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A Practical Approach to Digital Manufacturing

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Abstract

In today's fast-changing world, technology's rapid advancement significantly impacts industries, societies, and economies. However, with these advancements come new challenges, notably a growing shortage in the manufacturing sector. A 2021 BBC article emphasizes that this shortage is intensifying (The), prompting the need for the manufacturing industry to adopt more efficient production methods. Though necessary, this transformation poses challenges in adoption. One promising solution to address these challenges is Industry 4.0, which is heralded as the fourth industrial revolution. It utilizes technologies such as artificial intelligence, digital twins, and sensors to transform manufacturing. These technologies are crucial for redefining the manufacturing landscape by allowing systems to operate autonomously, thus improving production efficiency and adaptability. Nonetheless, the manufacturing sector struggles to effectively implement these technologies. Research by Yüksel (2022) explores the challenges companies face in adopting Industry 4.0, pinpointing factors that hinder progress (Yüksel H 2022). Many businesses are aware of the urgency but find it difficult to integrate new tools with traditional processes, making Industry 4.0 seem distant.Adding to the complexity is the substantial financial investment required. According to Sloan (2022), investments in these technologies are projected to reach trillions (Sloan 2022). This presents a dual challenge, highlighting the transformative potential of Industry 4.0 while questioning the return on investment. Businesses must determine if such large expenditures will provide substantial returns. Embracing Industry 4.0 involves more than just technology adoption; it demands a cultural shift within organizations. While transitioning presents financial, technological, and cultural hurdles, bridging the gap between current and future capabilities can offer significant benefits. This discussion seeks to explore future technologies and strategies to make digital manufacturing achievable, redefining success in today's industrial landscape.

Keywords
Digital manufacturing, Industry4.0, Digital Twin, Big Data .

1. Introduction
When undertaking research in the realm of digital manufacturing, it quickly becomes apparent that a wealth of scholarly articles and papers are available, each delving into principles and theoretical frameworks underpinning this transformative approach. These articles are invaluable in that they provide detailed explanations of the technological innovations, methodologies, and potential impacts associated with digital manufacturing. Concepts such as automation, connectivity, real-time data analysis, and the integration of IoT devices and artificial intelligence are thoroughly covered (Zhong et al. 2019). These studies contribute significantly to a deeper understanding of the potential that digital manufacturing holds for revolutionizing production processes. However, despite the extensive exploration of these foundational principles, there remains a significant gap in literature when it comes to translating these theories into practical applications. Many articles stop short of providing the actionable insights and concrete steps necessary for businesses to effectively implement digital manufacturing in real-world settings. The intricacies of managing the shift from traditional to digital processes, the specific strategies for overcoming technical challenges, and the methodologies to streamline adoption and deployment often remain underexplored. This gap leaves many companies

in a state of uncertainty, unsure of how to actualize the benefits of digital manufacturing in a practical, tangible way within their own operations.

Therefore, while the groundwork laid by these numerous articles is essential for conceptual understanding, there is a pressing need for research that focuses on the practical aspects—guides on implementation strategies, best practices for integration within existing systems, case studies that demonstrate successful transitions, and analyses of common pitfalls and how to avoid them. Addressing this gap is crucial for enabling businesses to move from theoretical knowledge to actionable plans, thereby fully leveraging the potential of digital manufacturing to enhance efficiency, productivity, and competitiveness in the modern industrial landscape.

2. Objectives

The primary objective is to bridge the significant gap between the theoretical foundations of digital manufacturing and their practical applications. Despite extensive scholarly research detailing the principles of digital manufacturing, encompassing automation, connectivity, real-time data analysis, IoT integration, and artificial intelligence—there remains a lack of actionable insights for real-world implementation. This objective seeks to focus on developing comprehensive research that addresses practical challenges businesses face when transitioning from traditional to digital manufacturing processes. By providing clear implementation strategies, best practices for integration, successful case studies, and analyses of common pitfalls, the aim is to enable businesses to transform theoretical knowledge into practical, actionable plans. This will help them leverage digital manufacturing effectively to enhance their efficiency, productivity, and competitiveness in the industrial landscape.

3. Translating Digital Manufacturing Theory into a Practical Methodology

3.1 Why, What and the How approach

There are numerous methodologies that offer detailed explanations on how to approach and resolve problems effectively. One such approach is the "Why, What, and How" methodology. Despite its simplicity, this approach is incredibly powerful in guiding problem-solving processes. In essence, as explained in Figure 1, the "Why, What, and How" methodology begins with asking "Why"—delving into the root cause and the underlying motivations behind the problem. This step is crucial, as empirical studies have shown that addressing root causes significantly increases the likelihood of successful outcomes (Soares Ito et al.)Once the "Why" is established, the next step involves defining "What" – clearly articulating the objective or the outcome desired from solving the problem. By establishing clear goals, this step provides direction and focus for the implementation team (Hart et al.). The final step is "How," which involves developing a practical plan and actionable steps to achieve the desired outcome.

This methodology can be applied to a wide variety of problems across different domains, from business strategy to technology implementation, due to its versatile structure. In an example published by Yan, it demonstrates how this framework can help one write better (Yan 2021). By consistently grounding problem-solving efforts in the "Why, What, and How," individuals and organizations can ensure that their solutions are both comprehensive and impactful, ultimately leading to more sustainable and successful outcomes.

