THE OHIO STATE UNIVERSITY
John Glenn College of Public Affairs
Ohio Manufacturing Institute

The Ohio Manufacturers' ASSOCIATION

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He has partnered with the Ohio Manufacturers' Association for more than 25 years, beginning with a 2001 examination of the importance of productivity and tax policy to Ohio's manufacturing base. He has worked with the OMA and its committees on workforce, energy, manufacturing, and economic development policies. The OMA presented him with its Legacy Award for service to Ohio's manufacturers in 2005 and again in 2016.

Before coming to Ohio State in 2015, Ned was a faculty member at the Levin College of Urban Affairs at Cleveland State University for 30 years. He was Dean of the Levin College from 2007 until 2015 and was named Professor of Economic Development Emeritus by Cleveland State upon his departure in 2015.

Manufacturing's Role In Ohio's Economic Development

I. INTRODUCTION

I am Ned Hill, Professor of Economic Development Emeritus at The Ohio State University's John Glenn College of Public Affairs, where I am affiliated with the Ohio Manufacturing Institute. My research focuses on regional economic development, manufacturing policy, and the industrial evolution of the American economy.

This written testimony draws on three bodies of work. The first is a book in progress, *An Unending Transformation: An Economic History of Ohio Manufacturing,* which I am writing with Dr. Fran Stewart and Bill Shkurti. The second is Ohio Manufacturers' Association's 2025 Manufacturing Counts, a statistical compendium detailing Ohio manufacturing's economic performance. The third is Joel Elvery's 2019 analysis of occupational change in the United States from 1860 to 2015, published by the Federal Reserve Bank of Cleveland.

Two disclosures. First, the historical analysis reflects the current state of my research for *An Unending Transformation* and has not been peer-reviewed. Second, Wyatt Newman, co-founder of RoadPrintz, Inc., discussed at length in Section V, is a close friend. I disclosed this relationship in my oral testimony and do so again here. My testimony does not represent the views of The Ohio Manufacturers' Association, The Ohio State University, or the Ohio Manufacturing Institute.

The argument developed across these sections is this: Ohio's manufacturing economy was built on federal investment in manufacturing knowledge, beginning with Washington's defense-driven armory program, which matured and provided the operations technologies and managerial practices that formed the foundation of what became the American System of Manufacturing. That foundation sustained Ohio's industrial might for more than a century. However, when the product cycle turned against Ohio's core industries in the 1970s, the practices and products that had been a source of strength became a source of economic weakness and social and political rigidity. Ohio lost nearly 733,500 manufacturing jobs from its 1969 peak of 1,411,000 to 2025.[1] Ohio's entrepreneurs are now building the companies of the next manufacturing wave.

II. OHIO MANUFACTURING TODAY: SCALE, STRUCTURE, AND SUPPLY CHAINS

Ohio's economy is best understood not as a manufacturing state or a farm state or a services state, but as a portfolio economy — a diverse mix of goods and services

[1] U.S. Bureau of Labor Statistics, All Employees, Manufacturing [MANEMP], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/MANEMP, May 7, 2026.

produced across eight large regional labor markets and numerous smaller rural communities. Manufacturing's leading position within that portfolio is what makes Ohio's broader prosperity possible. Ohio's manufacturing sector is, by any measure, a dominant force in the state's economy and a significant presence nationally.

As of 2024, manufacturing accounted for $137.9 billion of Ohio's gross domestic product — 16.5 percent of the state's total and more than any other private industry. Real estate and rental and leasing rank second at 11.7 percent; finance and insurance rank third at 11.1 percent. Manufacturing's lead is not marginal; it is structural. Ohio ranked fifth among all states in manufacturing GDP in 2024, trailing California, Texas, Illinois, and Indiana — the last of which edged past Ohio by less than one billion dollars. Ohio's manufacturing GDP has grown from $113.1 billion in 2021 to $137.9 billion in 2024, a 22 percent increase over three years.[2]

In 2025, Ohio had 677,500 manufacturing jobs, down from 687,345 in 2023. I present the 2025 data for Ohio because it is the most recent available for the state. I then use the 2023 data to compare Ohio with other states, as 2023 is the most recent year for which comparative state-level data are available. In 2023, manufacturing jobs accounted for 5.3 percent of all U.S. manufacturing employment. Only California and Texas employ more manufacturing workers, and both states have substantially larger total populations. Manufacturing represents 14.4 percent of Ohio's private-sector employment, second only to health care and social assistance.

The sector generates $49.9 billion in total annual wages — more than any other Ohio industry — and average annual pay of $76,493, well above the statewide private-sector average of $65,536. Average manufacturing pay grew 9.3 percent in 2023 alone. Ohio manufactures and exports $55.8 billion in goods annually to 210 countries and territories, with industrial machinery leading at $9.6 billion, followed by vehicles and parts at $8.6 billion and aircraft and parts at $5.1 billion. Canada and Mexico together account for more than half of Ohio's manufactured exports — a trade relationship whose stability directly affects Ohio manufacturing employment.

The Small Manufacturer

These aggregate figures are important yet incomplete. The feature that most defines Ohio's manufacturing economy is not the size of its anchors but the density of its smaller firms.

Of Ohio's 13,307 manufacturing establishments in 2023, 88 percent employed fewer than 100 workers. Nearly 45 percent — 5,987 establishments — employed fewer than 10. Yet large and small manufacturers are not independent actors; they are linked by supply chains that determine the viability of both. Honda, GE Aerospace, Whirlpool,

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[2] Ohio Manufacturers' Association, 2025 Ohio Manufacturing Counts: The Economic Impact of Ohio Manufacturing (Columbus: OMA, 2025). Data sourced from the U.S. Department of Commerce Bureau of Economic Analysis and U.S. Department of Labor Bureau of Labor Statistics. All statistics in Section II are drawn from this publication unless otherwise noted.

