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Chapter 1: Intelligent manufacturing and the shift toward fully autonomous factory systems

1.1. Introduction

Intelligent manufacturing (IM) is a disruptively novel production paradigm that derives from Industry 4.0. This paradigm shift in the way industrial manufacturing is undertaken is now encompassing the whole manufacturing supply chain. Autonomous factories will then be able to manage themselves upon only high-level goals defined and reassessed by humans, who will be responsible for strategic decision-making. Factories will endeavor to maximize their efficiency and product quality while minimizing environmental and social impact. Intelligent manufacturing involves the latest advances in digital automation, cognitive computing, data science, and information technologies, as they become available in the form of products and services for use in the manufacturing sector (Barari et al., 2021; Guo et al., 2021; ElMaraghy & ElMaraghy, 2022).

The concept of IM is now at the confluence of digitalization and intelligence, the former primarily encompassing advances in Digital Data Transfers, Industrial Internet of Things, Cyber and Internet Security, Cloud and Edge Computing, Digital Twins, Digital Simulation, and Digital Design, while the latter mainly refers to advances in Cognitive Computing, Autonomous Machine Learning, Autonomous Robotics, Artificial Intelligence, and Machine-to-Machine Communication. While digitalization in general, and data access and sharing in particular, are critical enablers of IM, they do not guarantee intelligent manufacturing by themselves. This is because making manufacturing intelligent supposes advancing upon the industries' ability to manage data productively or favorably, whereby product manufacturing systems can be faced with their growing complexity and the dynamics and time-varying nature of their operations, as well as taking advantage of their actual flexibility in adopting alternative operational modes (Haghnegahdar et al., 2022; Hughes et al., 2022).

1.2. Historical Context of Manufacturing Evolution

Manufacturing, in one form or another, is as ancient as human civilization itself. In fact, the almost universal shift from nomadic hunter-gatherer societies to settled agricultural societies likely constitutes the very first clear break from truly artisanal creation of food and crafts. The earliest factory-like systems followed closely on the heels of agriculture. Clay, used thousands of years ago for creating bricks and pottery, was limited by the relatively long time needed to cure each piece before it could be moved from the manufacturing site and used. The invention of the kiln, which enabled very rapid heating and cooling cycles increasing the rate at which pottery and bricks could be manufactured, essentially created the first true factories. Formicians engaging in co-operative labor could create tremendously larger amounts of useful items than any number of individuals working independently.

Fig 1 : Historical Context of Manufacturing Evolution

The earliest really efficient factories were labor intensive, as the cost of energy was enormous compared to the cost of labor. The invention of the steam engine, followed by various types of power-driven pumps and locomotive systems, allowed water, electrical and mechanical energy to replace labor in some parts of production lines performing some operations. The introduction of the assembly line for the mass production of automobiles revolutionized the use of these machines for mass production. The principle of factory systems previously developed for mass production of various goods relied on assembly line principles. Mass production methods require large quantities of basically identical input materials processed with almost no variation into identical output products. Over the last century, automation has rapidly expanded to traditional discrete processes such as automotive welding and painting, and to continuous operations as well, including the moving of whole components as well as bulk materials and liquids. The regulated factory system has thus evolved into a sort of hybrid system, incorporating large-scale factory automation, with skilled workers performing only those tasks of assembly, inspection, maintenance and repair still beyond the capabilities of today’s machines.

1.3. Key Technologies in Intelligent Manufacturing

Smart manufacturing technologies enable a factory to use data-driven decision-making and maximize automation, therefore reducing costs, increasing speed and efficiency, and improving the quality of manufactured products. Various Industry 4.0 technologies can be utilized to support automation and real-time data-driven decision-making in smart factories and create economically viable, flexible, efficient, and intelligent factory systems. The following discussion outlines some of the key technologies in intelligent manufacturing.

Artificial intelligence and machine learning methods enable new opportunities for factory operations by changing paradigms in traditional manufacturing methods. Operational decisions can be made through training of models using the data being generated in various stages of factory operations. Intelligent algorithms can be developed to conduct functions such as manufacturing process optimization, feed forward and feedback control of manufacturing processes, and product quality inspection and prediction. AI and ML approaches allow tracking of acceptable limits for product quality and dynamically changing settings for manufacturing machines when product quality starts to drift outside the defined boundaries. Reduction of factory operation cycles through intelligent scheduling of machine systems is continuing to receive a large amount of research attention. AI-enabled robotics and machine vision systems are continuously showing increased capability to adapt to dynamically changing work environments without the need for hand coding every possibility.

1.3.1. Internet of Things (IoT)

Devices in modern-day factories are often interconnected through various IoT technologies and comprise a part of the Factory of Things. These devices allow easy collection, monitoring, transmission, and sharing of data through communication interactions. Various IoT technologies can be incorporated into embedded computer systems for sensors, actuators, robotics, feedback for process control systems, and analytics for decision-making. These data can then be used for advanced analytics and machine learning applications. Within smart factories, IoT technologies are not only used to connect devices and sensors, but also to enhance flexibility through plug-and-play-enabled factory resources.

1.3.2. Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) is a field of computer science that provides machines, systems, and computers with the ability to perform tasks that typically require human intelligence. These tasks include visual perception, speech recognition, decision-making, and translation, among others. AI has progressed tremendously from the early days of rule-based systems, especially with more recent methods such as deep learning and reinforcement learning. AI is at the core of Intelligent Manufacturing since it allows intelligent systems to support decision-making and totally or partially automate tasks in the manufacturing environment. The term "Machine Learning" (ML) is frequently, but not always, used interchangeably with AI, as ML is a subset of AI that enables the machines to learn and adapt based on data and previous experiences.

AI and ML technologies comprise a vast range of algorithms and advanced technologies that can enhance various functions in design, manufacturing, management, and supply chain management by automating, improving, and/or augmenting human capabilities. For example, AI and ML algorithms are widely used in predictive maintenance, design optimization, defect detection, demand forecasting, production planning, scheduling, and logistics. Other practical applications include advanced driver assistance systems, self-driving vehicles, and smart factories' digital twins. An explanation of some prominent combinations of AI and ML technologies used in Intelligent Manufacturing is given in the following. Deep Learning (DL) implements neural networks with multiple layers of nonlinear transformations of input data. DL overcomes the limitations of previous generations of neural networks and can offer unmatched accuracy for some problems, given an abundance of labeled data of the appropriate kind. Supervised Learning (SL) relies on a labeled set of data to model a relationship between input variables and the ground-truth label and then use the model to predict the label of unseen data.