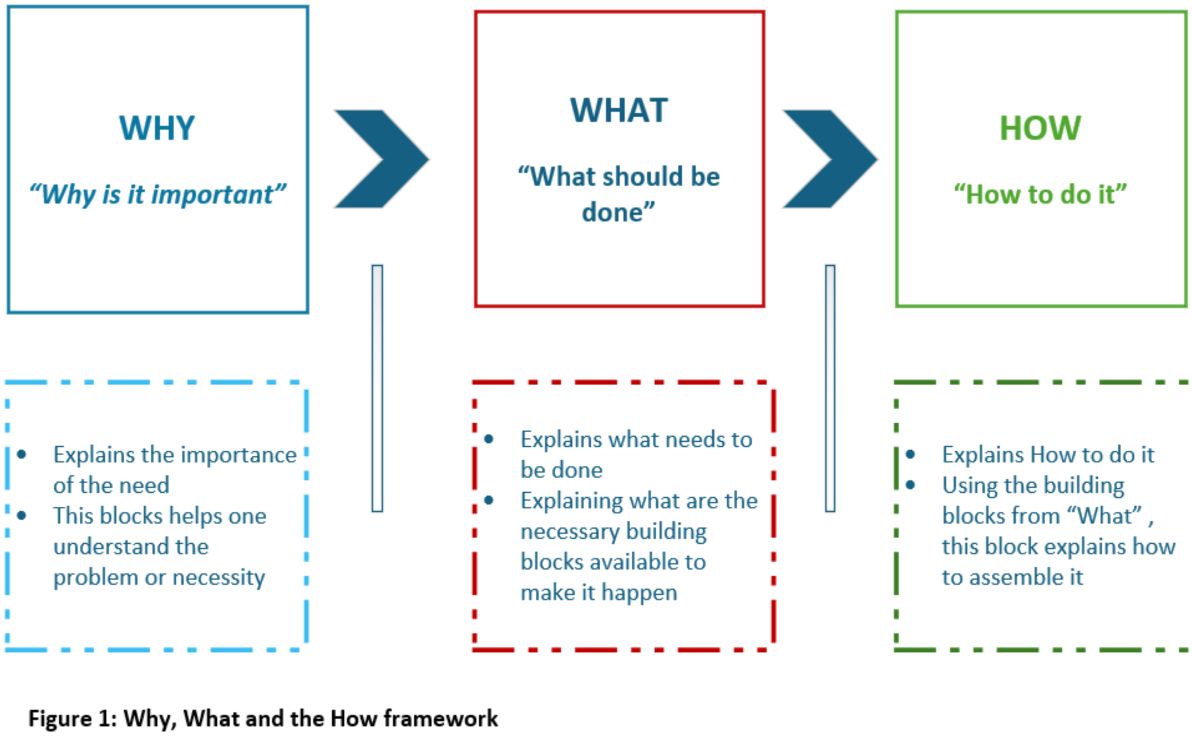

Figure 1. Why, What, and How the Framework

4. Why does the industry need to adopt Digital manufacturing

The manufacturing industry is currently navigating an era of unprecedented change and complexity, driven by both longstanding challenges and emerging pressures. The manufacturing industry across face a similar manufacturing challenge as explained in industry select (select, 2021). Addressing these challenges necessitates a shift toward digital manufacturing, which is not just an option but an essential evolution for staying competitive and thriving in the modern industrial landscape. Here's why digital manufacturing is crucial. Following are some of the key reasons WHY digital manufacturing is needed now more than ever before.

Enhanced Efficiency and Cost Reduction:
Digital manufacturing harnesses technologies such as the Internet of Things (IoT), big data analytics, and artificial intelligence to streamline processes and minimize inefficiencies. By providing real-time data and insights, these technologies enable manufacturers to optimize production schedules, reduce downtime, and minimize waste. This leads to significant cost savings and increases operational efficiency, which are vital in offsetting rising production costs and maintaining profitability.

An article highlighted in Reuters discusses significant concerns in pharmaceutical manufacturing at New Jersey plant, particularly focusing on the lack of a robust electronic tracking system. This absence presents potential issues, as it undermines the integrity of test results and other laboratory activities by increasing the risk of data alteration. This issue is part of a broader set of deficiencies identified during an FDA inspection, which also highlighted problems such as inadequate staff training, missing drug stability samples, and equipment neglect. These findings underscore significant challenges in maintaining quality controls and regulatory compliance within the facility (Taylor and Fick, 2024).

Supply Chain Resilience: I
n the face of global supply chain disruptions, digital manufacturing offers greater transparency and control. Advanced data analytics and machine learning tools can predict potential disruptions and suggest proactive measures, enhancing the resilience and reliability of supply chains. By adopting digital tools, manufacturers can ensure better coordination with suppliers, adapt to changing conditions swiftly, and maintain supply chain continuity.

A case study on supply chain risk assessment highlights some of the key challenges faced by supply chains. The study, conducted by Deloitte, explains that supply chain mapping, risk visualization, and risk indicators are among the initial tools needed to understand the system. 'Visibility means being able to track and monitor supply chain events and patterns as they happen,' but this limited version has drawbacks. A business continuity planning dashboard can be used to mitigate risks by helping respond to disasters as they occur, rather than proactively reducing risk. Another quote from the articles says that " A spectrum of reasons drive this, including a lack of collaboration across functions, the cost of implementing resilient approaches, lacking the data needed, and an inability to measure the benefits of the strategies. " (Langeland et al. 2016)

Building upon the insights from the case study on supply chain risk assessment, a comprehensive system can significantly enhance supply chain visibility and risk management. Such a system could provide real-time tracking and monitoring of supply chain events through advanced technologies like IoT sensors and blockchain, ensuring transparency across the network. This enables businesses to stay informed about shipment statuses, inventory levels, and potential disruptions. Unlike traditional methods that often react to risks as they occur, a system equipped with predictive analytics can anticipate potential disruptions by analyzing historical data, allowing for proactive risk mitigation. Additionally, detailed supply chain mapping within the system enables visualization of the entire network, highlighting vulnerabilities and dependencies for better contingency planning. Risk visualization tools can be integrated to provide risk scores based on factors like geopolitical issues and supplier reliability, helping prioritize efforts effectively. The system can also support business continuity planning via dashboards that consolidate data into actionable insights, aiding swift decision-making during adverse events. Moreover, it facilitates collaboration and communication across all stakeholders, allowing for swift response and resolution of challenges. By implementing this kind of system, businesses can improve not only their reaction to supply chain challenges but also anticipate and reduce risks, ensuring a resilient and robust supply chain network.

Customization and Flexibility:

Modern consumers increasingly demand products that meet their unique preferences, leading to a growing need for flexible and adaptive production systems. In response to this demand, digital manufacturing offers manufacturers the necessary agility to rapidly reconfigure production lines and implement mass customization. This is achieved through advanced technologies that integrate seamlessly with existing manufacturing processes, enabling tailored production without substantial downtime or inefficiencies. One example of such a technology at the forefront of this transformation is additive manufacturing, commonly known as 3D printing.

Additive manufacturing allows for the creation of complex and precise prototypes rapidly, offering the ability to test designs and make adjustments in real-time. This rapid prototyping capability is crucial for meeting specific consumer demands without significant delays. Additionally, additive manufacturing makes it possible to produce low-volume, highly customized products cost-effectively, which was traditionally challenging with conventional manufacturing methods. By leveraging digital manufacturing and additive technologies, manufacturers not only address the growing consumer demand for personalized products but also enhance their production capabilities, maintaining competitive edge through innovation and efficiency in the market. Below are additional examples of how manufacturing demands customization and flexibility, and how this pushes the limits.

Automotive Industry - Customizable Vehicles:

Companies like Ford and BMW offer customization options which allow buyers to select specific features, such as paint color, interior materials, and advanced technology packages, tailoring vehicles to personal preferences. This flexible production is enabled by modular production lines that can be reconfigured quickly to manufacture different variants of the same model.

Fashion and Apparel - Personalized Apparel:

Brands like Nike and Adidas provide tools for customers to design their own sneakers, selecting colors, materials, and even adding personal monograms. These custom orders are fulfilled through agile manufacturing systems that accommodate low-volume runs without significant disruptions to the standard production process.

Electronics - Configurable Gadgets:

Dell and HP allow customers to build custom computer systems, selecting components such as processors, memory, storage, and graphics cards. This flexibility in production is facilitated by a supply chain equipped to handle various component configurations, ensuring timely assembly and delivery.

Furniture - Bespoke Furniture Solutions:
IKEA offers customizable furniture solutions, where customers can design storage solutions according to their space requirements using modular components. This approach maximizes flexibility in production, allowing for tailor-made solutions delivered efficiently.

