Balancing Automation and Human Expertise: An Analysis of the Toyota Production System

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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1. Introduction

Automation has been central to the manufacturing industry, enabling companies to increase efficiency and grow their operations. Since the Industrial Revolution, mass production has been a popular approach, relying on economies of scale to drive down costs. The introduction of the moving assembly line by Henry Ford revolutionized the automotive industry by significantly reducing production time, allowing manufacturers to produce vehicles at rapid rates. Today's factories have increasingly adopted robotics and computer-controlled systems to further enhance productivity. However, while these advancements improve efficiency, they also introduce challenges related to flexibility, workforce adaptation, and knowledge retention. Additionally, a mass production approach can have significant disadvantages, particularly in economic downturns when insufficient customer demand results in unsold inventory and financial losses. In contrast, the Toyota Production System (TPS) introduced an entirely different approach that focuses on small batch production and the absolute elimination of waste.

A defining moment in Toyota's history came during the global 1973 oil crisis, which caused severe disruptions to global markets ("Oil Embargo", n.d.). Rising fuel costs and economic instability left many manufacturers struggling with a decline in demand for their products and were left with surplus inventory. By 1974, Japan had reached a period of zero economic growth, yet Toyota had greater earnings from 1975 to 1977 than any of its manufacturing competitors (Ohno, 1988). This success is attributed to their production system that emerged following World War II. Toyota's performance following the oil crisis garnered attention throughout the industry and raised questions about the limitations of mass production.

Toyota's approach was initially recognized for its cost-saving strategies and production efficiency. However, a less recognized strength of TPS is its ability to preserve human expertise even as automation has expanded. This insight is especially relevant today as modern manufacturing faces growing concerns about the loss of institutional knowledge. The mass retirement of baby boomers threatens to take with it decades of tacit knowledge formed through hands-on-experience (Burmeister & Deller, 2016). At the same time, the rapid development of AI-driven technologies raises the question of how companies can embrace automation without losing the human ingenuity that has sustained their operations.

I analyze TPS through the framework of Actor-Network Theory (ANT) to explore how it balances automation with the retention of human knowledge. ANT, developed by Bruno Latour, Michel Callon, and John Law, examines how human and non-human actors form interdependent networks to achieve specific outcomes (Cressman, 2009). Through this framework, I examine how Toyota reinforces strong network relationships between human workers, automated systems, and business principles to preserve expertise. My methodology for this analysis is a literature review primarily drawing on Taiichi Ohno's firsthand accounts of developing TPS and academic studies on the production strategies. By studying TPS through this lens, I show how companies can design automation systems that balance productivity, long-term growth, and knowledge retention.

2. Historical Context of the Toyota Production System

TPS first emerged out of financial necessity. In the wake of World War II, Japan's economy was in crisis, and Toyota faced intense pressure to survive in a market dominated by American manufacturers. On the day of Japan's surrender from the war, Toyota president

Kiichiro Toyoda challenged his company to catch up to U.S. automakers within 3 years or risk the collapse of the Japanese automotive industry. American giants like Ford and General Motors had capital-intensive mass production models that delivered high volumes of a limited range of car models, outproducing Japanese automakers at an estimated rate of 9:1 (Ohno, 1988). Lacking the financial resources to replicate this model, Toyota needed an alternative path forward.

Compounding Toyota's challenge was the broader devastation Japan faced after the war. The country had lost an estimated 2.6 to 3.1 million lives and over 56 billion USD in damages (Shiohara, 2023). Raw material shortages and damaged facilities further restricted production capabilities for manufacturers ("Occupation and Reconstruction", n.d.), and a struggling domestic market left Toyota on the verge of bankruptcy by 1949. A year later, a major labor dispute led to employee layoffs, wage cuts, and the resignation of Kiichiro Toyoda himself ("Labor Disputes", n.d.). In response, company leadership struck a compromise with the labor union that included a commitment to long-term and stable employment for the remaining workers, setting the stage for a new approach to managing production (Ohno, 1988).