1.3.3. Internet of Things (IoT)

This section aims to elucidate the technology called Internet of Things (IoT) and its role in intelligent manufacturing. The Internet of Things (IoT) refers to the connection of numerous devices via the internet. IoT techniques define a novel technology that uncovers completely new ways of manufacturing as well as managing manufacturing and service processes. Connected via sensors, devices employed on the shop floor, such as machines, products, and tools allow the collection of information over the internet and the control and monitoring from remote locations in real-time. IoT is a key enabler of both industry 4.0 and smart manufacturing. For many years, the manufacturing sector has made use of automation to reduce wasteful practices and increase efficiency. Manufacturing automation has developed over the years to cover automatic processes involving entire factories, automatons which could execute many tasks, including more complicated ones, nanotechnology-based machines, and IoT-based technologies, which enable an integration of complicated processes requiring complex monitoring and control. As advances in IoT technologies make manufacturing automation even more capable than before, we move towards autonomous factories that are dynamic, self-operating, and self-controlling systems.

Companies are turning to automation and sophisticated technology solutions to reduce costs, streamline operations, and function with less manpower. Intelligent logistic support systems, visualization of logistic systems through the ambient intelligence concept, including digital workplaces and smart worker assistance systems, massively distributed, collaborative, embodied agents, agreements and decision-support languages, fusion of shop floor data, and theory of constraints-based production control and optimization have been proposed as solutions with the potential to create a completely-autonomous enterprise. In this paper, we propose a different approach that incorporates intelligent automation and IoT. Intelligent automation based on advanced software, IoT, and collaborative robots can provide the core around which fully-autonomous factories could be built.

1.3.4. Robotics and Automation

Robotic technology has come to play a fundamental role in every aspect of the traditional factory. Now that the era of digital manufacturing is here, it is only natural for the automated systems used for the material- and information-flows to evolve and become even smarter. Conventional factory automation technologies developed in the past have primarily served to handle the flow of materials through repetitive tasks that are hot, dirty, or dangerous, but are well-enough defined, such as machining, assembly, transfer, welding, and more. In more recent years, newcomers to the scene, such as additive manufacturing, collaborative robots, smart conveyors, and sensor-guided autonomous mobile robots have expanded the role of automation systems. Integrated factories have traditionally operated by using pre-planned schedules based on forecasts of production demands to direct the flow of materials. Newer factories are being designed to be capable of adjusting to deviations in actual production versus plan, and in the near future, we will see factories that employ fully autonomous systems.

Integrated autonomous systems are on the path of becoming the Next Generation of Smart Factory. We will see new techniques being developed to maintain the Continuous Fitness of factory resources and proactively mitigate factory performance shortcomings. We will see visual guides generated by an intelligent design system, extending our palette of assembly processes – combining wisdom of craftsmen, human intelligence, and machine dexterity on the shop floor. Realizing such smart factories applies factory design and control innovations in areas such as modularized factory designs, options-routing scheduling and autonomous control of resource allocation, and a new toolbox of risk-management-based, performance trade-off analytics, demand management, forecast overload, enable the numerical optimization layers that boost the capabilities of filtering technologies used in hardware such as RFID, sensors, and vision systems.

1.3.5. Big Data and Analytics

Modern factories typically produce vast amounts of data, with a growing number of connected smart sensors and trackers placed throughout the machines in the shop floor, the products manufactured, and the devices used for production. Manufacturing data has a variety of forms: it can be structured or unstructured, collected in real-time or batch mode, or produced from a single source or multiple sources. The four Vs of big data, that is, volume, velocity, variety, and veracity, make it hard for legacy IT systems to support the management of this data, which is at times so big that it makes you feel anxious about its "bigness" – this is how revolutional the so-called 5th V of big data might be for the future of factories! Traditional business models that require data analysts to transform data into valuable information before it can be deployed for driving business decision-making are inefficient in such a digital environment.

Thus, intelligent manufacturing seeks to leverage the power of data analytics, which enables automation of decision-making thanks to real-time availability of actionable intelligence through all layers of the smart factory. Increasingly advanced applied data science tools are being developed externally to address the data management needs of manufacturing companies. Cloud-based systems provide an efficient option for companies that do not want to deploy expensive enterprise solutions to their overloaded IT departments and run the risk of developing white elephants. Companies enable internal development of data management systems less expensive than enterprise solutions by providing their data analysts with readily available tools that allow fast transformations of data into information or by utilizing smaller tools that plug into enterprise solutions.

1.4. Benefits of Intelligent Manufacturing

The development and adoption of intelligent manufacturing systems will provide several distinct benefits that are different from those anticipated from the adoption of discrete task automation systems. Several of these benefits, in fact, directly stem from the fundamental differences between task automation systems and intelligent manufacturing systems. To enable an orderly discussion of the benefits of intelligent manufacturing, we divide the benefits into four general areas: Increased Efficiency; Cost Reduction; Enhanced Quality Control; and Sustainability and Environmental Impact.

The traditional approach to deliveries is based on large production runs and therefore incurs in obsolescence costs associated with excess inventory. Automation does not reduce these costs. Intelligent manufacturing systems will be able to respond quickly and cost efficiently to consumer demand changes by increasing or decreasing production levels, depending on demand changes, thus minimizing obsolescence costs. In addition, these same intelligent manufacturing systems will have the capability of dynamically adjusting production levels in response to current consumer demand levels, especially for lower volume consumer products. Increased production and delivery efficiency will not only decrease demand-side costs from obsolescence, but will also significantly reduce the overhead costs of marketing and distribution. Even more importantly, it can speed up new product introduction to production, cutting time to market.

1.4.1. Increased Efficiency

The goal of every designing and engineering team when building a factory is to have increased efficiency by maximizing production line output. A smarter factory means that all factory systems work together, making intelligent decisions and continuously working toward maximizing the high-level plan. Today, a factory is not only a physical system but also requires complex information systems. All elements on both the physical and information levels of the factory need to work together to meet operational and market goals. As production becomes ever more flexible, different intelligent subsystems will need to dynamically merge and cooperate. At the same time, factories are moving toward lights-out manufacturing models where increased nighttime production at reduced cost is achieved by not needing operators present on the floor. Increased automation makes the need for intelligence and cooperation among subsystems even more critical.

Increased efficiency is achieved through greater automation of work and increased uptime for production systems. Factory automation is not a new area of research. For a long time, research in this area has focused on specific building-block technologies such as robotics, vision systems, mechanical designs for automated assembly, control algorithms, increased communication capabilities, and more recently, networked systems. All of these advancements have moved factories toward increased automation and focus on the factory floor to increase efficiency. However, systems design and optimization for the factory as a complex integrated system has remained a fertile area and critical area for continued research. But as factories evolve from complex engineered systems to intelligent systems, more work at the systems level will be needed.

1.4.2. Cost Reduction

Considerable cost reduction is an anticipated benefit of intelligent manufacturing. Enhancements of manufacturing intelligence made possible through improved lifecycle tracking and associated intelligent agents in intelligent mechatronic products are expected to streamline multiple work processes in design and fast changing production environments. Applications of AI agents to production environment changes are typically associated with product and process utilization improvements. Increases of product and process utilization directly drive down cost structure, leading to potential reductions of product prices to gain market share or market share expansion through technologically superior products.