Healthcare - Patient-Specific Medical Devices:
In the healthcare industry, 3D printing is used to create patient-specific medical devices, such as prosthetics and dental implants. These devices are tailored to fit the unique anatomical structure of each patient and represent a significant advancement in personalized healthcare.

Food and Beverage - Customizable Meals:
Fast-casual restaurants like Chipotle provide customizable meal options, where customers can choose their ingredients and portion sizes. The backend operations are designed to be flexible enough to handle such custom orders efficiently.These examples illustrate how businesses across various sectors implement customization and flexibility in their production processes, helping them meet consumer demand for personalized products while maintaining operational efficiency.

I. Quality Control and Assurance: Digital tools facilitate more sophisticated quality assurance processes. Real-time monitoring systems can detect defects or deviations during manufacturing, allowing for immediate corrective actions. This not only ensures compliance with stringent regulatory standards but also enhances product quality and reduces waste. The result is a reliable reputation for quality, which is crucial for customer satisfaction and competitive advantage.

II. Sustainability and Environmental Stewardship: In today's environmentally conscious market, adopting sustainable practices is imperative. Digital manufacturing supports sustainability by reducing material waste, improving energy efficiency, and facilitating the use of eco-friendly materials. This aligns manufacturing processes with environmental standards and consumer expectations, fostering a sustainable brand image and contributing to long-term viability.

III. Workforce Empowerment and Skill Enhancement: The shift to digital manufacturing empowers the workforce by providing tools and training for new skill sets. Automation takes over repetitive tasks, allowing workers to focus on more strategic functions. Continuous learning environments foster innovation, bridging the skills gap, and preparing the workforce for a technology-driven future. This cultural shift towards innovation and agility is essential for adapting to rapid technological changes.

IV. Enhanced Cybersecurity Measures: As manufacturing integrates digital technologies, cybersecurity remains a priority. Digital manufacturing involves implementing robust cybersecurity protocols to protect sensitive data and systems from threats. This protects intellectual property, ensures business continuity, and builds trust with stakeholders.

V. Innovation and Growth: Embracing digital manufacturing paves the way for innovation by facilitating experimentation and agility. Faster product development cycles, improved collaboration, and data-driven insights enable manufacturers to bring innovative products to market quickly, fostering growth and competitive differentiation.

The adoption of digital manufacturing is indispensable for addressing current challenges and seizing new opportunities. As industries evolve, embracing digital transformation ensures that manufacturers remain resilient, responsive, and competitive in a complex and dynamic market. By integrating digital technologies, the manufacturing sector can navigate its present challenges effectively and position itself for sustainable success in the future.

5. What needs to be done to adopt Digital manufacturing

Digital manufacturing represents a comprehensive toolkit designed to address a diverse range of challenges within the manufacturing industry. At its core, digital manufacturing encompasses various advanced technologies and methodologies that streamline production processes, enhance efficiency, and improve product quality. Each manufacturing industry and plant is unique, facing distinct challenges influenced by factors such as geographical location, specific processes, machinery, and market demands. This variability necessitates a tailored approach to problem-solving, which is where the digital manufacturing toolkit becomes invaluable. Through the digital manufacturing toolkit, plants are empowered to tackle their specific challenges and progress toward higher operational efficiency, innovation, and sustainability. Manufacturers can strategically deploy these tools to overcome obstacles and advance their production facilities to the next level, ensuring their competitive edge in the evolving industrial landscape.

5.1 What is a Digital manufacturing Template /toolkit

Digital manufacturing is essentially a toolkit designed to be assembled according to the specific business cases or challenges encountered within an organization. At the heart of a digital manufacturing plant are various interconnected components that work in synergistic harmony to realize the principles of Industry 4.0.

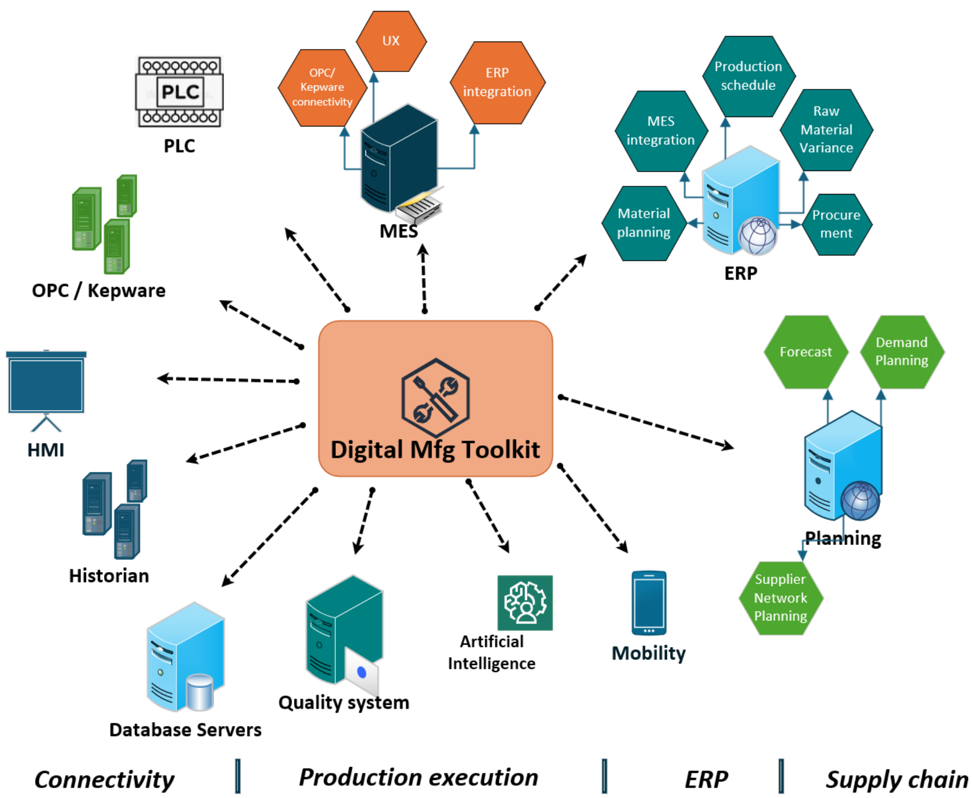

Figure 2. Digital Manufacturing Toolkit

As you can see in figure 2 the digital manufacturing toolkit involves the integration of an array of tools and systems, each playing a crucial role in streamlining business processes and addressing specific organizational challenges. The ultimate goal is to align with the principles of Industry 4.0, which emphasize automation, data exchange, and smart manufacturing.

It leverages cutting-edge technologies and interconnected systems to drive efficiency, agility, and innovation in manufacturing operations. By integrating various digital tools and systems, organizations can address specific business challenges while aligning with the advanced principles of Industry 4.0.

