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Intelligent Manufacturing Execution System: Making Real Time Decision a Reality

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Abstract

In today's competitive and rapidly evolving manufacturing landscape, relying on real-time data is essential for maintaining a competitive edge and making informed decisions immediately. Real-time data, which becomes available as it is generated, plays a pivotal role in enhancing operational efficiency. It enables manufacturers to continuously monitor machinery and processes, allowing for the quick resolution of any inefficiencies or discrepancies in the production line. Additionally, real-time data, combined with corrective actions, maintains stringent quality control by providing immediate feedback on production processes. This prompt feedback helps manufacturers address quality issues swiftly and ensure product consistency. In terms of supply chain optimization, real-time data offers operational visibility, facilitating improved inventory management and timely deliveries, and thus mitigating risks like overproduction or stockouts. Real-time decision-making reduces response times, enabling manufacturers to adjust production schedules, orders, and troubleshooting activities with agility. These insights also enhance forecasting accuracy, align production with market needs, and drive innovation by identifying areas for improvement in both products and processes. However, implementing a Manufacturing Execution System (MES) that enables real-time decisions using such data involves certain challenges. These challenges include the high cost and complexity of integrating new systems with existing infrastructure, the need for comprehensive staff training, and ensuring data security and integrity. Overcoming these challenges requires a strategic approach and investment. While integrating real-time data into the decision-making process presents challenges, this paper endeavors to address these obstacles and transform the manufacturing execution system into a more intelligent entity, boosting productivity and diminishing losses. By tackling these challenges, manufacturers can optimize their operations, consistently meet customer expectations, and foster a culture of continuous improvement and innovation, which is crucial for long-term business success.

Keywords
Digital manufacturing, Industry5.0, Digital Twin, Big Data, Manufacturing Execution system, real time decision making

1. Introduction
In today's competitive and rapidly evolving manufacturing landscape, the reliance on real-time data has become essential for maintaining a competitive edge and making informed decisions. These systems form the backbone of contemporary manufacturing processes, facilitating the seamless integration of real-time data collection, sophisticated analysis, strategic decision-making, and eventually paving the path for Industry 4.0. With the global manufacturing market valued at approximately 14.85 trillion USD, its critical role within the global economy is profound, underscoring the imperative for highly efficient and responsive manufacturing systems(Shevgan, 2025). The manufacturing industry is the backbone of the economy, and its growth must be enabled and sustained. One of the key factors for growth is optimizing and improving processes. To facilitate this, real-time decision-making with real-time data is critical. Numerous research articles have explained the need for real-time data and how it influences decision-making. The paper by Cowling and Johansson explains how real-time data affects scheduling in manufacturing

(Cowling et al., 2022). Another study highlights how real-time data can inform decision-making(Yu and Zhuo,2025). Extensive research has underscored the efficacy of using real-time data to make informed decisions, yielding positive outcomes. A thought-provoking article from Harvard articulates that data-driven manufacturing represents the new wave poised to propel efficient and responsive production systems. Yet, to transcend the hype, managers must navigate underlying challenges and paradigm shifts(Shih and Ludwig, 2016).

Translating the theoretical knowledge and insights garnered through research on real-time data in manufacturing into practical application can be fraught with challenges. Despite extensive evidence supporting the potential of real-time decision-making with live data from the plant and improving operational efficiency, several barriers must be overcome to realize its full benefits in a real-world setting. The successful deployment of real-time data systems necessitates comprehensive staff training and collaboration among different teams when interpreting the data. Additionally, employees must be equipped with the skills to interpret and act on data insights, which requires a cultural shift towards data-driven decision-making. This transition can be difficult, as it involves altering established workflows and overcoming resistance to change within the organization. While the theoretical benefits of real-time data in manufacturing are well-documented, actualizing these benefits requires overcoming significant hurdles in technology integration, cost, and training.

This paper is dedicated to tackling the significant challenges faced during the development of an intelligent Manufacturing Execution System (MES) that enables real-time decision-making. It seeks to offer comprehensive insights by meticulously deconstructing these challenges into clear, actionable steps. The paper aims to empower manufacturers with the knowledge required to design and implement a robust and sophisticated intelligent MES system that enhances operational efficiency with real time decision making and embraces the future of manufacturing.

1.1. Research Questions

RQ1: How can manufacturers overcome the major barriers—such as lack of vision, team misalignment, infrastructure limitations, and decoupled systems—to successfully implement an intelligent MES capable of real-time decision-making?
RQ2: What methodology or framework can guide organizations in migrating from conventional MES systems to an intelligent, AI-enabled MES that supports proactive, real-time decision-making?
RQ3: How can real-time data be effectively integrated, interpreted, and utilized across cross-functional manufacturing teams to improve efficiency, reduce scrap, enhance quality, and support continuous improvement?

2. Objective

The objective of this paper is to address the critical challenges associated with integrating real-time data into decision-making within Manufacturing Execution Systems (MES), thereby transforming them into more intelligent and efficient entities. By providing comprehensive insights and actionable strategies, the paper aims to help manufacturers overcome barriers related to technology integration, cost, and training, facilitating a seamless transition towards data-driven decision-making in real time. Ultimately, this paper endeavors to empower manufacturers to optimize their operations, improve forecasting accuracy, and foster a culture of continuous improvement and innovation. These advancements are essential for achieving significant productivity gains and sustaining long-term business success in the competitive landscape of digital manufacturing and Industry 5.0.