Lincoln Electric, Goodyear, and Cleveland-Cliffs are anchors — but anchors need chains. The fabricated metal shops, precision machining firms, plastics and rubber producers, specialty chemical manufacturers, and component suppliers that populate Ohio's supply chains are the businesses that make the anchors viable.

The employment multiplier in manufacturing is among the highest of any sector. When a large Ohio plant thrives, dozens of smaller suppliers, logistics firms, maintenance providers, and business services firms also thrive alongside it. When a plant closes, those downstream firms feel the impact before unemployment statistics reflect it.

The county-level distribution clarifies this structure. Cuyahoga County leads in absolute manufacturing jobs at 65,418, followed by Hamilton at 49,181 and Franklin at 36,207. However, the counties with the highest manufacturing employment density are not the large urban counties. Shelby County leads with 46.5 percent of all manufacturing jobs, followed by Auglaize at 39.0 percent, Williams at 38.2 percent, and Holmes at 36.8 percent. These are small-county economies whose entire economic character is defined by manufacturing — and whose manufacturers are overwhelmingly small.

III. HOW OHIO GOT HERE: DEFENSE POLICY AS INDUSTRIAL POLICY

Ohio's manufacturing history is long enough to be humbling. The state entered the Union in 1803 as an agricultural frontier. By 1920, it was the nation's fifth-most populous state and among its leading industrial powers. Understanding how that transformation occurred illuminates the conditions under which manufacturing economies develop and the role federal policy plays in shaping them.

The analytical framework my co-authors and I have developed to understand this transformation is the waves-and-bridges model of industrial evolution — presented in Exhibit A at the end of this testimony. Rather than describing industrial history as a sequence of revolutionary ruptures, we describe it as a continuous evolutionary process driven by five distinct forces: operations technology (OT), management practices (MP), military-to-manufacturing transfers (MM), the integration of knowledge with production systems (IK), and the product cycle (PC). Each wave is a period of broad diffusion; each bridge is a transition period when a new capability exists but has not yet been codified into forms that ordinary manufacturers can adopt. Across most waves, the federal government seeds new manufacturing capabilities, and private enterprise then diffuses them.[3]

[3] Edward (Ned) Hill, William Shkurti, and Fran Stewart, *An Unending Transformation: An Economic History*; (manuscript in progress). The waves-and-bridges model of industrial evolution is developed fully in the book’s appendix. Exhibit A of this testimony presents the summary table.

President Washington's Defense and Industrial Policy

In his First Annual Address to Congress on January 8, 1790 — before Ohio had been surveyed for statehood — President Washington explicitly called for the promotion of domestic manufacturing.[4] His argument was not economic; it was military. Writing of "[a] free people," Washington told Congress that "[t]heir safety and interest require that they should promote such manufactories as tend to render them independent of others for essential, particularly military, supplies."

President Washington's first policy proposal to Congress was to build American industry; it was the nation's first industrial policy. A republic dependent on foreign suppliers for its arms could not defend itself. That logic led to the federal armories: Springfield in Massachusetts, established in 1794, and Harpers Ferry in Virginia, established in 1798. Both were military installations, funded by the federal government, and built to arm the republic.

The War of 1812 and Its Consequences

The fragility of that vision was exposed within two decades. During the War of 1812, American forces struggled with weapons of inconsistent quality and supply chains dependent on European imports. The humiliation was completed on the night of August 24, 1814, when British forces marched into Washington and set fire to the Capitol and the White House. The seat of American government burned.

The lesson was unambiguous. The United States could not rely on imported arms, imported technology, or imported manufacturing knowledge. What followed was a systematic federal commitment to developing American production capability — not merely producing weapons, but developing the methods by which weapons could be produced reliably, consistently, and at scale.

At Harpers Ferry, John Hall developed what his contemporaries recognized as an entirely novel system: rigid gauging and fixture design that made parts interchangeable not because a skilled craftsman made them so, but because the system made it impossible for them to be otherwise. The knowledge resided in the gauge, not the machinist. At Springfield, Superintendent Roswell Lee built the management counterpart: systematic cost accounting, systematic inspection, and a hierarchical organizational structure that Alfred D. Chandler, Jr., assessed in his pathbreaking book, *The Visible Hand*, as the most sophisticated management controls in any American industrial establishment before the 1840s.[5] Lee's system tracked objects and products rather than human performance. Two West Point-trained officers completed what Lee had begun: Daniel Tyler prescribed time-based performance norms in 1832; James Ripley enforced them from 1841 onward. These were organizational innovations as

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[4] Washington, G. (1790, January 8). First Annual Address to Congress. Retrieved from The American Presidency Project: https://www.presidency.ucsb.edu/documents/first-annual-address-congress-0

[5] Chandler, A. D., Jr. *The Visible Hand*. (Harvard University Press, 1977), pp. 73-75.

much as technical ones, and their impact on American industry exceeded their military application.

The American System Crosses the Mountains

By 1851, The Times of London had named what American manufacturers demonstrated at the Crystal Palace Exhibition: the American System of Manufactures. What distinguished it from European craft production was the integration of precision tooling, interchangeable components, and systematic management — the convergence of Hall's operations technology and Lee's management practices.