Core Components of the Digital Manufacturing toolkit and Their Roles:

- **Servers and Programmable Logic Controllers (PLCs)**
  Servers play a central role in processing and managing the vast amounts of data generated in a plant. PLCs, meanwhile, are essential for automating machinery operations, taking on complex control functions like monitoring inputs, executing pre-defined programs, and regulating outputs. This automation is fundamental for reducing human error and enhancing productivity.
- **OPC UA/Kepware/PLC connectivity (Open Platform Communications Unified Architecture)**
  OPC UA acts as the backbone of communication between disparate industrial devices. Its role is crucial in ensuring interoperability, allowing equipment and applications from different manufacturers to communicate seamlessly across a variety of operating conditions. This leads to a flexible and scalable production environment, where data can be readily exchanged and utilized for process optimization.
- **Human-Machine Interfaces (HMIs)**
  HMIs enhance the link between human operators and the machinery they manage. These interfaces simplify complex data into user-friendly visualizations, enabling operators to make informed decisions quickly and effectively. This is particularly important in maintaining productivity and responding to any operational anomalies promptly.
- **Historian and Database Servers**
  These systems store comprehensive records of operational data, capturing every event in the production lifecycle. Analyzing this historical data allows for identifying production trends and patterns, ultimately informing strategic decisions, predictive maintenance, and continuous improvement initiatives.
- **Quality Systems**
  Quality control is vital in maintaining product standards. Integrated quality systems monitor processes in real time, identifying variances and defects immediately. This real-time feedback loop helps in making necessary adjustments, ensuring output consistently meets quality specifications and regulatory requirements.
- **Artificial Intelligence (AI)**
  AI technology is pivotal in optimizing processes through data-driven insights. It enables predictive analytics, equipment maintenance scheduling, anomaly detection, and automation of mundane tasks. By learning from data patterns, AI assists in reducing downtime, improving process efficiency, and guiding strategic planning.
- **Planning Systems**
  Effective planning systems are critical in synchronizing production schedules with available resources and market demand. They optimize inventory management, energy consumption, and production timelines, ensuring operations are cost-effective and aligned with business goals.
- **ERP (Enterprise Resource Planning)**
  ERP systems unify various functional departments, from procurement and inventory management to finance and human resources, creating an integrated information framework. This cohesion facilitates streamlined operations, improved collaboration, and real-time access to business intelligence.
- **MES (Manufacturing Execution Systems)**
  MES provides real-time monitoring and control of manufacturing processes, from order initiation through to finished goods. It bridges the gap between enterprise-level ERP systems and plant-floor operations, fostering greater transparency and accountability in production workflows.

- **Mobility Solutions**
  These solutions empower the workforce with instant access to essential data and systems, facilitating remote monitoring and control of processes. By enhancing mobility, organizations can ensure that decisions are made based on real-time information, regardless of physical location, thus fostering a more responsive and adaptive production environment.
- **Data Lake and reporting**
  All the data collected from the machine , manufacturing systems, quality , ERP, planning and other systems the coexist to support manufacturing are fed in to the data lake . The importance of this is critical as this helps with the overlay of current sets of data presenting trends and insights so that one can necessary action immediately.

Digital manufacturing is more than just a technological upgrade; it represents a strategic shift in how manufacturing organizations operate. Understanding the toolkit is critical as forms the foundation on **how** to build the digital manufacturing solution. By embracing these technologies and integrating core systems, companies can position themselves at the forefront of the industrial revolution, unlocking new levels of efficiency, productivity, and innovation while fostering a culture of continuous improvement and adaptability. This seamless integration is the key to navigating the complexities of the modern industrial landscape and achieving long-term business success.

5.2 A typical Digital Manufacturing Flow

To effectively identify the foundational components in digital manufacturing, it is essential to grasp the flow of operations within the industry. Digital manufacturing spans a diverse range of sectors, including the food industry, life sciences, construction, etc. Each of these sectors relies on a complex network of machines that are integral to driving production processes seamlessly.

A critical aspect of any manufacturing process is maintaining stringent quality control measures to ensure that products meet specified standards. These quality controls act as a safeguard, ensuring that deviations from quality are promptly addressed. However, a significant challenge that persists across industries is the reactive approach to problem-solving. Traditionally, when issues arise, they are subjected to extensive analysis before corrective actions are implemented. While analysis is important, the time taken to identify a solution can result in substantial production delays and financial losses, as the production line continues to operate sub-optimally. To address these challenges, the future of digital manufacturing focuses on adopting proactive measures and predictive problem-solving strategies. This evolution involves leveraging real-time data analytics to anticipate potential issues and implementing preventative actions before problems develop. Such an approach minimizes downtime and enhances overall efficiency, safeguarding against unforeseen challenges that could disrupt production.

As illustrated in Figure 3, the toolkit blocks described in Figure 2 are arranged into a cohesive flow chart, delineating how data traverses through a manufacturing facility. In a conventional factory setting, various groups or functions exist, such as engineering who operate on layer 1 in Figure 3 , operations, and quality assurance who operate on layer 2 in Figure 3, each executing specialized tasks based on their roles and responsibilities. Typically, the engineering department manages the historian systems, operations oversee the production data, and the quality assurance team handles the quality data.