The outbreak of the Korean War in 1950 offered a crucial opportunity for recovery. As Japan became the principal supply base for UN forces, the U.S. relied heavily on its manufacturing sector to produce equipment for the war effort ("Economy of Japan", 2025). Unable to hire more workers, Toyota instead had to increase efficiency. This surge in demand provided Toyota with much-needed revenue and helped ease its raw material shortages. The company used this momentum to reshape in its operations, but leadership recognized that wartime contracts were not a permanent solution. Realizing the need for long-term efficiency and self-reliance, Toyota sought out new approaches to sustain their operations.

It was in this environment that Taiichi Ohno, who joined Toyota Motor Company as a shop floor supervisor and would later rise to executive, was tasked with rethinking the company's manufacturing approach. As an assembly manager in the early 1950s, he introduced a series of improvements that would evolve into TPS. At the time, Toyota could not afford to replicate the large-scale mass production methods of American firms, which required significant investment into new machinery, larger volumes of raw materials, and additional storage infrastructure. Without economies of scale to drive down costs, Ohno turned his attention inward, examining every stage of the production process for ways to eliminate waste. Instead of producing in bulk, he proposed only building what was needed when it was needed, thus minimizing excess inventory and related costs. Over time, TPS evolved into what is now widely known as lean manufacturing, a framework that has since been adapted in industries beyond manufacturing.

3. The Toyota Production System: Philosophy, Principles, and Practices

TPS was developed under Taiichi Ohno to address Toyota's unique manufacturing constraints. While its core principles have remained, TPS has continued to adapt to new technologies, markets, and organizational needs. In ANT terms, TPS can be viewed as a network composed of human actors, like employees and customers, and non-human actors, such as production systems and operational philosophies. This section focuses on the key elements of TPS that are most relevant to this analysis and are still in practice today: the foundational pillars of Just-in-Time (JIT) production and Jidoka, the supporting philosophy of Kaizen, and operational tools including Andon, Kanban, and standardized work procedures (Toyota, 2024).

3.1 Just-in-Time (JIT) Production

JIT functions as a non-human actor in the TPS network by regulating the production flow between human and machine actors. JIT refers to producing only what is needed, when it is needed, and in the exact quantity required. This system eliminates waste associated with overproduction, such as capital tied up in inventory, excess storage, and the depreciation of unsold goods. Ohno also observed that high inventory levels allowed defective products to accumulate unnoticed, leading to larger downstream issues. Instead of stockpiling, JIT maintains a continuous, responsive flow of parts that aligns directly with demand. This concept was inspired by Ohno's observation of American supermarkets, where shelves are restocked based on what customers actually purchase. He envisioned each production stage as a customer, pulling only the necessary parts from the previous stage. This pull-based system reversed conventional manufacturing logic by allowing downstream processes to dictate what, when, and how much to produce. As a result, Toyota could remain highly adaptable to shifting customer demand. However, achieving this responsiveness required new organizational strategies.

3.2 Jidoka: Automation with a Human Touch

In the network, Jidoka acts as a non-human actor that provides machinery the agency to interrupt production. Jidoka translates to "smart automation", the practice of embedding human judgment into machines to enhance worker capabilities. Toyota equipped its machinery with mechanisms that could detect abnormalities and stop production automatically. When a problem occurred, workers were alerted and could intervene immediately to investigate and address the root cause. Ohno drew inspiration from an automatic loom developed at Toyoda Spinning and Weaving, which halted operation when a thread broke, preventing defective fabric from being woven. Applying this principle to the assembly line freed workers from having to constantly supervise machinery. They could instead monitor multiple machines and focus on quality oversight and continuous problem-solving, also enriching their role on the production floor.