Research focusing on intelligent manufacturing emphasizes workforce utilization effectiveness as an important means to reduce or absorb cost overheads associated with training personnel to implement intelligent automation in factories. Other researchers highlight the contribution to cost reduction implied in improvements of mass customization capabilities offered by intelligent manufacturing technologies focusing on minimizing or eliminating transition costs. In contrast, other models assume an appropriately designed intelligent manufacturing environment implemented across traditional organizational and management boundaries such as shared or joint responsibilities for product life cycle effects on cost structure with customers or end users for higher system or service level performance.

Applications of intelligent products for intelligence enhancement of intelligent manufacturing systems is expected to not only capture product and process faults on a proactive basis, but also provide in situ fault resolution or remote assisted and enabled fault resolution options. Capturing product and process usage data through embedded sensors and associated data networks further supports the precognition of product and process faults towards enabling a smooth transition from preventive to predictive maintenance operations. Intelligent prediction of product and process failure modes utilizes and enhances economies of scales realized by larger data bases built from usage data across similar products and processes.

1.4.3. Enhanced Quality Control

To ensure quality assurance, the manufacturer must confirm the product's operational parameters against a known set of guidelines that it conforms to within acceptable limits. If not done effectively, the ongoing costs of scrap, decreased purchases, and the loss of trust from clients can destroy a business with devastating ripple effects throughout the host economy. The rapid advent of technology means that software and hardware systems can support far enhanced verification systems as they mature within intelligent factories. The digitization of standard operating procedures and acceptance criteria means that quality procedures can be monitored far more closely than ever before. This means that not only can equally capable checks be performed each time a product is inspected, but all previous results can be stored and rapid comparative analysis done for each different product at every instant of time. In addition, the standards can be updated through a pre-connected network to improve the identification of specific production problems.

The availability of low-cost computing resources permits these analyses to be done on increasingly large pools of data, permitting extensive data treatments that improve the sensitivity of the identification process. In addition, systems based on different technologies can be used in conjunction to cross-check results. The investments already made into implementing sensor networks by many manufacturers allow product attributes to be checked at many locations from the start to finish of their processing. The addition of digital twins to the process will greatly improve the quality control task by allowing the behavior at every position in the digital twin to be checked against expected outcomes realistic to the quality of the product expected. By integrating these additional attributes based on digital twins, hypersensitivity can be achieved, especially by senior manufacturers who are regarded as the quality leaders within their sector. The use of additional attributes will also permit new quality attributes to be verified, improving the total quality of production results and diminishing the number of times that work is totally rejected.

1.4.4. Sustainability and Environmental Impact

Sustainability continues to be a major goal of much of the business and societal ecosystem. Gone are the days when companies only focused on profitability. Returning to shareholders is still crucial, but so too is being good corporate citizens. Achieving sustainability by decreasing emissions and reducing waste is how companies become better corporate citizens and foster loyalty from the buying public who wish to see more ethically aware business practices. The shift toward intelligent factories can contribute toward sustainability more so than through traditional efforts. While building something front of mind that is more durable or has less embodied energy per unit is valuable from a sustainability and environmental impact stance, it is however very one-dimensional. Intelligent manufacturing has the chance to have a much wider footprint, and this effect can occur at multiple levels. Efficacy and efficiency improvements at manufacturing companies can lead to more sustainable products, from being manufactured using less energy and fewer emissions to having longer operational lifetimes with less impact from servicing and consuming electricity, gas, or water. Intelligent systems can also help with the last step in the product lifecycle: recycling and repurposing products and materials. More intelligent products can call home to service providers and tell them when they are about to be replaced, diminishing the uncertainty around collecting used products. More data on the lifecycle of products can also help reduce the uncertainty surrounding second sourcing of materials. Another major difference is that intelligent factories can operate on a much bigger scale than traditional sustainability programs can. By digitally connecting factories to transportation and logistics systems, emissions can be reduced significantly. Intelligent factories can share resources such as energy, storage space, and additive manufacturing capabilities throughout production networks, leading to major reductions in manufacturing circularity.

1.5. Challenges in Implementing Intelligent Manufacturing

Realizing the vision of intelligent manufacturing poses technical and business challenges that are fundamental to the supporting and intervening factors we outlined earlier. Adoption of intelligent systems aligned with principles on factory autonomy may be hindered by low perceived business value and high initial investment, technology, and data-related concerns, especially if they require replacement of legacy equipment or overhauling of existing systems. Intelligent manufacturing may also require significant investment in workforce training, particularly if there is a need to upskill current workers to operate complex algorithms or systems or there are limited skills or experience accessible within the factory.

High Initial Investment

Intelligent manufacturing represents a fundamental shift in how factories operate and change the current factory paradigm. Investment into advanced sensors, communication networks, and data analytics systems are significant. Consumer products that are built using augmented reality principles may also need significant investment. Unless there is a clear and present recognition by factory management of the return on investment, especially in the short-run, the use of intelligent systems in factories may face prolonged setbacks.

Skills Gap and Workforce Training

The increasing complexity of intelligent systems, along with their growing integration across the factory ecosystem, introduces obstacles that go beyond the pure technological domain. New capable workers are required who have the capacity to both operate and make happen. There is currently also capacity shortage, especially of engineering and computer science degree programs capable of training the next generation of factory workers. Demand for graduates with skillsets relevant to intelligent manufacturing are forecast to exceed supply.

Data Security and Privacy Concerns

The promising capabilities of intelligent manufacturing will only be achieved within a trusted supply chain ecosystem. Intelligent systems must address issues of unfair advantages or inappropriate actions related to private data, data sharing and trading, security, and surveillance. Factories are currently grappling with lessons learned from recent cyber attacks and security breaches, leading to reluctance in exposing their operation systems and data to intelligent systems.

Integration with Legacy Systems

A further complication in addressing the concerns surrounding intelligent manufacturing is the presence of legacy systems that operate along the factory value chain. Data are typically collected and managed without considerations for cybersecurity, privacy, or ownership, resulting in companies perceiving low accessibility to their data and low accountability for the quality or accuracy of data that have been gathered. Concerns also exist around storage and computing, including cloud-based solutions that face latency problems, data hoarding in silos, lack of enterprise-wide standards for cloud solution development, and machine learning analytics that make it difficult to explain their decisions.

1.5.1. High Initial Investment

One of the frequently highlighted challenges and concerns in the literature related to intelligent manufacturing is that of the scale of initial investment to enable this transition. The implementation of sophisticated data-driven manufacturing capabilities often requires a deep structural change, which might be particularly demanding for small organisations. However, the full benefits of intelligent manufacturing only accrue after this initial implementation phase, which may take different prevalent timescales, ranging from short-term operational improvements to ensure competitiveness on a tight turnaround to long-term investments that allow for significantly increased operational capabilities. Improvements in manufacturing performance typically occur throughout the entire automation life-cycle and must be monitored throughout the entire life-cycle of the intelligent automation solution. While fully autonomous factories might not make sense for every size segment, vertical segment or in every region of the world, leading edge early adopters may be ready to engage in substantial investments, or to explore co-investment and co-operation options with technology suppliers and/or real industry partners, as well as venture capitalists and innovation funding programmes, with risk-reward sharing mechanisms.