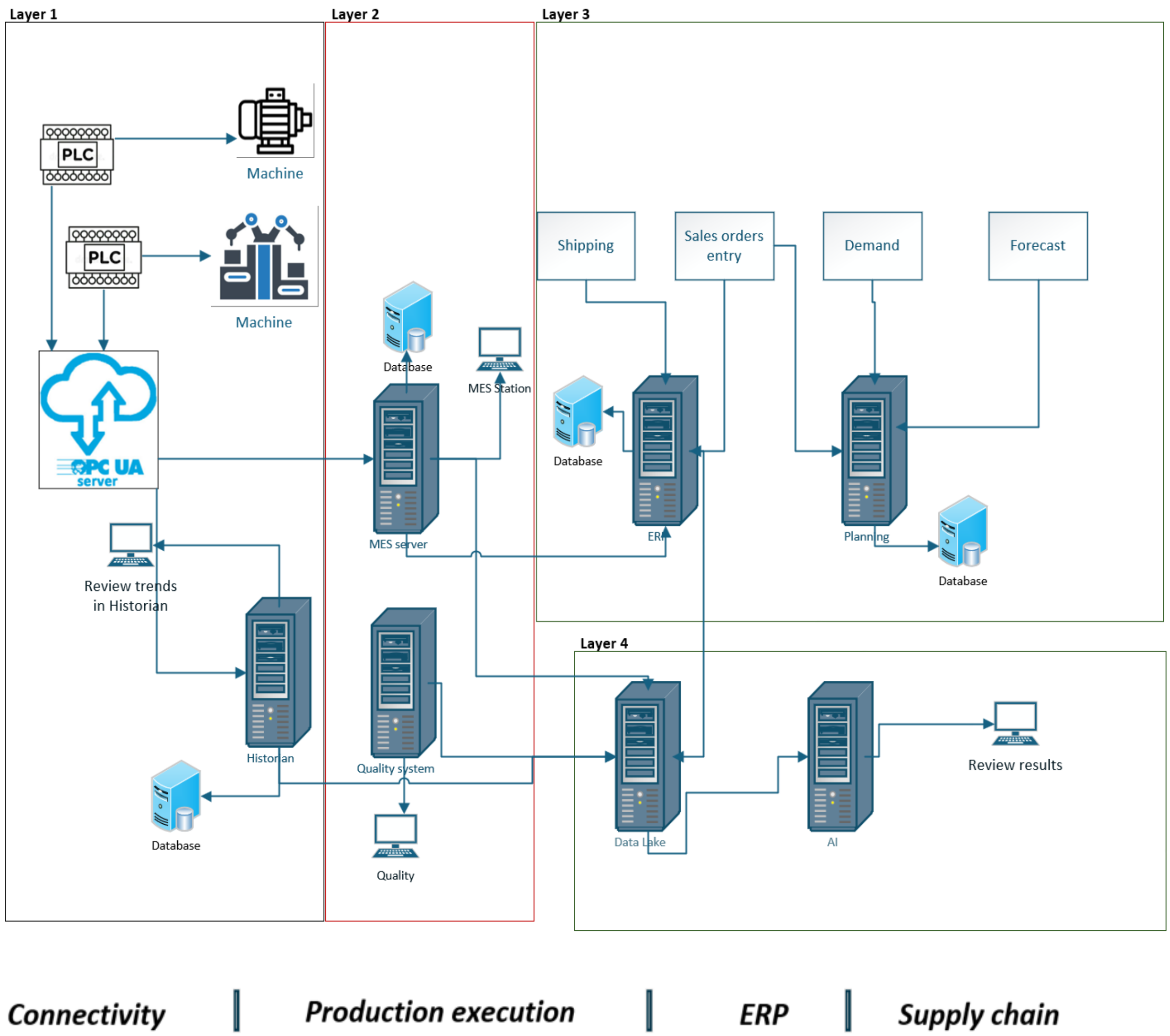

Figure 3. Typical Digital Manufacturing Flow

A significant industry challenge today is the lack of integration among these groups, which hinders the ability to make swift, impactful decisions. Individual departments tend to analyze their data in isolation, leading to reactive rather than proactive measures. Despite the presence of in-process quality checks designed to uphold product standards, inefficiencies persist. These checks allow for timely detection of anomalies, prompting corrective actions; however, they often result in considerable waste in the form of scrap materials.

Additionally, companies face enormous pressure in adapting to Industry 4.0. Without understanding the core problem of their own, more layers and tools get added, which increases complexity and makes coherence across teams for making real-time decisions even more challenging. For example, in the above Figure 3, one can see that production, operations, engineering, and planning each have their own set of tools, yet they are dependent on each other. As more layers come into play, making real-time decisions becomes challenging.

To counter these inefficiencies, factories should aspire to foster a more integrated approach that enables real-time data sharing and collaboration across departments. By creating a unified strategy, teams can collectively interpret data and respond to issues more promptly, reducing waste and improving overall efficiency. This integration facilitates not only immediate corrective actions but also creates a feedback loop that continuously optimizes processes, ultimately driving the factory towards greater operational excellence and more sustainable practices.

For example, in factories, startup scrap is usually high, and in the construction industry, where the production lines are longer, a multitude of machines must work in tandem. I have observed significant amounts of scraps being produced as engineering and operations teams attempt to resolve issues based on their existing knowledge and the tools they have traditionally employed. What is lacking in this process is an understanding of the leading indicators that impact startup performance and the lagging indicators that are indirectly responsible. Using the above example, if one applies blocks from the toolkit, it becomes evident that machine connectivity, historian systems, and the overlay of digital twins can be effectively implemented. By utilizing these three components, the system can predict and influence the behavior of the indicators. As a result, there is a very good chance that the startup process can be achieved with much less effort.

In the realm of operations management, a pivotal responsibility is to ensure that production schedules remain on track and to accurately gauge the progression along the production line. This task resembles the prediction or estimation of arrival times in aviation, where precision is vital. Such information is indispensable for production teams, enabling them to proactively address any emerging challenges. To manage this effectively, several key elements must be in place: detailed process parameters, seamless ERP system integration, real-time production metrics, and comprehensive insights into raw material consumption and availability.

For troubleshooting unexpected events, crucial data points are drawn from historian systems, manufacturing execution systems (MES), quality systems, and maintenance systems. While identifying the root cause of issues remains a primary objective, a more strategic approach involves forecasting potential issues before they manifest. Embracing this foresight allows for immediate corrective actions, leveraging MES insights, quality systems, historian data, artificial intelligence, and digital twin technologies. This approach elevates operations from reactive to proactive, minimizing disruptions and optimizing productivity.

In the downstream segments of production, ERP systems play a central role in overseeing financials, production processes, procurement activities, sales, and other core functions critical to daily organizational operations. Furthermore, effective supply chain planning hinges on accurate forecasting and demand analysis. It is essential to evaluate whether the plant can meet demand projections and to identify potential bottlenecks that must be addressed in strategic planning. By integrating these insights with long-term strategic objectives, organizations can ensure a responsive, resilient, and efficient operational model that consistently meets market demands. Through rigorous analysis, predictive modeling, and cross-functional collaboration, organizations are empowered to maintain operational excellence and achieve sustained growth.

As you can see, there are use cases at each point where different solutions are implemented, and the roles and responsibilities of each group evolve. The goal of digital manufacturing should be to bring these groups together while proactively highlighting issues and enabling prompt decisions to correct problems and maintain the course of production. Once these fundamentals are understood and implemented, digital manufacturing starts to take shape. Without this foundational knowledge, the focus might shift toward acquiring more tools to address isolated issues, leading to more systems being added to the customer ecosystem. This can complicate efforts to effectively implement digital manufacturing.
It is important to remember that tools such as AI, digital twins, historian systems, and MES are components; the real power lies in how these elements are orchestrated in harmony. This synergy is when digital manufacturing truly takes effect.

6. How to build a Digital manufacturing template

When it comes to building a digital manufacturing template, it's critical to understand the entire flow within the company rather than focusing on one particular layer. Every layer mentioned has its own challenges; however, there is a direct or indirect impact on the subsequent layers. Instead of addressing problems individually, one needs to understand their dependencies and where they fit into the digital manufacturing landscape before proceeding with implementation.

6.1 Eagle eye view approach

As you can see in Figure 4, taking an eagle's eye view approach is recommended to see the issues across the landscape. The phrase "eagle's-eye view" implies looking at the situation from a high vantage point. In digital manufacturing, this means not focusing solely on specific issues or components but instead considering the entire system as a cohesive whole. This comprehensive perspective allows for better strategic planning and integration of various elements within the manufacturing environment. Each layer has its own set of challenges as mentioned in Figure 4, and there is a direct or indirect impact on challenges between them. This is further explained in section 6.2.1

The components mentioned below might not be available at all the manufacturing sites, but it's important to break them down by layers as this approach fits most manufacturing plants. The problems mentioned in the boxes below are examples, and there could be more at each site. It's critical to identify the challenges across layers, and this is the first step in building the digital manufacturing template. Once problems are identified, it is important to understand their dependencies and where they fit into the digital manufacturing landscape.