3.3 Kaizen: The Philosophy of Continuous Improvement

Kaizen, a non-human actor, engages all human actors in continuous feedback and network recalibration. Kaizen, Toyota's philosophy, is the belief that employees at all levels should regularly seek opportunities to improve their processes. Rather than relying on top-down direction, Toyota encourages bottom-up innovation. Factory workers, not just managers, are expected to observe inefficiencies and propose refinements. During TPS's early development, Ohno worked closely with operators on the floor, making small, continuous changes to improve performance. This included reconfiguring factory layouts so machines performing sequential tasks were placed closer together, allowing a more efficient flow of production. Employees were trained in multiple skills so they could oversee various machines and contribute more holistically to system improvements. This collaborative, evolving environment helped embed practical knowledge directly into the system, rather than relying on any single worker's memory or experience.

3.4 Procedures in TPS

TPS operational tools like Andon, Kanban, and standardized work procedures function as non-human actors that coordinate actions, signal disruptions, and provide stability across the network. Andon is a visual alert system that signals when a production issue occurs. When a problem is detected by a machine or a worker, a light is activated to call attention to the issue.

Workers are empowered to pull the Andon cord to stop production if necessary. By doing so, they reinforce Toyota's proactive approach to quality control and ensure problems are addressed immediately. Andon enhances Jidoka by making disruptions visible and encouraging rapid, team-based intervention. The continuous response to problems allows TPS to be adaptable to changing circumstances.

Kanban is a scheduling tool that supports JIT by regulating inventory and production flow through simple visual cues. Each production stage operates based on Kanban cards from the next stage, which specify what to produce, in what quantity, and by when. If no Kanban is received, production pauses, which prevents unnecessary output. This keeps workflows tightly aligned with demand and eliminates ambiguity around production expectations.

Standardized Worksheets document the exact procedures for workers to complete. As TPS developed, Ohno tasked experienced floor employees with documenting their most efficient work procedures. These sheets outlined step-by-step instructions, target cycle times, and required inventory to complete specific tasks. By following these procedures, all workers could maintain consistency, reduce unnecessary actions, and benchmark their efficiency. However, these standards were not static, as Toyota encouraged workers to challenge and revise them if better methods emerged. In this way, the worksheets served not only as training tools but also documented collective worker expertise. This increased worker efficiency and ensured productivity levels would not suffer if an experienced worker left their role.

4. External Perspectives on TPS

TPS has attracted widespread attention from academics and industry professionals, generating varied interpretations of its effectiveness and limitations. Some point to Toyota's internal business philosophies as the keys to its success, while others focus on the challenges other organizations have faced in trying to replicate TPS outside its original context.

4.1 Toyota's Commitment to Quality

One major reason cited behind Toyota's long-term success is its commitment to satisfying customer needs through high-quality products and adaptable manufacturing. Unlike many mass production models that prioritized output volume and cost efficiency, Toyota focused on designing systems that could respond flexibly to customer preferences and eliminate waste in the process. Michael Ballé (2018) argues that TPS is fundamentally "a concrete theory about how to satisfy customers so that they remain customers," emphasizing that production should meet individual needs rather than forcing consumers to conform to standardized products. This focus helped Toyota distinguish itself in an industry that largely emphasized scale over personalization.

Toyota's quality-first approach proved highly effective. By embedding quality control into every stage of production and empowering workers to stop the line at the first sign of defects, Toyota minimized errors and earned consumer trust. Between 1970 and 1980, Japanese automakers increased their share of the U.S. passenger car market from roughly 3% to 20%, with Toyota playing a significant role in that expansion (Winston & Train, 2007). The company's strong performance during the 1973 oil crisis gained national attention, and its production philosophies were soon adopted by other Japanese manufacturers. This helped Japanese automakers provide vehicles that were higher in quality and lower in cost than many of their American counterparts (Brawner et al., 2022). By focusing on the needs of customers rather than maximizing throughput, Toyota reinforced its competitive edge while redefining standards across the industry.