That system crossed the Appalachian Mountains in the heads and hands of mechanics. Their work is visible in the precision-machined components of Whiteley's Champion Reaper in Springfield, Ohio; in the lock mechanisms of Hamilton's safe industry; in John Parker's steam engine castings at the Phoenix Foundry in Ripley; and in Thomas White's sewing machines in Cleveland. These were small manufacturers who applied systematic methods to new products in a new market — the direct ancestors of the small manufacturers this Committee is convened to support.

Each generation built on the one before it. Ohio's machine tool builders — Warner & Swasey in Cleveland, Cincinnati Milling Machine Company, and Lodge & Shipley in Cincinnati — gave Ohio factories the capacity to cut, shape, and stamp steel at scale. When Henry Ford introduced the moving assembly line at Highland Park in 1913, Ohio's machine tool industry was already positioned to supply the precision components mass production demanded. The relationship was not accidental: Ohio's machine tool builders had spent decades developing exactly the production methods that made Ford's system possible.

The breadth of Ohio's industrial base at the dawn of the twentieth century was evident at the founding meeting of the Ohio Manufacturers' Association in November 1910, convened by Colonel J.C. Battelle of Columbus Iron and Steel. The sixteen companies that sent representatives — from Jeffrey Manufacturing's coal-mining machines in Columbus to C & G Cooper's steam engines in Mount Vernon, from Niles Tool Works' heavy railroad machinery in Hamilton to Lodge & Shipley's precision lathes in Cincinnati — spanned the state and the full range of Ohio's industrial economy. In their time, they were the state's manufacturing anchors.

Wilbur Thompson, a colleague and one of the founders of urban economics, distilled the logic of what that industrial base implied into a single sentence: "Tell me your industries, and I'll tell you your future." He could have said it in Ohio in 1910 and been right. He said it in Detroit in 1970 and was right again — with very different consequences.

IV. WHEN THE PRODUCT CYCLE TURNED

The same industrial depth that made Ohio a manufacturing powerhouse for a century also left it vulnerable when the product cycle turned. Understanding that vulnerability — and its specific mechanism — is essential for evaluating current policy options.

Joel Elvery's 2019 analysis of occupational change in the United States from 1860 to 2015, published by the Federal Reserve Bank of Cleveland, provides a precise measure of how manufacturing economies adapt over time. Using the index of dissimilarity to measure the share of workers who would need to change occupational group for the distribution of occupations to match that of ten years prior, Elvery constructed state-level occupational change indexes across 15 decades.[6]

Ohio's pattern is instructive. Across the 15 periods Elvery analyzed, Ohio's occupational change index was in the lowest quartile in six periods and in the second-lowest quartile in five others. Across the entire 155-year span of the study, Ohio's index never reached the top quartile. In 2015, Ohio ranked 47th among the 50 states, with an index of 4.2 percent — meaning fewer than 5 workers in 100 would need to change occupational groups to make Ohio's 2015 occupational distribution match that of 2005. The national average across the study period was 6.8 percent. This is occupational stability quantified.

The stability was not random. It reflected the depth and density of Ohio's manufacturing specialization. A state whose economy is organized around interlocking industrial clusters — steel feeding autos feeding machine tools feeding fabricated metals — develops an occupational structure that is highly stable precisely because the industries are so interdependent. Workers, employers, educational institutions, and communities all specialize. The system becomes, in a word, locked.

In good times, that lock-in is a source of strength. Ohio's industrial clusters generated productivity gains, knowledge spillovers, and supply-chain efficiencies that sustained competitive advantage for decades. But when the product cycle turned — when steel, autos, machine tools, tires, and appliances simultaneously entered the mature and declining phases of their competitive arcs — the same lock-in that had been a source of advantage became a source of rigidity. Ohio lost 789,400 manufacturing jobs between 1969 and 2010, a decline that accelerated in the 1980s and deepened during the China shock of the early 2000s.[7]

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[6] Joel A. Elvery, "Changes in the Occupational Structure of the United States: 1860 to 2015," Economic Commentary 2019-09 (Federal Reserve Bank of Cleveland, June 26, 2019). All occupational change statistics in Section IV are drawn from this source.

[7] 1969 was the year of peak manufacturing employment in Ohio and 2010 was the low point. Manufacturing employment in 2025 was 677,500. U.S. Bureau of Labor Statistics, All Employees, Manufacturing [MANEMP], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/MANEMP, May 7, 2026.

Ohio's highest-ranking occupational change index in Elvery's study — 7.4 percent, ranked 19th in 1990 — reflects not successful adaptation but dislocation. The large shift out of production occupations and into healthcare and management was the labor market's response to plant closings and corporate restructuring, not a planned economic transition.

The communities that housed those workers absorbed the consequences. Former industrial strongholds — Youngstown, whose steel industry collapsed; Akron, which lost its rubber industry; and Dayton, which watched its manufacturing base contract across multiple sectors — experienced population loss, fiscal stress, and erosion of social infrastructure that follow concentrated economic decline. Benjamin Chinitz observed that the industrial composition of a regional economy shapes its capacity for self-renewal for generations.[8] Ohio's experience confirmed this: the regions most dependent on a single dominant industry were the least able to diversify when that industry contracted. Columbus — which built a deliberately diversified portfolio of products and services anchored by Honda's North American headquarters — offers the counterfactual. Portfolio diversity is not a luxury for regional economies; it is a survival condition.

V. OHIO'S NEXT WAVE: FOUR CASE STUDIES

Ohio is not standing still. The same mix of invention, tinkering, entrepreneurial ambition, and manufacturing craft that carried the American System over the Appalachians is now fueling the companies of the next manufacturing wave.