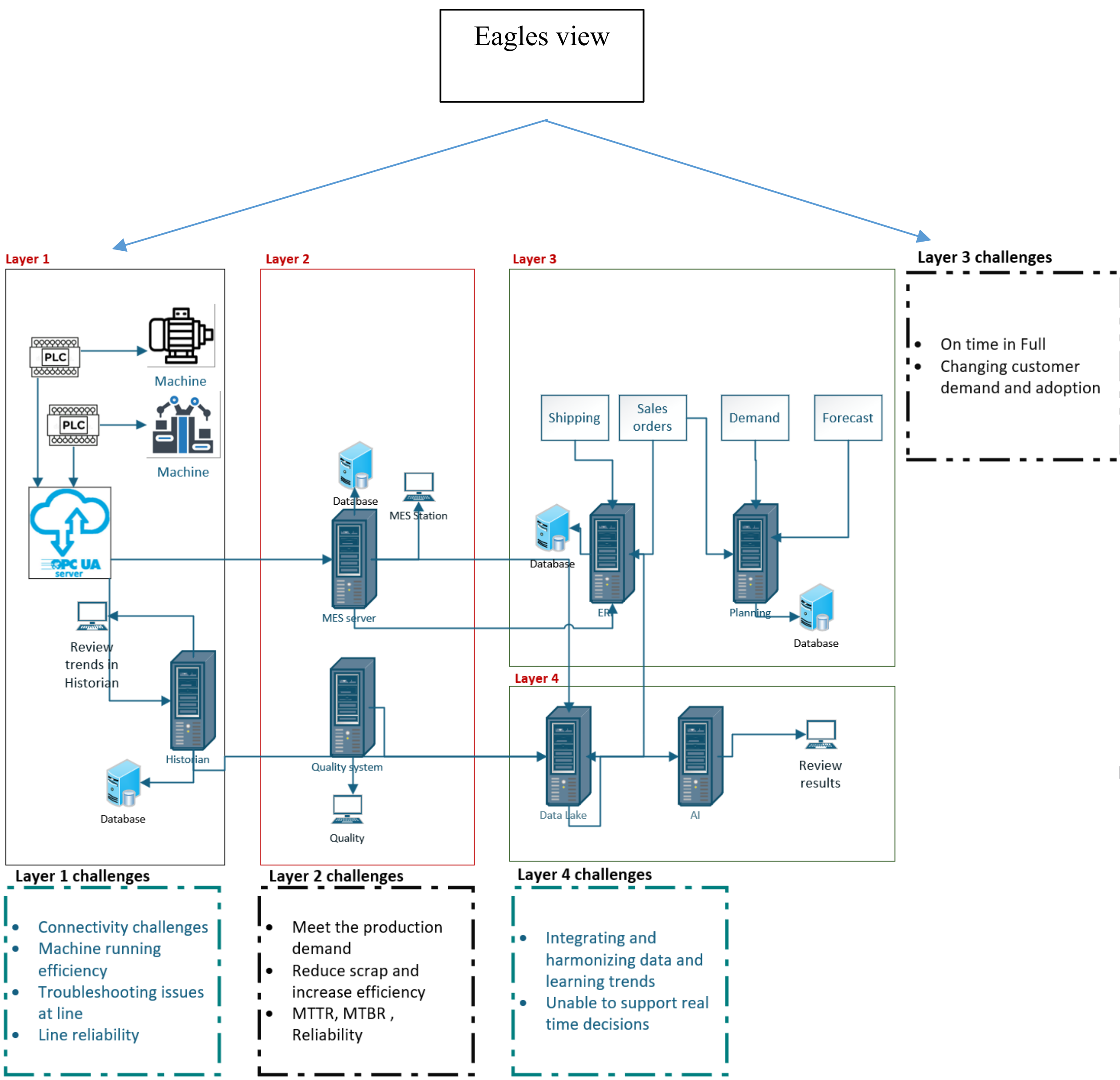

Figure 4. Eagles eye approach

The text notes highlighting the problems identified in Figure 4 in the boxes are exemplary, suggesting that they're not exhaustive and may vary greatly from site to site. Each manufacturing site has specific conditions, equipment, and processes that can lead to unique challenges. Recognizing both typical and site-specific problems is key to developing flexible, applicable solutions.

In Figure 4, for example, the Layer 1 challenges faced by Engineering & Maintenance involve ensuring connectivity, machine efficiency, and line reliability. This directly impacts Layer 2, where the production, operational, and quality teams are focused. The operations team is responsible for ensuring production demand is met, while the quality team focuses on maintaining product quality and minimizing scrap production. This directly affects Layer 3, which involves planning and meeting customer demand. Layer 4 extracts and interprets all the data, producing results that are typically discussed in stand-up meetings.
As one can understand, there is a strong dependency among layers, yet the modern-day challenge is to adopt a collaborative approach to solving core issues. What remains a challenge in the landscape mentioned in Figure 4 is the ability to take real-time actions and how the issues from one layer affect another.

6.2 Implementation approach

The goal of the digital manufacturing template is to solve problems in real-time and predict manufacturing issues rather than conducting a postmortem analysis and then trying to fix them. While predicting or forecasting a manufacturing issue will not happen overnight, a roadmap should be set for the digital manufacturing template to achieve this.

From Section 5.1, using the eagle's-eye approach, the key issues are identified. As part of this exercise, there are three key elements that should be considered:

1. How the issues from each layer affect one another. This step in the plan is to understand how these issues are interconnected and how they affect productivity or have an impact on them.

2. Getting groups to work together. It is important to identify how to bring the groups together to work collaboratively. A key practice in the implementation is to merge systems and create a common platform as much as possible. Once system consolidation occurs, collaboration begins, and the teams can orchestrate the problems into solutions.

3. Create solution to address problems in real time. Develop solutions for the issues encountered to address them in real-time.

Addressing the above key three steps should present a renewed digital manufacturing landscape.

6.2.1 How the issues from each layer affect one another

As a first step, once the layers are broken down, we need to identify how each issue is interconnected and assess its impact. For example, in Layer 1, if the critical machines are not connected and we are unable to achieve connectivity using OPC UA or other methods, troubleshooting becomes a challenge. In this case, the issue is only analyzed when the machine runs into a problem. Real-time troubleshooting is crucial because it directly impacts Layer 2, which could affect production. This, in turn, may have a cascading effect on order promises, potentially impacting customer delivery and affecting the OTIF (On Time in Full) metric. In Figure 5 below, arrows of the same color indicate the cascading effects on other layers. The important action here is not to address each problem individually but to understand which has the most cascading effects, estimate the time required to fix it, consider the associated costs, and then address it.