Large capital investments in intelligent manufacturing technologies might be expected to manifest themselves in very quiet times where excess manufacturing capacity and deep cost cutting do not allow organisations to invest for future performance description. Major stresses resultant from a major recession could act to modify and reshape global supply chains with particular segments that are already under deep stress, necessitating innovative investment support measures and tools to accelerate restructuring and re-capitalisation in particularly vulnerable segments. Leading manufacturers and innovative industrial partners may work together on exploratory investment concepts that tap into national or international scientific evaluation and quality assurance funding services to capitalise innovative collaboration. These jointly developed intelligent industrial automation tools and solutions have the potential to improve operational productivity significantly while further reducing the environmental impact and promoting resource efficiency and closed-loop principles. This work is of potential great value and might also involve new locations.

1.5.2. Skills Gap and Workforce Training

To utilize potential and realize the Intelligent Manufacturing concept, it is critical to establish a new digital workforce-oriented ecosystem, collaborative tools, and partnerships. While legacy workforces may lack adequate Industrial Intelligence skills, the future of digitized manufacturing will be constantly changing. As factories increase innovation efforts and digitization-transformation processes are accelerated, updating, recruiting, and reskilling the workforce through training are becoming more critical to the success of companies. Transforming the traditional manufacturing model requires addressing the skills gap by collaborating with industry, government, and academia to attract and prepare the next generation of manufacturing workers. Collaboration is important as it is necessary to develop AI tools that can deliver the desired benefits, but also to enhance transparency and trust, which are critical to the successful implementation of AI tools. Removing the fear factor related to AI tools through education and raising awareness will facilitate faster company transformation.

Company transitions toward smarter, more automated factories and supply chains will require a diverse and skilled workforce. Information from factories will have to be collected, reviewed, and assessed while taking appropriate actions, which will require new skills and worker training. These critical changes will require adding on-the-ground factory workers with four-year engineering and technology degrees as well as two-year engineering technology technicians and cyber-physical systems degree holders. In addition, smart factories will need human-robot teams with the skills to work alongside robotics and drones. Advanced Manufacturing requires educators across K12, community colleges, technical training programs, and four-year colleges and universities to teach exchange and prepare students for high-demand Advanced Manufacturing careers. Manufacturing workers of all kinds will need training on new technologies, such as text mining and natural language processing, state-of-the-art augmented reality, productivity, and risk assessment tools.

1.5.3. Data Security and Privacy Concerns

As intelligent manufacturing systems continue to proliferate, concerns regarding data and privacy security have become inevitable. Concerns in regard to any form of security such as data security usually arise whenever connections to the external network have been established, primarily because when such attempts to connect to devices, particularly production equipment of a manufacturing operation from the outside via an external network are made at any time, such connections create possible openings to cyberspace and expose the production management system of the manufacturing operation to serious risks. These connections also affect connections to other facilities or devices of the manufacturing operation through internal networks. The impact of possible success of cyber-attacks can possibly be going offline, causing production loss and enormous damages, intellectual property theft and also behavioral surveillance, thus affecting the company's competitiveness, even nation-wide sabotage.

Privacy issues also arise because supply chain relationships involve visibility into different organizations, thereby presenting an opportunity for privacy issues associated. What is most worrisome is the callous disregard displayed on the part of most companies on the required basic standard for securing detection and prevention of data breaches. Nonetheless, several organizations in diverse jurisdictions have proffered for consideration of prudent behaviors or guidelines that focus primarily on data access and protection as well as data security frameworks being adopted while addressing cybersecurity risk mitigation.

1.5.4. Integration with Legacy Systems

The increasing sophistication of intelligent manufacturing solutions offers manufacturers unprecedented insight into the operation of their plants, maximizing asset and labor usage and minimizing waste. However, achieving those gains must start from a strong base of existing systems and technology without which any new implementation will be incomplete. Crowded factory floors are often filled with legacy systems often working together in ways never intended by the original manufacturer. These non-networked islands of automation usually lack both the communication capabilities and the data structures that would give them an intelligent manufacturing edge. Most of the systems do not provide for machine learning, which can help create a truly intelligent system.

Faced with internal and external requirements for modernization, manufacturers are increasingly looking for systems integrators with experience in bridging these islands of automation. For many manufacturers, the initial implementation of intelligent manufacturing technology will likely augment and modify their existing factory technologies rather than avoid disruption at any cost with full replacement. It is more logical and scalable to gradually prefix initial implementations of new technology with partial implementations that fit efficiently with existing legacy systems. The key need for integration with legacy systems covers compatible hardware and flexible, adaptable, and open software solutions. Hardware solutions encompass components such as sensors, cameras, displays, controllers, and capabilities such as interoperability, security, physical size, form factor, and robustness. Software aspects and functionalities that enhance integration with existing systems include distributed architecture flexibility, cyber volatility, and services that can match and modernize existing operating protocols, networking and data structure capability, structured data access, and data format capability.

1.6. Case Studies of Successful Intelligent Manufacturing Implementations

Some impressive intelligence systems have been put in place and the following section provides examples in specific sectors. Most of the implementations are not truly autonomous yet, but more examples of pilot product lines are being developed around the world, initiated by the electrification of industry and the shift toward widespread sustainable manufacturing.

Birds-of-a-feather flock together, and the landmark shift away from internal combustion engines to fully electric vehicles has provided many automotive factories with the impetus to implement smart sensors, track-and-trace digital twin models, and cloud and edge computing, to achieve flexible, adaptive manufacturing systems. There is ongoing work on open standards for such a production paradigm. A recent event has showcased this initiative, and further events are expected. A manufacturer in Spain is now implementing a system with capabilities aimed at increasing process flexibility and robustness.

Like the automotive industry, the electronics manufacturing industry has shifted gradually toward more unified products requiring bespoke manufacturing systems that increasingly require more ingredients from high-tech industry businesses. Captive outsourcing is gradually losing its advantages in buying component systems and related savings, and new niches are being opened to local electronics businesses providing on-shore foundry services.

The complexity of approved vaccines has brought back enormous interest in plug-and-play modular biomanufacturing for the production of core components in specially designed reactor modules. The answer to why not even 3D printing depends on further process embedding in robotics and their merge with training of operators responsible for such bio-nanosystems.

1.6.1. Automotive Industry

Intelligent Manufacturing and the Shift Toward Fully Autonomous Factory Systems 1.6.1. Automotive Industry

The automotive manufacturing industry is one of the strongest sectors in the global economy. Unlike the vast majority of sectors, automotive grew significantly during and after the pandemic. For global OEMs, delays in the supply chain, especially semiconductor microchips, created demand for plants in the USA and chip supplier partnerships to alleviate risk. In Asia, the automotive sector is one of the main economic contributors and employers. Countries represented by automotive manufacturers include Japan, South Korea, China, India, and Thailand. Suppliers of Automotive Parts represent a significant part of the economy in Asia.