RoadPrintz, Inc. — Cleveland

RoadPrintz was founded in Cleveland in 2017 by Wyatt Newman, a Case Western Reserve University robotics professor, and Sam Bell, a master mechanic who closed his memorably named auto repair shop — the Lusty Wrench — to devote himself full-time to their venture. Their product is an operator-driven, truck-mounted robotic road-marking system: a robotic arm mounted on a Ford F-550 truck, controlled entirely from within the cab, that paints pavement markings — turn arrows, crosswalks, bike lane symbols, legends, and school zone markings — with precision, consistency, and speed that manual stencil crews cannot match, without putting workers on the pavement.

The founding story is a small-manufacturer story. Newman and Bell started with a loaned robot from Motoman, a robotics company based in Dayton, Ohio. Motoman's head of business development listened to their pitch and extended credit to a two-person startup. Heavy fabrication — the steel platform, welding, and truck upfitting — was performed by Q.T. Equipment, a family-owned company in Akron run by the Root family, who also invested in the company and loaned the founders their first truck. The

[8] Chinitz, B. (1961). Contrasts in agglomeration: New York and Pittsburgh. *The American Economic Review*, *51*(2), 279–289.

paint RoadPrintz now uses — AquaTough, a water-cleanup thermoplastic-grade paint — is manufactured by Aexcel in Mentor, Ohio. The Ohio supply chain did not merely support RoadPrintz; it made RoadPrintz possible.

RoadPrintz operates out of an incubator retrofitted within Cleveland's former White Motor Company plant — a massive facility built in the early twentieth century to manufacture trucks at scale. Now, one of its bays houses a digitally integrated robotics company that builds the tools for the next manufacturing wave. The building is a physical embodiment of the argument this testimony makes: each wave of American manufacturing builds on the last, and the next wave is already under construction in Ohio.

Early growth depended on federal grant support. RoadPrintz has received approximately $2 million in competitive grants, including NSF Small Business Innovation Research Phase I and Phase II awards that funded the research and development that produced the current system. NSF SBIR funding was essential to RoadPrintz's early development. The company now has five full-time employees, five awarded patents developed in collaboration with Case Western Reserve University, and paying customers, including the Missouri Department of Transportation and the city of Houston.

The Value Proposition They Didn't Know They Had

RoadPrintz's founders understood their product's advantages in efficiency and precision. What they did not fully appreciate — until a user told them — was the product's true value proposition. A Cleveland public works employee, speaking to the RoadPrintz team after spending a day driving the truck and painting lines, described what it meant in terms simpler, clearer, and more powerful than any market analysis: His wife liked it when he was inside the cab painting instead of walking next to traffic, because she knew he would be coming home that night.

RoadPrintz had built a worker safety device. The inventors learned this from the person who would benefit from the machine on the job.

The Missouri Department of Transportation first engaged RoadPrintz after reading about the company's 2024 ATSSA Technology Innovation Award. MoDOT is a department at the leading edge of adopting technology to advance worker safety — the kind of agency that takes its obligation to send workers home at night seriously. When the RoadPrintz team traveled to St. Louis to work with MoDOT, they encountered workers who had posted a memorial honoring colleagues killed in the line of duty. That memorial made concrete what accident statistics express in the abstract: road marking requires workers to operate in or immediately adjacent to live traffic for extended periods, and accidents and deaths do occur. They are not necessarily the result of inadequate safety practices at any agency; they are inherent in the conventional way roads are stripped. MoDOT was not operating below the industry standard, and today it is operating at the frontier while trying to raise that standard by example.

Economists rely on revealed preference to gauge what people and organizations actually value—not what they say they value—by observing their actions. MoDOT has revealed its preference unambiguously. Soon after losing two team members to traffic-related deaths in the line of duty, MoDOT found RoadPrintz, purchased two trucks at $500,000 each, and is considering a third. A state agency that spends a million dollars on a technology specifically to keep its team members out of live traffic is not making a rhetorical point. It is making an economic one: the value it places on its workers' lives exceeds the cost of the equipment. That is what revealed preference means. No productivity metric captures it, but every purchase decision reflects it.

Path Robotics — Columbus

Path Robotics, headquartered in Columbus, was founded in 2018 by brothers Andy and Alex Lonsberry while they were completing their doctoral work at Case Western Reserve University in Cleveland. The company began in a basement shop at CWRU and gained critical early traction in July 2018 by winning a pitch contest sponsored by MAGNET — the MEP center serving Northeast Ohio — which provided rent-free office space near Cleveland State University and industry connections that helped the company survive its earliest stage. Path relocated to Columbus in 2019, drawn by access to Ohio State University's engineering talent pool, and has since become one of Ohio's most significant advanced manufacturing companies.

The problem and the technical solution

Path Robotics addresses one of American manufacturing's most quantifiable workforce crises: the shortage of skilled welders. The American Welding Society projects a shortage of approximately 400,000 welders — a gap that translates to an estimated $26 billion in unmet manufacturing capacity annually.[9] Path's response is Obsidian™, a proprietary physical AI model trained on millions of inches of real welds that uses advanced vision and machine learning to perceive the weld environment and adapt in real time — without requiring pre-programmed paths or CAD files. Unlike conventional industrial robots, which can only repeat exact programmed sequences, Path's systems handle fit variations, complex joints, and varying materials that make finish welding notoriously resistant to automation. The result is a welding cell that delivers four times the productivity of manual welding at more than 30 percent lower cost, while redeploying skilled welders to the complex work that most requires human craft.