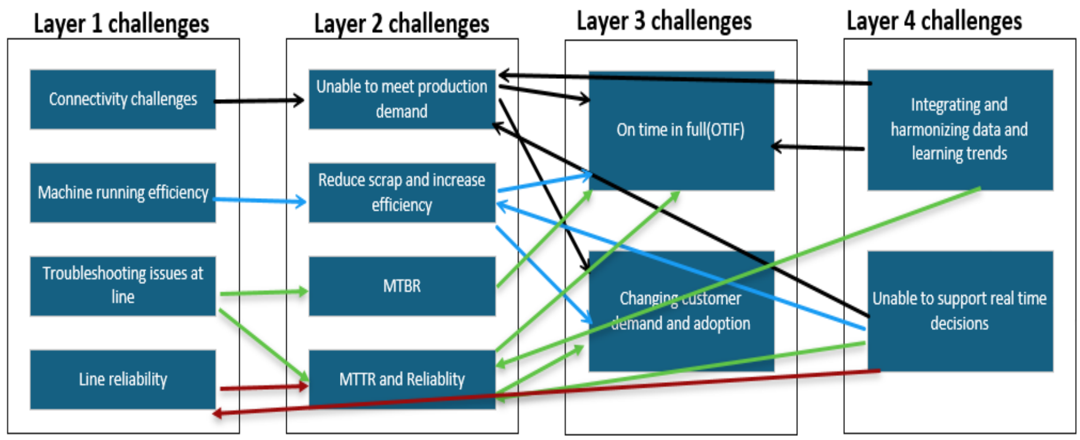

Figure 5. Issues from different layers affecting one another

6.2.2 Getting the groups to work together

As seen in Figure 4, engineering uses a historian, production has an MES, and quality has its own system. This situation is common across different landscapes and can vary between organizations. One key goal during implementation is to encourage these groups to work together to achieve synergy and improve real-time problem-solving. To address this, consolidating systems can be beneficial. For example, if the production line produces scrap, the cause might be that one of the key machine parameters is out of range. If the MES can trend the process parameters of the equipment, overlaying the time when the scrap was produced could reveal a correlation between the event and its cause. Similarly, if a quality metric measured in the quality system is out of spec, leading to downtime because production was not satisfactory, overlaying the process parameters, quality measurements, and downtime can help identify correlations. There are numerous examples on this topic, but the recommendation is not to consolidate every system in the landscape, as this is nearly impossible. However, consolidating critical touchpoints such as the MES, quality system, and process parameter trends, or creating a framework for groups to collaborate, should be prioritized.

6.2.3 Create solution to address issues in real time

One of the key goals of digital manufacturing is to address issues in real-time. During implementation, this should be set as an objective. When designing the digital manufacturing landscape, there must be an issue analysis loop in real-time. There are several ways this can be implemented:

Digital Twin: In this scenario, when an issue occurs, operations receive alerts in real-time. However, it is important to ensure that the digital twin is not implemented in an environment where post-facto analysis is done. Although this may offer slight improvement, it does not fully achieve the goal of digital manufacturing. The digital twin, coupled with recipe management of the item produced on the line, should be set up so that deviations can be detected in real-time, allowing for actions to be taken based on a correlation explained in section 5.2.1.Integrating Machine Learning: As shown in Figures 4 and 5, integrating operations, quality, and engineering, and enabling them to analyze trends related to issues, would also aid in making real-time decisions.

6.2.4 A renewed Digital manufacturing landscape

Considering the implementation from Sections 5.2.1 to 5.1.3, the renewed landscape is represented below. This is one such possibility, and numerous solutions can be developed based on objectives. However, the goal of digitization and problem-solving remains unchanged: how to address problems in real-time and predict production issues.In the example below, depicted in Figure 6, the MES system is transformed into a digital manufacturing system encompassing production, quality, recipe management, a digital twin, critical process parameters history, and trends—all within one system. This integration fosters collaboration, with the right reports and tools available in the system.
Additionally, artificial intelligence is integrated with the ERP system, making it an intelligent platform.

All these consolidations and implementations aim to address and predict problems in real-time.