Up to now, the automotive supply chain is composed of multiple tiers, where assemblers and OEMs outsource the manufacturing of parts. With the recent trend of vertical integration, at least the manufacturing of the vehicle microchips has started flowing back to the OEMs. The First Automotive Revolution paved the way for mass manufacturing, decades of innovations and advances on Analytical models, Sensing technologies, Robotics, Machine Learning, and Computational Capability are today propelling the Second Automotive Revolution toward the Smart Factory 4.0 paradigm. Along with fast changes in regulation, the convergence of the global automotive sector toward Electric Vehicles is presenting several challenges to the OEMs and Suppliers. Many key technologies such as battery management systems and formulations suitable for Cybersecurity and Safety are not yet fit for mass manufacturing implementations, and the recent pandemic showed the limitations of empty factories in the electric and supply chain shortages. What Automotive manufacturers are starting to review is to take advantage of the Data available in the market in real-time timescales to create an ecosystem of partners and suppliers with automation experts, Data, Technology, and Capabilities to create the Shift Toward Fully Autonomous Factory Systems.

1.6.2. Electronics Manufacturing

At the same time, semiconductor packaging equipment suppliers and semiconductor assembly and test manufacturers provide MPI with carefully designed equipment to allow for simple upgrades when new component types are developed and require a different machine configuration. MPI is then intrinsically supported in a co-engineered and stepwise approach of better automation over time of their operations while the suppliers help support their customers' business goals for low manufacturing costs and faster time to market. Low manufacturing cost targets and increased demand for faster time to market are also related. MPI focuses on the packaging of parts for the consumer electronics market, which has higher demands for time to market, while the relatively smaller markets for automotive, medical, and FPGAs are more cost sensitive.

In parallel, there is a second push toward automation: it is cheaper, something inherent to the materials used and processes evolved, for the equipment manufacturers to manufacture the capital-intensive equipment in China and assemble them in the country close to their supply chain to take advantage of lower logistics costs. Workforce expensing in China is generally cheap; it is also becoming increasingly expensive, such that some parts and processes are being repatriated. The machine builders of the expensive semiconductor machines are increasingly reluctant to manufacture and ship delicate machines that now make the majority of their profits back to China. In this context, the semiconductor equipment manufacturers must find motivation to automate their equipment for customers in China to reduce such labor content. The repatriated production has been typically directed toward machines that are faster to manufacture, such that the cycle of semiconductor manufacturing equipment can be reduced, typically to assembly houses.

1.6.3. Pharmaceuticals

Pharmaceuticals to avoid costly patent litigation are creating new products as fast as possible. This has led to explosive growth in pharmaceutical products going off patent and demands by the pharmaceutical industry itself for more efficient consumer-centered manufacturing. The regulatory agency has required flexibility in drug manufacturing and presents a challenge but also an enormous market opportunity for the industry. Increasingly, we see multi-product facilities, particularly in the upper-tier contract manufacturing space - these are often high-end tech, low-cost market companies.

The pharmaceutical industry has experienced demand shocks from price competition and demand from customers for custom high-quality products. Due to successful lobbying in Congress, these were normally ignored and did not lead to special treatment in patent protection or antitrust policies affecting other industries. Drug companies have found relief in increasingly high-tech flexible manufacturing, often with a new and complex twist - they no longer manufacture enough of any one item to justify the fixed cost of equipment to be used for that product only. They have shifted instead to contract manufacturers for batches much smaller than those normally done in other consumer goods industries and at margins far in excess of those for any other consumer goods. The regulatory agency has sided with drug companies, granting them what is essentially direct control over product safety, circumventing the independent validation of quality and product safety traditionally done by government agencies in all other industries. But as stated previously, high-tech flexible manufacturing is often no longer done in house. Rather these contract manufacturers have themselves invested in flexibility for both large and small batches.

1.7. The Role of Government and Policy in Promoting Intelligent Manufacturing

The post-war U.S. resurgence was driven by intelligent investment of government and private sector. It was government investment in R&D and R&D tax credits that first led to the development of information technology that enabled modern manufacturing.

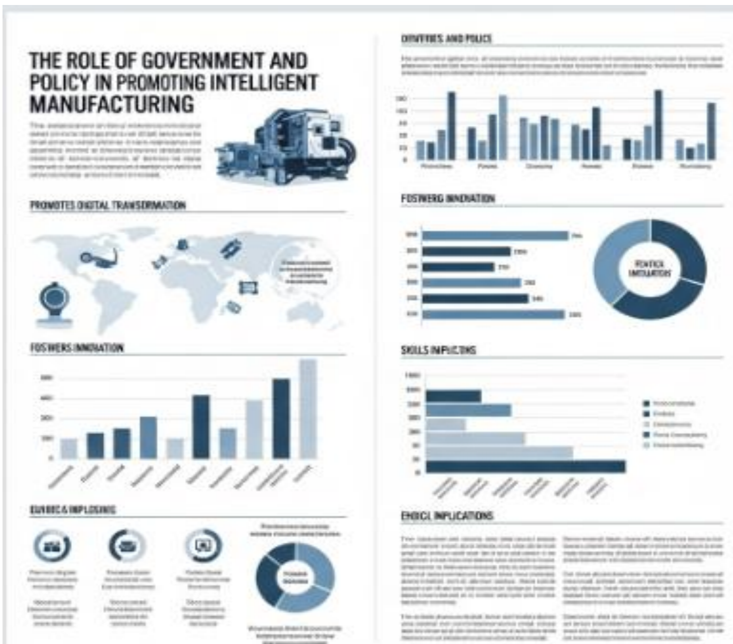

Fig 2 : The Role of Government and Policy in Promoting Intelligent Manufacturing

Manufacturing Order 8802 in 1941 provided funding for thousands of black engineers and physicists to work in aerospace and research labs. Out of that came the transistor, laser, and photonics. The cytogenetics that allowed the sequencing of the human genome, and at least 15 Nobel Prizes were initiated through government support of basic research.

Support for national scientists and engineers and their infrastructure is critical. In 2021, the U.S. invested $691 billion, 46 percent of the world's R&D, more than any country, including China. For every dollar invested in R&D, U.S. economic activity grows by $2.50. But only 24 percent of U.S. funding comes from the government while in Japan and China, the government provides about 70 percent of funding. With budget sequestration, government funding is declining. Discretionary outlays for NIST accounted for only 0.02 percent of total discretionary outlays and much less than outlays for government agencies such as Defense, Health and Human Services, and Agriculture.