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[9] American Welding Society. (2022). Welding workforce data: Analysis of the 2022-2026 outlook. AWS Foundation; Tasch, J. (2015). Addressing the welding shortage through education and automation. Welding Journal, 94(10), 32–35; and Path Robotics, "Physical AI for Manufacturing: The Welder Shortage Crisis," 2024/2025.

The business model

The company has raised more than $300 million in venture capital, including a $100 million Series D in 2024.[10] Rather than selling capital equipment — a barrier that puts automation out of reach for smaller manufacturers — Path delivers its systems through Path Foundry™, a contract manufacturing model that enables any manufacturer to access autonomous welding capacity without upfront capital expenditure, with production starting in as little as four weeks.

The Washington connection

Path's recent defense contracts directly echo President Washington's original argument. In early 2026, Path signed an agreement with HII — the nation's largest military shipbuilder — to integrate its autonomous welding technology into naval shipbuilding operations. The underlying AI — the vision systems, machine learning models, and software stack — is designed and built in Columbus, Ohio. President Washington argued in 1790 that American security required American manufacturing capability. Path Robotics is building that capability for the twenty-first century.

IC3D — Columbus

Michael Cao spent his engineering career at Honda, contributing to the design of the Acura NSX. His exposure to additive manufacturing there sparked a question he could not shake: why was 3D-printer filament — the consumable every printer requires — still produced mainly for industries with specifications entirely different from his own? No one had made it specifically for precision manufacturing applications. Cao founded IC3D in 2012, starting in his Columbus basement with support from Ohio State University's engineering community. Today, IC3D manufactures production-grade thermoplastic filaments, operates a large-format contract manufacturing service, and builds its own industrial Virago printers — with a print chamber four feet on each side, large enough to enclose a small car. Its customers span automotive, defense, aerospace, utilities, and consumer products: Ford, Goodyear, NASA, Boeing, all three military services, American Electric Power, Procter & Gamble, and Timken, among others. IC3D holds a Department of Defense CAGE code and is a member of America Makes, the national additive manufacturing institute. It is a supply chain company for the next manufacturing wave — producing the materials and providing the production capacity that other manufacturers need to adopt additive manufacturing.

M-7 Technologies — Youngstown

Youngstown, Ohio, is often cited as the poster child for American deindustrialization. When the Campbell Works steel mill closed in 1977, it put 5,000 people out of work,

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[10] Path Robotics. (2024, October). *Path Robotics raises $100M Series D to transform manufacturing with AI-powered robotics* [Press release]. https://www.path-robotics.com/news; Crowe, S. (2024, October 23). Path Robotics secures $100M for autonomous welding expansion. *The Robot Report*.

triggering a cascade throughout the region. [11] Bluestone and Harrison estimated that the closing of Youngstown Sheet & Tube removed "$32 million from the public treasury" and another $34 to $38 million in various unemployment and relief programs over three years.[12] Among the businesses that nearly failed was a bronze foundry started in 1918 by Michael Garvey's grandfather to serve the twenty-three independent steelmakers then operating in the Youngstown area. His grandfather built a prosperous enterprise serving primary metal producers across a 400- to 500-mile radius. Then, in the 1980s, the steel industry collapsed.

Michael Garvey returned from Wall Street in 1985, at age 24, after his father fell critically ill. He inherited an insolvent company.[13] A fire then destroyed the foundry. What remained was a machine shop with three employees. He decided not to rebuild the foundry. Instead, he studied what the machine shop could become.

The transformation began with measurement. Garvey recognized that precision measurement was the foundation of any effective machine shop — an insight that, across a century and a half, echoes the quality-control gauges John Hall had developed at Harpers Ferry. Even when the company could barely afford them, Garvey invested in digital measurement technologies and built that capability into a business model centered on extending the service life of precision parts for industrial customers. It took ten years to turn the company around.

Today, Garvey operates three interconnected companies. M-7 Technologies is a manufacturing engineering research company specializing in portable coordinate measurement and in-situ measurement technology. Grale Technologies provides digital measurement services. Center Street Technologies operates one of the world's largest 3D printers — large enough to park a pickup truck inside — using additive manufacturing technology developed by Strangpresse, another Youngstown company. The printer builds components to micron-level tolerances for aerospace and defense customers and is supported by America Makes, the national additive manufacturing institute headquartered in Youngstown and funded in part by the federal government as a Manufacturing USA institute. M-7 has grown from three employees to fifty, with revenue increasing by approximately 18 percent annually over 35 years.

Garvey memorably describes the enterprise as a place where the Flintstones meet the Jetsons. The first object he printed in the world's largest 3D printer was a bridge — a deliberate choice. His company had evolved from a family foundry serving steel mills to

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[11] Buss, T. F. and Redburn, F. S. *Shutdown at Youngstown: Public Policy for Mass Unemployment.* Albany: State University of New York Press, 1983.

[12] Bluestone, B. & Harrison, B. The Deindustrialization of America. New York: Basic Books, 1982., p. 75.
[13] MAGNET: Manufacturing Advocacy and Growth Network. (2021, April 14). M-7 Technologies: Transforming a family foundry into a digital pioneer. https://www.manufacturesuccess.org/success-stories/m-7-technologies

a digital manufacturing enterprise building precision components for aerospace customers. The bridge connected where Youngstown had been to where it was going.

The transformation did not happen in isolation. MAGNET — the Manufacturing Extension Partnership center serving Northeast Ohio — provided technical assistance, industry connections, and access to collaborative networks that Garvey credits as essential to navigating Industry 4.0. M-7's story is, in part, a story of what the MEP can do when it works — and what is at risk when it does not. Garvey draws a broader lesson from his own transformation: "Manufacturing is not a solo sport." Collaborations with MAGNET, research organizations, and other manufacturers opened doors to expertise no small company could have assembled alone. His advice to other small manufacturers facing the Industry 4.0 transition is direct: "We have everything here except the ambition. We create the ambition, then we're off to the races."