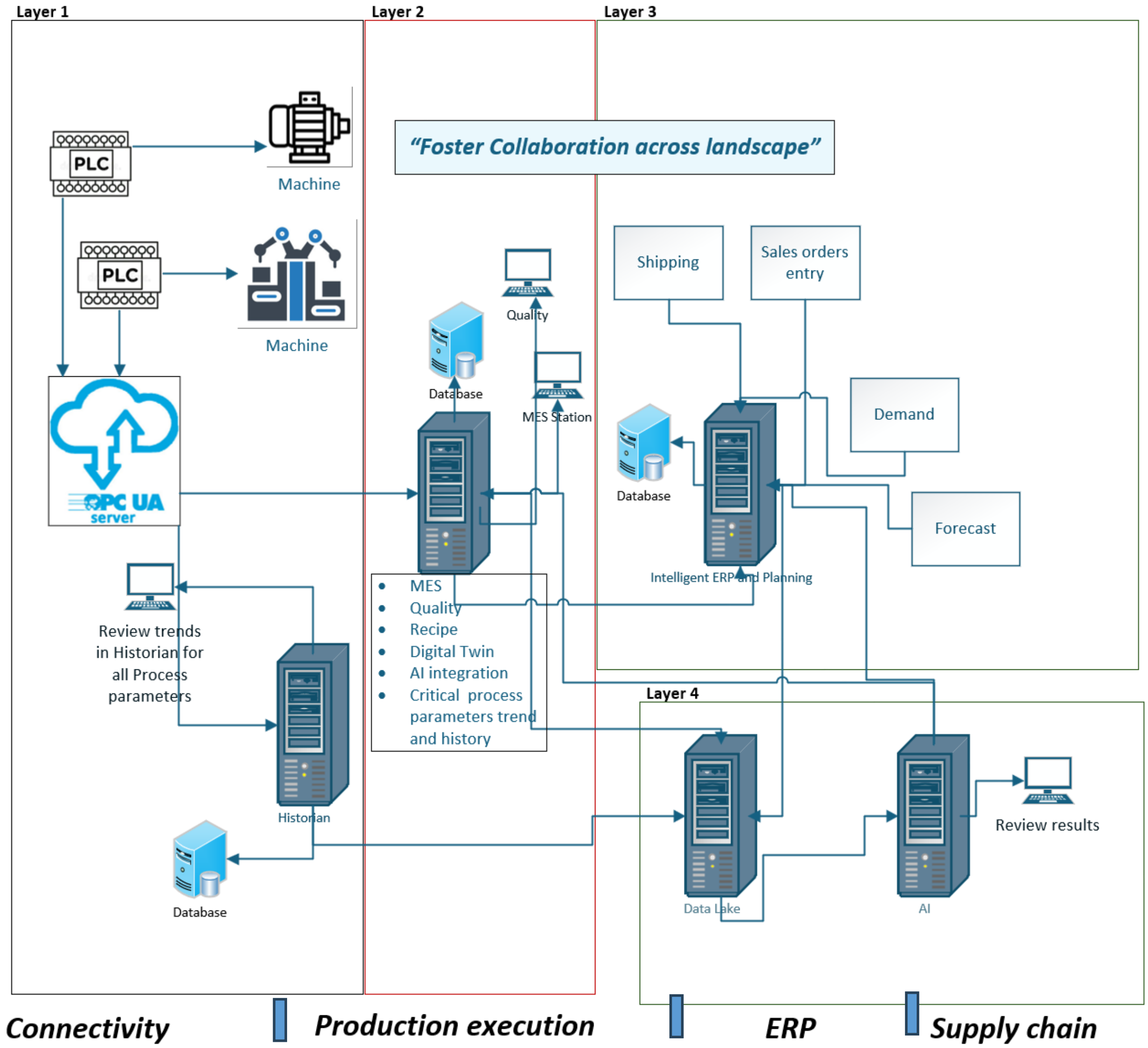

Figure 6. A renewed Digital Manufacturing landscape

Continuous improvement mindset

One of the core principles of manufacturing is Kaizen and the 5S framework (Chikwendu et al. 2020). The process of monitoring, measuring, and taking sustained action is key to a digital manufacturing process, as digital manufacturing is a continuous evolution. As the landscape becomes integrated, it is natural to encounter a new set of issues, and the 5S principles should be applied to mitigate these issues while aiming for continuous improvement.

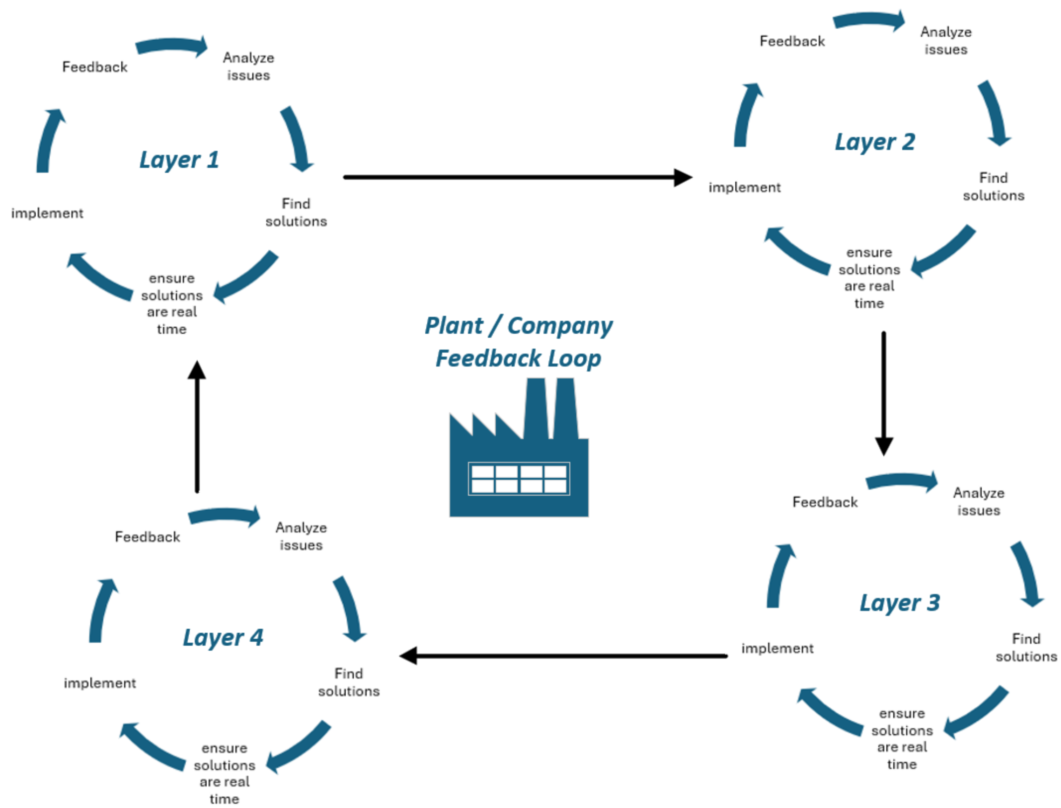

Figure 7. Feedback loop within layers and across landscape

As layers grow and complexities tend to rise, it's important to have a continuous feedback loop, as explained in Figure 7, within layers and ensure it's still integrated across the landscape so that the transformation aligns with the objective.

7. Conclusion

In conclusion, digital manufacturing represents a pivotal evolution in the industrial sector, enabling companies to enhance efficiency, agility, and innovation. By seamlessly integrating advanced technologies such as IoT, AI, and real-time data analytics, manufacturers can optimize operations, reduce costs, and meet the growing demands of a dynamic market environment. This transformation is not without its challenges, including potential security risks and the need for substantial investment in technology and skills development. However, the benefits—ranging from improved supply chain management to enhanced product customization—underscore the critical role of digital manufacturing in shaping the future of industry. As the implementation takes effect the layers integrate and become cohesive, real-time decisions can be made, improving production efficiency, reducing scrap, addressing supply chain issues, and ultimately establishing a foundation for scalable solutions to ongoing challenges.

As companies continue to navigate this digital shift, focusing on embedding robust cybersecurity measures, fostering a culture of continuous learning, and embracing sustainability will be essential to drive long-term success. Ultimately, the evolution of digital manufacturing holds significant promise for creating smarter, more resilient, and more responsive industrial landscapes, setting the stage for future innovations that can further revolutionize the way industries operate and interact with the world. It is imperative that stakeholders from all levels—technological, managerial, and policy-making—unite in leveraging these advancements to nurture an ecosystem that supports growth, innovation, and sustainability in the manufacturing domain. The journey ahead is challenging yet filled with opportunities for those who are willing to adapt and innovate.

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Biography

I am **Subash Senthil Mohanvel**, and my journey in digital manufacturing spans over two decades, driven by a passion for innovation and strategic transformation. As the Director of Digital Manufacturing at West Pharmaceutical, I lead the charge in integrating advanced technologies like SAP S/4 Hana and IoT into manufacturing and quality processes. My educational foundation, with a master's degree in information technology from the Royal Melbourne Institute of Technology, has equipped me with the skills to navigate and pioneer in the evolving digital landscape.

My career journey is defined by a series of significant achievements. I take pride in having led transformative projects that include automating guided vehicles, developing cutting-edge MES systems, and innovating industry 4.0 solutions that enhance operational efficacy. Recognitions such as the Manufacturing Leadership Council award and the Global Recognition Award for my contributions in manufacturing technology fuel my drive for excellence.

A core facet of my work involves pioneering mobile applications for maintenance and production, leveraging technologies like Neptune and SAP Mobility to streamline operations. I've enjoyed the privilege of mentoring diverse teams, fostering a culture of high performance and collaboration between onshore and offshore units. Holding numerous certifications and with a history of successful project execution, my mission remains steadfast: to shape the future of digital manufacturing through continuous innovation and excellence.