production while others, such as Brazil, have failed. From an examination of the history of machine tool production it becomes clear that traditions of knowledge must be kindled and kept alight for high-precision machine tool production to be possible.

After the post-war dominance of the United States and then the invention of CNC, deliberate policies designed to support high value-added manufacturing enacted in Japan, Germany, and states within their respective cultural and economic backyards created excellent conditions for machine tool production. Along with a deprioritization of such manufacturing in the US and Britain, this led to a gradual shift in the geography of precision machine tool production over the course of the 1960s-1980s. After 1990 the partial liberalization of the Chinese economy, combined with aggressive and robust industrial policy and central planning, facilitated their rise to numerically eclipse all other countries in machine tool production and consumption. Outside of Western Europe, East Asia, and what remains in North America, there is almost no sign of successful living traditions of knowledge flourishing in the machine tool manufacturing industry.

The dynamics of the machine tool market reveal that individual companies tend not to have very much power in influencing the landscape. Some companies maintain strong positions in key market segments and some suppliers have a stranglehold over certain essential components, but there is no evidence of one single company or even coordinated group of companies deliberately affecting the trajectory of the industry. Instead, the companies that produce machine tools around the world rely upon the conditions that define the market, ranging from local concentrations of talent, capital, and customers to national systems of industrial policy and international trade agreements and governing bodies.

In order to be made efficiently to serve real demand, machine tools require well organized factories and supply chains, close collaboration with leading customers, and state systems that facilitate access to skilled labour, capital, and end markets. In its infancy, machine tool production also requires protection from superior foreign competitors. The failure of many countries to achieve self sufficiency in machine tools stems from an inability to marshal the political will and coordination for long term effective industrial policy. This can indicate a deliberate prioritization of other industries or values, but the case of most countries which have tried and failed to produce machine tools is one of overall poor coordination.

Traditions of knowledge in advanced manufacturing require complex systems of skilled individuals within certain cultural contexts and coordinating hierarchies. These things do not automatically grow and flourish irrespective of the surrounding society but either wither, grow strong, or never sprout at all depending on knowable and mutable conditions. This is essential for making sense of disparities in industrial capacity. Power must be coordinated and well considered policies and economic systems must remain in place to support a national system with advanced industrial capacity.