Ohio is now home to three of the country's most significant industrial additive manufacturing facilities: Center Street Technologies in Youngstown, whose printer is large enough to park a pickup truck inside; IC3D in Columbus, whose Virago printers measure four feet on each side; and GE Aerospace's Additive Technology Center in West Chester — near Cincinnati — which operates nearly 90 metal printers, including six of the largest in the world, producing parts for the GE9X, the world's largest jet engine. President Washington's vision of American manufacturing independence has found a twenty-first-century expression in Ohio. Together, RoadPrintz, Path Robotics, IC3D, and M-7 Technologies illustrate the breadth of Ohio's next manufacturing wave. RoadPrintz is a startup that built a digital production system that removes workers from the most dangerous exposure in their occupation. Path Robotics is a venture-backed company deploying AI to address a critical workforce gap. IC3D is a former Honda engineer's basement idea that became a Department of Defense-certified supplier of additive manufacturing materials and equipment. M-7 is a century-old family business that reinvented itself through digital technology and is now competing for aerospace and defense contracts from Youngstown. All four were built on Ohio's research capacity and Ohio roots. All four depended on federally funded services at critical stages. All four are competing in the national markets.

VI. INDUSTRIAL EVOLUTION AND OHIO'S NEXT WAVE

The diffusion of advanced manufacturing technology follows competitive demand and technological necessity. Consider two five-axis CNC machines operating in Ohio just before the Great Recession — arguably the most precise computer-controlled machine tools then available. One was at GE's jet engine facility in Evandale, producing blisks — bladed turbine disks whose complex aerodynamic geometries cannot be machined any other way. The other was in Holmes County, in the heart of Ohio's Amish and Mennonite furniture country, where Gerber Wood Products in Kidron operates five-axis CNC routers to carve ergonomically contoured seat blanks for smaller chair assemblers across the country — producing at volumes and tolerances no craftsman with a scorp and a travisher could match at competitive prices. GE needed five-axis capability to solve a physics problem. The Holmes County shop needed it to solve an economic one. Both followed competitive demand to the same machine. Jet engines and chair seats. That is how technology diffuses in a manufacturing economy.

The Five Disruptive Forces

The research behind *An Unending Transformation* identifies five independent variables — disruptive forces — that drive industrial evolution: operations technology (OT), management practices (MP), military-to-manufacturing transfers (MM), information and knowledge integration (IK), and the product cycle (PC), listed in order of cumulative historical impact. MM and IK run throughout the testimony's historical account — Washington's armories are an MM story; Hall's gauging system is an IK story. The analysis below focuses on the two forces most directly relevant to current policy: the relationship between operations technology (OT) and management practices (MP), and then the product cycle.

These forces interact, and that interaction is the central finding of the research. OT acting alone — new technology adopted without the management practices needed to deploy it — produces a productivity decline before any gain. This is the Productivity J-Curve, and it appears in every wave transition in the historical record. Springfield Armory's real cost per weapon spiked to $113.57 in 1840 as Warner reorganized production for the new model musket — a cost increase that preceded the savings interchangeable production eventually delivered.[14] More than 170 years later, nearly two-thirds of surveyed manufacturers reported limited results from Industry 4.0 investments in 2016, not because the technology failed but because the management practices needed to deploy it had not yet been codified.[15] The pattern is the same: OT arrives; performance falls before it rises. Those cost spikes and productivity shortfalls are not evidence of failure. They are the predictable costs of reorganizing production around a system that has not yet matured.

The J-curve occurs because technology arrives before it has been codified — the process that makes a technology both productive and teachable — and before managerial methods exist to deploy it at scale. New operations technologies also follow a cost-decline curve as they mature: as demand grows and production scales, the technology travels down its cost curve and managerial codification catches up. Bridge

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[14] Deyrup, F. J. *Arms Makers of the Connecticut Valley*. (Northampton, MA: Smith College Studies in History, Volume XXXIII, 1948).

[15] Breunig, M., Kelly, R., Mathis, R., & Wee, D. Industry 4.0 after the Initial Hype: Where Manufacturers Are Finding Value and How They Can Best Capture It (McKinsey Digital, 2016). The survey engaged 300 industry experts in Germany, the United States, and Japan in January 2016. Among manufacturers specifically, 63 percent reported no or only limited progress in implementing Industry 4.0 applications.

5.5 — the current transition to AI-enabled production systems — is repeating the same experiment.[16]

The product cycle operates differently from the other four forces. Its primary effect is on the geographic distribution of production within an industrial era — or wave — rather than on the pace or character of production itself. When Ohio's steel, auto, rubber, and machine-tool industries simultaneously entered late maturity at Bridge 4.5's arrival in the late 1960s and 1970s, the product cycle's redistribution mechanism was already in motion. The state lost 733,500 manufacturing jobs from its 1969 peak because four dominant industries reached the same bridge at the same time in late maturity.[17] The structural advantages that had made Ohio a manufacturing powerhouse in Wave 3.0 became economic, social, and political rigidities at Bridge 4.5. That is the Devil's Bargain.[18]

Five Mechanisms that Close Bridges

The research also identifies five mechanisms by which bridges close, moving industries and economic regions from one wave to the next. Through these mechanisms, competitive pressure and deliberate action drive codification, which in turn closes bridges. Bridge length depends on how well and how quickly these mechanisms operate.