1.8. Future Trends in Intelligent Manufacturing

As intelligent systems continue to reshape industry, the factories of the future will explore fully autonomous manufacturing processes through further enhancement of system interconnectivity and deeper insights through advanced AI and Deep Machine Learning systems. Fully Autonomous Factory systems will increasingly include autonomous robots and cyber-physical systems that are able to more fully integrate with an automaker's Enterprise Resource Planning system, allowing them to make intelligent decisions on what to assemble, and how to assemble it without need for human direction. Using advanced AI and machine learning, these autonomous systems will be integrated with an organization's ERP systems to automatically review inventory supportability issues, which would allow the robotic systems to make intelligent decisions with respect to what assembly to perform based on available work-in-progress inventory. As the number of semi-conductor chips produced increases, and as the sequencing of chips used in each electronic assembly continues to grow, methods for tracking parts movements and FIFO system supportability will likely become of intense focus. Advancements in remote inspections through increased connectivity and visualization tools may allow proprietary technology to be better guarded, and speed up the rate of knowledge transfer, thereby lessening the potential time hurts to emerging market manufacturers.

An increasing number of companies are also exploring the use of Collaborative Robots in the industrial sector, offering assistance to, and coordinating with human workers on-line. Collaborative robots work alongside the human workers, sharing the space with them as they work, helping to off-load the more repetitive, heavier tasks, and allowing the human workers to focus on the more skilled activities for which they have been trained. Using smart cameras and embedded programming intelligence, collaborative robots can be programmed and re-programmed much easier than traditional industrial robots. They offer manufacturers flexibility. They can be moved around and reprogrammed for different tasks, even by the production operators themselves!

1.8.1. Fully Autonomous Factory Systems

The next exciting stage in intelligent manufacturing is the full incorporation of Artificial Intelligence (AI) or Advanced Cognitive Technologies (ACT) within factories that will allow them to handle all manufacturing decision-making, planning and control, system performance assessment, workflow optimization, and system security, in partnership with cognitive systems and humans, where appropriate. Fully Autonomous Factory Systems (FAFS) will be the future intelligent factories in which all operational processes, with few exceptions, will be managed by cognitive systems with their own initiative. A fully autonomous intelligent factory will be able to integrate both the manufacturing and logistics systems in a seamless manner to ensure efficient and optimized product and service production and delivery with minimal intervention of human operators during the functional phase of the system. A fully autonomous intelligent factory will be characterized by a very high degree of obsolescence. It will allow production system design, planning, and configuration activities to be outsourced to intelligent agents in cyberspace that could be driven by Digital Twins (DT) based on advanced computer simulation. The digital twin of the physical factory will continuously monitor performance and condition, using this information to optimize production workflows. In a fully autonomous factory, intelligent agents will be responsible for directing all of the autonomous robots, vehicles, and equipment (ARVE) in the system from order initiation to completion. They will have unfettered access and will interact with ARVEs in the factory by wirelessly launching applications. Autonomous vehicles will be able to ferry their cargo automatically to dipping points when they need to be replenished. When a delivery is made, the autonomous robot will be able to charge itself with a new order and continue to fulfill its delivery tasks without any human intervention. This will allow manpower to be released from such dull, dirty, and dangerous activities. It will also ensure an extremely high degree of synchronicity between the different production tasks in the fulfillment of the overall order.

1.8.2. Collaborative Robots (Cobots)

Collaborative robots (cobots) are designed to operate in the same space with humans and assist them in completing a specific task. Unlike traditional industrial robots, which are capable of performing a specific set of tasks at high speed and high accuracy, cobots offer a limited subset of capabilities but the ability to show flexibility, adaptability, and ease of operation. Cobots are mainly used in manufacturing, logistics, health care, agriculture, construction, and retail.

Cobots are being used to offer productivity advantages in a wide variety of tasks that require human-like dexterity and flexibility. The collaborative robotic space is rapidly increasing as companies outside of traditional industrial automation markets begin to incorporate cobots into their applications. The original vision for smart factories included the use of lightweight collaborative industrial robots. The primary advantage of using a cobot compared with using an industrial robot is imparting some flexibility in the assembly process. Cobots tend to be easy to set up and reconfigure for multi-skill and multi-product assembly. Cobots are less expensive than traditional industrial robots and are physically safer around humans. The use of cobots also makes economic sense in certain applications where human assembly partners are needed to manage variability in low-volume or customized products.

1.8.3. Augmented Reality in Manufacturing

Augmented reality (AR) is an immersive technology with the potential to facilitate the development of people-centered intelligent systems, which can collaborate with all the actors involved in the product life cycle. It allows a flexible, accurate, and comprehensive interaction with the physical environment, broadening the amount of information provided to the user. In this context, AR interfaces may be adopted at different levels throughout factory operations and products, supporting all kinds of users, such as expert operators, customers, and decision-makers. Although AR interfaces have undergone research for several years the technology is only now at the stage that enables its utilization in real systems. This is due to increased hardware capabilities, user acceptance on mobile technology, and cost reduction associated with mobile devices.

Several companies have carried out successful implementations of AR interfaces in manufacturing settings. Unlike the automotive industry, where AR applications are mainly used for car assembly, industries such as aerospace and healthcare are using AR in assembly, maintenance, training, design, and manufacturing planning. An increasing number of AR applications in the manufacturing sector have been identified. A few companies have developed solutions in support of the different manufacturing process phases. For example, solutions are available for design review, assembly and inspection, maintenance, and training. Most AR applications are developed for the assembly phase, with applications available to support design review, manufacturing task training, assembly real-time guidance and inspection, and assembly in difficult lighting conditions.

1.9. The Impact of Intelligent Manufacturing on Employment

In 2013, a notable study conducted on the potential impact of computerization on employment in manufacturing in the United States revealed that an astonishing 47% of jobs were at risk of automation. Just three years later, predictions indicated that automation, driven by advances in robotics and artificial intelligence, would lead to a net loss of 5.1 million jobs by 2020. Such estimates raise concerns that intelligent manufacturing could lead to major job loss globally, perhaps on the same scale as that created by earlier industrial revolutions.