4.2 Toyota's Scientific Method

A four-year Harvard Business Review study of over 40 manufacturing plants across the U.S., Europe, and Japan sought to understand why TPS was successful for Toyota but remained difficult to replicate. The researchers concluded that Toyota operates as a "community of scientists," where structured problem-solving and experimentation occur at every level of the organization (Spear & Bowen, 1999). They argue that while outsiders often view Toyota's standardized procedures as rigid and inflexible, the specifications actually create the foundation for adaptability. Each process is designed to signal problems immediately and trigger an investigation which enables continuous improvement to their processes.

Jeffrey Liker and James Morgan (2006) also discuss how employees engage in a rigorous problem-solving process of analyzing the current state, testing proposed improvements, and adapting based on the results. This iterative process encourages dynamic learning and avoids the inefficiencies of trial-and-error experimentation. Crucially, it embeds operational knowledge into the system itself, reducing dependence on individual workers and ensuring continuity even as workers change. As a result, efforts to copy TPS by adopting surface-level tools without embracing this underlying culture of inquiry and adaptation are unlikely to succeed. Liker (2020) further builds on this point, arguing that Toyota's long-term success comes not from isolated tools, but from deeply ingrained management principles that foster respect, learning, and adaptability throughout the organization.

4.3 Challenges in Replicating TPS

Despite Toyota's success, TPS has proven difficult to replicate for some, in part because of early misconceptions about its origins and effectiveness. Japan's competitiveness in Western car markets following the 1970s was often misattributed to various factors. Many believed Japan's success was driven by favorable exchange rates, luck, advanced technology, or Japanese labor laws, rather than their manufacturing system (Holweg, 2007). This perspective led companies to overlook the systemic innovations underlying TPS and delayed serious study or adoption of its principles outside of Japan. Some perspectives argue that Toyota's success is rooted in Japanese cultural traits, like collectivism or the "survival work culture" that emerged in the post-war economic struggles (Nakane & Hall, 2002). However, Steven Spear and H. Kent Bowen (1999) dismiss these perspectives as it does not explain why other Japanese manufacturers like Nissan and Honda have not achieved the same level of performance or why Toyota has been able to implement TPS in its international locations.

A more compelling argument is that TPS is difficult to implement because it is not a set of static tools but a deeply ingrained philosophy. Many manufacturers have attempted to adopt Toyota's techniques without embracing its broader culture of continuous improvement. Toyota itself does not consider tools like Kanban or Andon to be fundamental elements of TPS, but rather as temporary means to achieve their core objectives. The failure to recognize TPS as a dynamic and evolving system, rather than a rigid set of procedures, is a key reason why many attempts to replicate it fall short.

There are some philosophies underlying TPS, however, that may challenge traditional manufacturing approaches. For instance, TPS requires worker autonomy and problem-solving responsibility, as employees are responsible for continuously seeking improvement to their processes with Kaizen. Toyota’s culture is also one that is tolerant of failure, treats employees as knowledge workers accumulating wisdom rather than just a pair of hands, and utilizes a defined hierarchy that encourages employee pushback (Takeuchi et al., 2008). However, in companies where workers are treated primarily as laborers completing pre-defined tasks, this level of engagement would be difficult to achieve.

4.4 Supply Chain Vulnerabilities

Another criticism of TPS is its reliance on low inventory stock, which increases vulnerability to supply chain disruptions. The 2011 Tohoku earthquake and tsunami revealed this weakness, as Toyota’s JIT model left it heavily dependent on a seamless flow of parts. The company struggled to secure critical components, highlighting the risks of operating with small part stocks. Following the disaster, Toyota adapted by diversifying suppliers, mapping its supply chain in greater detail, and maintaining increased reserves of essential components. However, another earthquake in 2016 showed that Toyota still struggled to recover as quickly as competitors like Honda and Nissan (Webb, 2016).