The first is the practitioner-innovator: someone who encodes what a new technology can do and how to integrate it into production in a teachable, replicable form. Hall encoded the gauging principle into a system that any trained mechanic could operate or adapt to produce at scale. Taylor codified scientific management in written procedures and training systems. Ohno codified lean production into a teachable production system. Without this work, tacit knowledge remains tacit, and the bridge never ends.

The second is the training and extension network: a mechanism that widely diffuses codified practices, reaching manufacturers who cannot develop them on their own. Springfield Armory operated as a public demonstration site from 1830 until the Civil War — open to private manufacturers, sharing castings and machinery designs, and training mechanics who then carried the American System westward into Ohio. The Manufacturing Extension Partnership and the Cooperative Extension Service are the contemporary equivalents—MEP primarily deploys operations technology and shop-floor practices, and the Cooperative Extension Service deploys operations technology, management practices, and knowledge integration across the full agricultural enterprise—both solving the same diffusion problem with the same logic. MAGNET, the

[16] McElheran, K., Yang, M., Kroff, Z., and Brynjolfsson, E. (2025, April 20). The rise of industrial AI in America: Microfoundations of the productivity J-curve(s). SSRN-5036270

[17] U.S. Bureau of Labor Statistics, All Employees, Manufacturing [MANEMP], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/MANEMP, May 7, 2026.

[18] The Devil's Bargain and Its Aftermath: Industrial Evolution and the Future of American Manufacturing is a working paper from the research I am conducting with my colleagues on industrial evolution.

MEP center serving Northeast Ohio, provided the connection that launched Path Robotics from a CWRU basement in 2018 and the technical assistance that rebuilt M-7 Technologies from a three-person machine shop into a digital manufacturer competing for aerospace and defense contracts. These are not anecdotes. They are the mechanism of bridge closure operating in the present wave.

The third is patient capital: funding that sustains codification until it achieves commercial viability. No private manufacturer had the capital or patience to fund the twenty-four years between Hall's proof of concept in 1825 and Buckland's achievement of production-level interchangeability in 1849–50. The Ordnance Department provided that patience. The approximately $2 million in NSF SBIR funding that supported RoadPrintz produced a five-person company with five patents, paying customers in multiple states, and a product that keeps workers alive — a manufacturing enterprise that early-stage private capital would not have seeded at the time of the investment.

The fourth is the procurement mandate: the mechanism that converts voluntary adoption into required standards, transforming a practitioner-innovator's system into a public standard adopted by an entire network of manufacturers. The Ordnance Department required private arms contractors to adopt armory gauging standards as a condition of contract. That requirement converted Hall's innovation from an experiment at Harpers Ferry into the American System of Manufacturing.

The fifth is the practitioner fellowship: the network through which tacit knowledge flows between firms — the reciprocal exchange of operational knowledge among practitioners who share a generalized production practice. Pratt and Whitney, Brown and Sharpe, and the Connecticut Valley machine tool cluster operated under an open-door norm: demonstrate competence on the shop floor, and you receive a tour and a conversation in return. IC3D participates in America Makes on the same principle. The fellowship is how the last mile before codification happens — the knowledge that cannot be written in a manual but can be shown on the shop floor.

The open-door norm of the Connecticut River Valley — no intellectual property barriers, no non-compete agreements restricting practitioners' movement between firms — transformed individual practitioner-innovators into a regional cluster advantage. What economists now call a thick labor market or an open knowledge network was being built by the Superintendents at Springfield and the officers of the Ordnance Department, without a theory to describe it: a dense concentration of specialized practitioners exchanging knowledge freely, with the Armory operating as a publicly funded test kitchen open to private observation. That structure is what Enrico Moretti documented in Silicon Valley's thick labor markets and what AnnaLee Saxenian identified in Silicon Valley's open network culture — in contrast to Route 128's closed, hierarchical firms, which ultimately lost the competition.[19] The anchor institution seeds the cluster. The

[19] Moretti, E. (2012). *The New Geography of Jobs*. Houghton Mifflin Harcourt and Saxenian, A. (1994). *Regional Advantage: Culture and Competition in Silicon Valley and Route 128*. Harvard University Press.

cluster generates the spillovers. Where knowledge flows freely among practitioners, bridges close faster. Where it is locked behind intellectual property restrictions and non-compete agreements, tacit knowledge stays tacit, and the bridge extends.

Ohio's Position in Bridge 5.5

Ohio enters Bridge 5.5 with real assets and real vulnerabilities. On the asset side: the Honda-anchored lean supply base spanning the state's auto supplier network; the precision manufacturing heritage evident in GE Aerospace's Additive Technology Center in West Chester, Center Street Technologies in Youngstown, and IC3D in Columbus; the university research capacity at Ohio State, Case Western Reserve, and the state's engineering colleges; and a practitioner network that has been building Wave 6.0 capability from the ground up.

On the vulnerability side: 88 percent of Ohio's 13,307 manufacturing establishments employ fewer than 100 workers. These small manufacturers face the same Bridge 5.5 transition that large manufacturers navigate with engineering staff and capital budgets that small firms lack. The Productivity J-Curve is real for them: adopting new OT without codified management practices to deploy it produces cost spikes and productivity dips before the system matures. The question is whether the five mechanisms of bridge closure are operating effectively enough to close the bridge before the product cycle completes its redistribution of Ohio's current industrial base.