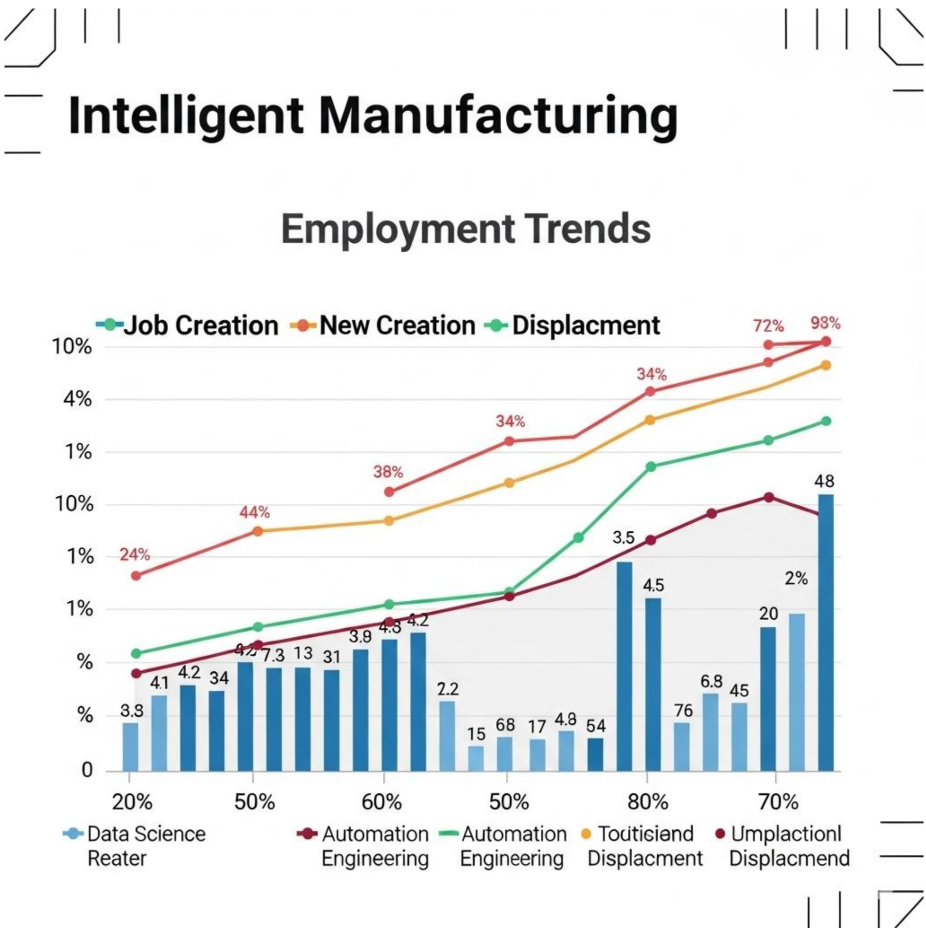

Fig : The Impact of Intelligent Manufacturing on Employment

While it is true that job loss may occur in the short term as a result of the widespread adoption of intelligent manufacturing capabilities, the declines in demand for low-skill, labor-intensive jobs in manufacturing may have less to do with the expansion of advanced manufacturing technology than with the offshoring of manufacturing to low-cost economies. In fact, the declining share of employment in manufacturing job losses may have been exacerbated during the Great Recession, the decade-long economic downturn that began with the collapse of Lehman Brothers in 2008 and temporarily vaporized demand for manufacturer goods.

In the long run, though, intelligent manufacturing has the potential to produce substantial positive economic effects. Industrial output would likely increase, along with Gross Domestic Product and tax revenues, helping to fund much-needed government programs. For manufacturers, automation would bring greater productivity and innovation, improving international competitiveness and generating revenue growth. In turn, this would create new high-skill jobs, in the design, programming, installation, support, and maintenance of intelligent manufacturing systems. Equally important, intelligent manufacturing may help revitalize and safeguard the future of domestic manufacturing from offshoring.

1.9.1. Job Displacement vs. Job Creation

While manufacturing is an important sector for many countries, it has steadily been shrinking as a share of GDP in developed countries during the past several decades. Advances in automation, robotics, and communication technology allow for the same amount of output to be produced in manufacturing with fewer employees. In addition, lower-paid workers in manufacturing industries in emerging economies are now doing some of the work that used to be performed in higher wage industrialized countries. These trends lead many observers to expect that a major consequence of intelligent manufacturing will be large-scale job displacement as companies either replace the human labor for a wide range of tasks with machines, or they decrease their workforce to maintain large margins while using novel technologies to greatly increase productivity. One of the major driving forces behind investment in intelligent manufacturing systems by firms is the prospect of greatly increased productivity growth, increased margins, and then lower prices for end products that spur economic growth, all made possible by investment in intelligent factory systems. While it is clear that intelligent manufacturing will significantly affect the structure and the number of jobs in traditional manufacturing industries, it is also equally clear that intelligent factory systems will create a new set of jobs for humans. However, to deny that these potentials for loss of activities normally associated with human labor are not real would be hubristic as major advances in technology and automation in the past have led to distress in local populations as well as in some economic sectors. In addition, the pace of fundamental shifts in how almost all economic activity is performed, whether it be in manufacturing or in other sectors such as health care, will be rapid rather than gradual, and therefore will be more impactful in terms of skills mismatches and loss of jobs.

1.9.2. Evolving Skill Requirements

Intelligent manufacturing encompasses a wide range of new and improved technologies which has a direct impact on the future workforce. In intelligent manufacturing systems, the interaction between humans and other intelligent and automated resources is more frequent and critical than in traditional systems. The human operator cannot be treated merely as a physical resource in the system. Human's unique capability for creative problem-solving, reasoning, and judgment to perform complex, decision-oriented tasks are required for collaborative work roles. However, as we shift toward a new manufacturing paradigm based on intelligent technologies, there will be a co-evolution of intelligent technologies and the nature of the work that requires skills suited to such collaborative arrangements. Intellectual effort will shift to solving problems such as setting the system to operate autonomously under the requisite constraints, supervising a fleet of autonomous robots and other resources, orchestrating human-robot collaboration, managing the integrity of the information and software control systems, and managing product quality, training, safety, and security.

However, the industry dilemma persists. While technology pushes the demand for highly-skilled workers, at the same time, the current labor force is increasing rapidly among the low-skilled and low-wage segments. Addressing this workforce skill gap is vital to strategies in the field of manufacturing. Over the next decade, as workers in the knowledge-focused sectors retire, demand will strongly outpace supply for highly-educated individuals, and available talent will no longer meet industry requirements. In adapting to the rapid evolution towards intelligent manufacturing, workers will need support and investment along the talent pipeline to stop the rising tide of under-skilled workers. In addition to public investment through education and workforce programs, the private sector should play a role in skill development through talent sourcing and investing in ongoing training programs.

1.9.3. The Future Workforce

For the foreseeable future, most factories will accommodate both humans and machines. Recognizing the fundamental role that humans play by inventing, programming, maintaining, upgrading, and physically working side by side with intelligent machines will allow successively more complex automated processes to take place and maximize efficiency. The shift toward more advanced manufacturing will be accompanied by new jobs and functions across all manufacturing sectors and among many connected support industries, from additional development and programming of specialized software to development of sensors and data analytics, logistical planning, robotics maintenance technicians, factory floor monitoring implementation, and higher level integrated oversight of multinational manufacturing operations. These roles will call on technical skillsets that are in short supply today, not only in traditional technical areas such as engineering design but also at the technician and laborer level, including the need for more skilled mechanics, electricians, and maintenance personnel. At the same time, operation personnel that interact with machines and analytic systems, and integrate across the factory functions, will demand a newer, more technical skillset that is currently lacking in many workers. In addition, the success of the transition toward more autonomous intelligent manufacturing systems will require that directives be developed and guidelines followed that establish a transparent, fair operating environment for both human workers and autonomous machines.