Though companies are powerless against disruptions like natural disasters, the company was intent to learn from them to build resilience. The lessons learned from these disasters, such as closer supplier relationships, flexibility in product design to switch out parts, and targeted stockpiling of important components, helped Toyota to mitigate the semiconductor shortage caused by COVID-19 (Leonard, 2021). The adaptability built into the production system also enabled their French operations to quickly switch to producing hybrid vehicles when they were unable to source the required parts for combustion engines. Similarly, Toyota's real-time inventory tracking and adaptive production planning enabled by Kanban allowed them to navigate disruptions in the Panama Canal more effectively than competitors ("Testing TPS Resilience", 2022). These adjustments highlight buffer room within the JIT approach and demonstrate that lean manufacturing can have resilience when risk mitigation measures are in place.

5. Applying Actor-Network Theory to TPS

The ANT framework states that social and technological outcomes emerge from interactions between heterogeneous actors. Actors are either human or non-human, and their identities are shaped by their relationships within a network. Actors do not exist in isolation and can be viewed as networks within themselves. Crucially, a network organizer constructs, stabilizes, and maintains relationships among other actors within a network to meet their shared objectives (Cressman, 2009). As TPS is not just a collection of manufacturing techniques, but a carefully refined socio-technical system that integrates human knowledge with automated processes, this framework provides valuable insight into Toyota's success. Previous analyses of TPS often examine specific tools or principles or focus on the contribution to manufacturing efficiency. However, these perspectives may overlook the role of actor relationships in sustaining human expertise. By applying ANT, this section investigates how Toyota maintains productivity while embedding worker knowledge within its automation strategies.

ANT dictates that actors can be both human and non-human, and that actors all have agency within a network. To understand TPS as a system, these actors must first be identified. Human actors can be broken down into production line workers, production managers, executive and corporate employees, and Toyota's customers. Non-human actors can be broken down into the two core business pillars (JIT and Jidoka), defined procedures (Kanban, Andon, standard worksheets), organizational structures (company hierarchy, production line modularity), and underlying philosophies (Kaizen, Respect for People, absolute waste elimination).

For TPS to function effectively, its human and non-human actors must be aligned. ANT highlights how Toyota achieves this balance, ensuring continuous production improvements without disrupting knowledge retention. TPS operates as a self-reinforcing network where actors mutually sustain each other. Machines have agency as they stop automatically when defects are found (Jidoka), which enrolls workers to investigate, refine processes, and apply their expertise. Workers are not passive actors within the system as they possess the agency to influence the network through problem-solving and feedback. Workers are driven by financial incentives with job security, personal fulfillment in producing a good product, and recognition for their work. Workers will contribute to the network but may resist changes that would threaten job security, which draw in the actors of upper management and business philosophies.

Managers want to maintain profitability and operational efficiency, which relies on both machines and human workers. Production managers facilitate problem-solving and update procedures (standardized worksheets) based on feedback from the production floor, embedding worker expertise into written guidelines. This flow ensures human insight is hardwired into the system and allows new hires to seamlessly integrate into the workflow and develop their own knowledge. If workers identify a flaw in the process or a new opportunity for improvement, the feedback cycle will propagate changes throughout the process. The system is constantly recalibrating itself as human and non-human actors influence each other. By structuring automation to enhance rather than replace human input, Toyota prevents production from becoming overly dependent on individual expertise or specific machinery while still benefiting from collective human knowledge.

During his development of TPS, Taiichi Ohno acted as the principal network organizer, coordinating the relationships between human workers, automated systems, and organizational goals. However, with Ohno's retirement in 1978, the organizing role transitioned to a non-human actor in the network: the Respect for People philosophy. This respect extends towards customers with a deep commitment to producing high-quality, defect-free products that meet diverse and changing needs. This necessitates the continual flexibility and evolution of TPS itself, ensuring the production network remains resilient, adaptable, and knowledge-preserving even as expectations shift. Crucially, this respect extends to employees, by embedding stability, trust, and continuous development into the network's structure.