The case studies in Section V illustrate how bridge closure mechanisms work. RoadPrintz is a practitioner-innovator story: Newman and Bell encoded operator-driven robotic road marking into a system that any trained road crew member can learn in minutes. Path Robotics is a training-and-extension story that began with an MEP center's bet on two doctoral students and is now enabling AI-enabled welding through Path Foundry, making it accessible to any manufacturer without upfront capital expenditure. IC3D is a patient-capital and fellowship story: a Honda engineer who saw a production problem built a solution in his basement with support from Ohio State University and its engineering network, and grew it into a Department of Defense-certified supply chain company through the America Makes network. M-7 is a fellowship story: Garvey's account of M-7's rejuvenation is that manufacturing is not a solo sport — the collaborative networks he accessed were as essential as the technology investments. MEP provided technical expertise, as did a grassroots peer network that local manufacturing leaders formed when they realized they would not be rescued from the Statehouse in Columbus or the corridors of Washington, D.C. The Mahoning Valley Manufacturers Coalition knew that help would arrive only if they could figure out how best to use external resources and contribute their time and effort.

The historical pattern holds across 260 years of Ohio manufacturing. The federal government seeds new manufacturing capabilities. Entrepreneurs and engineers codify and diffuse them. Workers build them into competitive products. Their descendants are forging the future.

VII. CONCLUSION

President Washington's armories did not merely produce weapons. They produced the Springfield Armory, and with it, the Connecticut River Valley knowledge cluster that became the seedbed of the American System of Manufacturing. The mechanics, machinists, and superintendents who moved through that Armory formed what economists now call a thick labor market: a dense concentration of specialized practitioners who exchanged knowledge across firm boundaries, without intellectual property walls or non-compete agreements, with the Armory operating as a publicly funded test kitchen open to private observation. The federal government did not build that economy. It built the anchor institution that made economic development possible. The returns flowed outward — to the cluster, to the region, to the nation — in ways no appropriations ledger could have anticipated.

The mechanism is not unique to mid-1800s Springfield. It is what Enrico Moretti documented in Silicon Valley's thick labor markets and what AnnaLee Saxenian identified in Silicon Valley's open network culture—in contrast to Route 128's closed, hierarchical firms, which ultimately lost the competition. The anchor institution seeds the cluster. The cluster generates spillovers. Low-barrier access to knowledge—the open-door norm of the Connecticut Valley machine shops, the America Makes fellowship, the MEP center's shop floor—is not a policy preference. It is the structural condition under which the mechanism works.

Ohio received that system in the heads and hands of mechanics, built it into machine tool industries, steel mills, rubber plants, and automobile suppliers, and sustained a middle class for generations of Ohio workers. When the product cycle turned, the costs were real and concentrated. Ohio's communities bore them.

Ohio is now building the next cluster. RoadPrintz, Path Robotics, IC3D, and M-7 Technologies are not isolated success stories. They are the current expression of a mechanism the historical record has confirmed over 260 years: the anchor institution seeds the conditions; entrepreneurs, engineers, and workers build the economy.

President Washington's return on his armory investment extended beyond the Ordnance Department's ledger. It was the American System of Manufacturing, which laid the industrial foundation of the republic. Ohio's manufacturers built on that foundation for more than a century. Their descendants are still building on it.

EXHIBIT A

Waves and Bridges of Industrial Evolution in the United States: A Summary

From: Hill, Stewart, and Shkurti, An Unending Transformation (manuscript in progress).

Wave or Bridge	Period	Primary Forces & Defining Change
Pre-industrial Mills and Workshops	To 1790	Water-powered mills and craft workshops. Knowledge is tacit; markets are primarily local.
WAVE 1.0 — Industrial Revolution	**1760s–1850s**	**Water and steam power (OT)**
Bridge 1.5a — Armories Bridge	1810s–1850s	Interchangeable parts, precision tooling, quality control (OT, MM, IK)
Bridge 1.5b — Civil War Bridge	1861–1865	Management of large organizations (MM, MP)
WAVE 2.0 — American System of Manufactures	**1850s–1910s**	**Electricity, railroads, steel, the corporation (OT, MP, MM)**
Bridge 2.5 — Scientific Management Bridge	1890s–1913	Codification of production knowledge; time-and-motion study (MP)
WAVE 3.0 — Mass Production	**1913–1960s**	**Assembly line; internal combustion engine; mass consumer markets (OT, MP)**
Bridge 3.5 — Chandler's Bridge	1920s–1970s	Divisional organization; scale and scope economies; WWII organizational surge (MP, MM)
WAVE 4.0 — Programmable Automation	**1969–1990s**	**Programmable logic controllers; mainframe computing and early ERP (OT, IK)**
Bridge 4.5 — Lean Management Bridge	1990s–2010	Toyota Production System codified and diffused; quality management (MP, IK)
WAVE 5.0 — Digital OT Integration	**2000s–ongoing**	**Internet-connected shop-floor systems; commoditized PLCs; robotics (OT, IK)**
Bridge 5.5 — Industry 4.0 Crisis Bridge	2010s–ongoing	Digital OT not harmonized with management practices; Tower of Babel problem (OT without MP)
WAVE 6.0 — AI-Enabled Lean Production	**On the horizon**	**AI as integration layer fusing OT and IK; NextLean management practices (OT, IK, MP converging)**

Wave rows (white with bold lettering) are periods of broad industrial diffusion. Bridge rows (gray) are transition periods when new capabilities are available but management practices for deploying them at scale have not yet been codified. Forces: OT — Operations Technology; MP — Management Practices; MM — Military-to-Manufacturing Transfer; IK — Information and Knowledge Integration; PC — Product Cycle (allocates manufacturing activities across regional economic markets).