The shift toward higher levels of intelligent machine collaboration will also provide a path to increasing the age range of the workforce, through the development of more sensitive autonomous capabilities, enhanced operator-automation interaction, and adjustable operating environments incorporating alternate safety modes. As enhanced the affordability, flexibility, and operational performance of intelligent automation systems becomes available, the new workforce will demand manufacturing jobs that provide more than just compensation, but also provide interesting work that engages the employees and acknowledges and utilizes their creativity.

1.10. Global Perspectives on Intelligent Manufacturing

Intelligent manufacturing has a broad and rich history in many different regions around the world, both as a well-recognized vision and as an established area of research and development. Leading institutes in North America, Europe, and Asia have made significant investments in intelligent manufacturing research with exciting results. Driven by diverse local motivations, certain intelligent manufacturing developments are seen as more advanced in particular countries. Notably, research is often conducted by collaboration between industries and academic institutions in these regions. This chapter highlights various intelligent manufacturing perspectives and plans from several leading regions, demonstrating a spectrum of interest and plans in intelligent manufacturing.

In the USA, advanced digital capabilities and an increasingly interconnected world give US manufacturers the ability to leverage technology to actively enhance and transform products, processes, and business models, creating value and meeting the demands of consumers and customers in a global economy. Top economic leaders in the country understand that while the US manufacturing sector supports a diverse and growing economy, it continues to face intense pressures. It must compete to produce in a global economy that is increasingly driven by technological breakthroughs and cost considerations. The key foundation sectors that allow US manufacturing to compete are the advanced design, advanced technology, advanced materials, and advanced manufacturing processes, which are interconnected and must be advanced simultaneously to maintain the world's strongest manufacturing sector. In fact, advanced manufacturing is defined in the United States by the advanced technologies developed in the intersection of the advanced physical and biological sciences, engineering, and information sciences.

1.10.1. North America

North America is an important player on the world stage of intelligent manufacturing R&D and its application. North America made an early commitment to intelligent manufacturing with the formation of the National Institute of Standards and Technology and its Advanced Manufacturing Office now headquartered in the Manufacturing Extension Partnership, and with the establishment of the Digital Manufacturing Design Innovation Institute. While its investments have allowed it to build up its technological capabilities in software and services, implementation is heavily dependent on the private sector and accelerated through public-private partnerships such as the Manufacturing USA strategy. In the U.S., manufacturing and its supply network has benefitted from increasing levels of reshoring and are expected to continue to do so, which is increasing investments in automation, bringing many entities into the intelligent manufacturing fold.

Government policy in Mexico has prioritized the establishment of supply chains to partners that can reduce costs for the final assembly of products. More recently, Mexico has also focused investment in sophisticated manufacturing with technology transfer from North America partners, and is advancing in the building of specialized technical skills for these operations. At the same time, certain industries are implementing an emerging trend to regionalize their supply network, as has been accelerated by the pandemic, which include both the need for digital technologies for supply chain management and also the need for the regionalization of certain industry products to mitigate risk.

1.10.2. Europe

About 15% of the added value in Europe comes from manufacturing. The contribution of the machinery sector alone exceeds 7% and is growing almost twice as fast as the European economy. European companies provide the vast majority of the world's output of machinery and equipment. The manufacturing and food sectors are the largest consumers of research and development. The automation and control systems sector is almost entirely powered by private investment. About one third of European machinery and equipment sales goes to the information and communication technologies and electronics sectors. While ICT and electronics demand world-leading flexibility and agility, aerospace, automotive, energy and health are taking leading positions worldwide in terms of quality, reliability and innovation. The new challenge for Europe in the coming years is to manage to drastically increase the overall productivity of its manufacturing and reduce the time-to-market. As regards robotics, Europe is the second industrial robot manufacturer worldwide, with a market share of about 25%, although it relies heavily on the Japanese and North American supply and technology. Europe is the first market for service robots. However, innovation in 3D printing, biotechnology, industrial nanoelectronics, micro and nanofabrication, new materials for structure and production, innovative technologies for collaborative robotics and intuitive actuation and sensor technologies, as well as the integration of advanced tools for robotics symbolic cognition, still reflects the complex landscape of European research in these areas. In addition, innovation in automation, recognizing that any innovation without the right instruments in place cannot deliver results, is a crucial building block to create a European Industry 2020.

1.10.3. Asia-Pacific

The impact of COVID-19 has speed up Government focus on Industry 4.0 initiatives to spur economic growth. New generation manufacturing, smart manufacturing, industrial internet, advanced manufacturing, and a great variety of other jargons are all coming into existence in the Asia-Pacific region. Smart Manufacturing is being emphasized by many major economies including Japan, Korea, and China. Standardization efforts and promotion of cybersecurity readiness for OT are also gaining momentum. In China, the intelligent manufacturing framework, a key area of strategy, gives priority to development programs that establish ambitious targets and governance structures; support the development of standardization efforts; are managed from the top by major companies and conglomerates; enable technology diffusion to SMEs; and help mitigate the role of export dependence as technology matures. For Korea, the business models related to 5G, digital twin/factory, AI application, cyber physical systems, autonomous robot, and cloud computing are emphasized. Industry 4.0 and advanced manufacturing in a narrower sense are on the agenda in the U.S., Japan, and Western Europe. Yet, unlike North America and Western Europe, the industry, manufacturing, and service in the Asia-Pacific region are itself yet very young. So not only are the countries of Asia and the Pacific focused on but the disparity among industries and services within each country are taken into account as well. In addition, the labor issues are diverse and are treated differently among the countries in the region and also different issues among the countries in the region with a common narrative.

1.11. Conclusion

This chapter has introduced the concept of intelligent manufacturing and highlighted its central role in the shift toward fully autonomous factory systems. By integrating intelligent components to currently relatively independent factory systems, productivity growth can be achieved based on the next wave of manufacturing innovations. Recent technological development in a number of key areas, e.g., sensors, AI, robotics, machine learning, and communication solutions, provide the technological basis for autonomous factories. Although this development opens up significant opportunities, the required integration of these developments into holistic intelligent factory systems poses a significant research challenge. The presented methodology is suitable for addressing these challenges, as it supports the translation of future factory requirements resulting from broader industrialization strategies into the definition of innovative intelligent factory solutions. The methodology provides a structured way to do that.

While the chapter has defined intelligent manufacturing and outlined the functional building blocks for factory autonomy, it has purposefully refrained from being highly prescriptive about the blueprint of solutions. Such specification would not only stifle innovation, but also be premature given the early stage of many key supporting technologies. The methodology defines a roadmap and a set of guiding principles but is agnostic to the actual technological solutions that will prevail. Rather than being prescriptive, the presented guideline should help to promote the reflection on the novelty and relevance of specific research efforts and initiatives. In doing so, the methodology could help to identify potential gaps and calls for action. Over time, further insight and experience should help to identify more specific pathway solutions.

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