The Respect for People philosophy is central to stabilizing Toyota's production network. This philosophy was reinforced after the 1950 labor dispute, when Toyota committed to stable employment and long-term workforce development. This is also reflected by how managers delegate responsibility to floor employees, encouraging innovation and problem-solving rather than strictly following commands. Unlike the overspecialized, repetitive tasks that Ohno observed in American factories, Toyota workers gain skills across production processes. This structure is supported by executives who prioritize workforce stability over short-term cost-cutting. The Kaizen philosophy further stabilizes the network by ensuring that workers continuously refine procedures. Employees do not passively follow TPS principles or utilize its tools but actively contribute to shaping them. This approach reinforces institutional knowledge retention, as improvements made by experienced employees become embedded within the evolving system. Toyota's focus on employment stability and structured yet adaptable processes prevents the knowledge loss that can occur in environments with high employee turnover. It also provides the reassurance to employees that they will remain crucial to the network, even as they improve the processes and machinery around them.

Applying ANT to TPS reveals that Toyota's automation strategies succeed not just in terms of efficiency but in preserving human expertise through well-structured networks. TPS is a network of interdependent actors, where human workers, automated processes, and organizational structures continuously reinforce and stabilize one another. A key insight from this analysis is that Toyota maintains knowledge stability through active network reinforcement and a continuous feedback loop that keeps the system adaptable. Toyota ensures that tacit expertise is consistently captured, shared, and applied in daily operations. This approach prevents reliance on individual skills and instead creates a system where expertise is naturally sustained through workflow processes and automation. Toyota's production network remains dynamic not only because employees continuously refine internal processes, but also because evolving customer expectations consistently pressure the system to adapt. In this way, Respect for People ensures that both internal and external actors contribute to the ongoing recalibration and resilience of the TPS network.

Companies seeking to implement TPS must focus on stabilizing and nurturing actor relationships rather than simply adopting tools like Kanban or JIT. Toyota's approach demonstrates that successful automation in manufacturing requires careful alignment of actors. ANT highlights that Toyota's network is not static but continuously evolving, with each actor adapting to maintain overall system efficiency and knowledge retention.

6. Conclusion and Lessons for the Future of Manufacturing Automation

The Toyota Production System offers a compelling model for integrating automation into manufacturing while preserving human knowledge. Unlike traditional mass production approaches that prioritize standardization at the expense of worker adaptability, TPS is an interdependent system where humans and machines complement and reinforce one another. By analyzing TPS through the lens of Actor-Network Theory, I argue that Toyota’s success stems from the careful alignment and continuous recalibration of its production network. These insights provide valuable lessons for the future of automation in manufacturing.

A key takeaway is that automation should enhance human capabilities rather than replace them. Toyota’s use of Jidoka ensures that machines identify defects, but it is human workers who investigate causes and implement solutions. This structure challenges the assumption that automation and efficiency must come at the cost of human engagement. As advancements in Artificial Intelligence and robotics continue, maintaining meaningful human roles within production networks will become even more critical.

Toyota’s strategies also offer a model for mitigating the loss of tacit knowledge associated with an aging workforce and employee turnover. As experienced workers retire, industries risk losing decades of knowledge and intuitive problem-solving abilities that are difficult to document and transfer. By embedding expertise into standardized procedures, fostering continuous improvement through Kaizen, and promoting long-term employment stability, Toyota ensures that operational knowledge is preserved and adapted over time. These practices highlight the importance of organizational structures that respect and cultivate employee insight at every level.

More broadly, this analysis reveals that successful automation requires stable and adaptive networks, not just the adoption of technical tools. Toyota's model shows that the resilience of a production system depends on nurturing relationships among human, technological, and philosophical actors. Companies that recognize automation as a socio-technical process, rather than purely technical, will be better positioned to build manufacturing systems that are efficient, adaptable, and sustainable in the long run.

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