3. Literature Review

The increasing reliance on real-time data in manufacturing has been widely documented as a critical enabler of operational efficiency and agile decision-making. Cowling and Johansson demonstrated that real-time information significantly improves scheduling accuracy and responsiveness within dynamic production environments (Cowling and Johansson 2002). More recent studies, such as Yu and Zhuo (Yu and Zhuo,2024), extend this understanding by showing how high-frequency data updates can enhance production planning and control through predictive insight. Industry analyses, including Shih and Ludwig (Shih & Ludwig, 2016), further argue that while data-driven manufacturing promises transformative benefits, organizations often struggle with technological complexity, cultural resistance, and fragmented systems.

Research on Industry 4.0 and smart manufacturing also highlights persistent organizational challenges. Bakhtari et al. emphasize that gaps in leadership vision and cross-functional alignment inhibit successful digital transformation. Studies on team collaboration, including those by Che Ibrahim et al., underscore the importance of integrating engineering, operations, maintenance, and IT to fully leverage real-time insights. Concurrently, literature on manufacturing infrastructure stresses the barriers posed by legacy systems, data silos, and limited interoperability. Within this context, the evolution toward intelligent Manufacturing Execution Systems (MES) emerges as a focal point. Scholars identify AI-enabled analytics, predictive maintenance, and integrated digital architectures as essential for realizing Industry 5.0 capabilities, shifting manufacturing from reactive to proactive, intelligence-driven operations.

4. Method: Current Challenges faced at the manufacturing plant in building an intelligent Execution system

There are various challenges faced by industry today. While the challenges faced at each plant or company could be different, when you start classifying, we can organize them into different categories. Majority of them are listed below.

1. Team structure and their collaboration
2. Lacking Vision
3. Execution strategy
4. Infrastructure challenges
5. Decoupled systems/conventional MES systems

4.1 Team structure and their collaboration

In today's manufacturing sites, a multitude of teams are intricately involved in ensuring seamless operations. A world-class manufacturing paper categorizes the entire manufacturing process into eight departmental categories (Sean). Within these, the production department is further segmented into specialized divisions such as Engineering, Quality, Infrastructure & IT, Operations, Maintenance, Human Resources, and Management. These divisions, as depicted in Figure 1, illustrate a common structural blueprint, with minor site-specific variations.

An article on Industry 4.0 challenges highlights that organizational constraints often stem from the interaction between various groups (Bakhtari et al, 2020). Despite the differing dynamics among these groups, core teams like Engineering, Production, and Maintenance hold pivotal roles due to their direct impact on production outputs. Research on team collaboration, discussed by Che Ibrahim et al., emphasizes how co-located teams foster effective communication and knowledge sharing, thereby strengthening relationships and boosting engagement with project objectives. Moreover, integrating teams is vital for transitioning away from the adversarial culture prevalent in traditional procurement models, paving the way for seamless operations and shared success.

While each team is goal-oriented, the real challenge lies in engaging them in a unified objective and translating this into team-specific actions. This complex endeavor is a significant focus for numerous plants, reflecting the contemporary pursuit of efficiency and excellence in manufacturing.

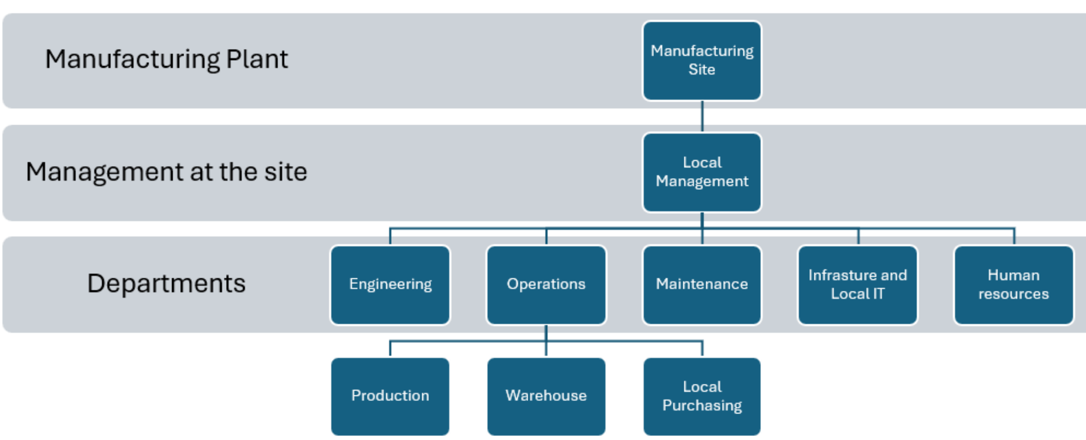

Figure 1. Departments at the manufacturing plant

4.1.1. Study - Analysis of team structure and decision making at manufacturing sites

A comprehensive study was conducted across fifteen manufacturing sites as part of a rollout project encompassing various business units and divisions, revealing consistent behavioral patterns. Within these sites, engineering was tasked with ensuring machine connectivity and played a key role in overseeing projects aimed at maintaining continuous machine operation. This effort was supported by both local engineering teams and a central engineering unit providing overarching guidance. Similarly, operations teams were responsible for ensuring that production schedules were met efficiently while actively working to reduce scrap, with a central team offering oversight and direction. The IT department played a crucial role in deploying technological solutions, tailoring system-based solutions to meet the specific needs of all departments to ensure seamless integration and support. Maintenance teams contributed significantly by assisting the operations teams and focusing on preventing machine breakdowns, with a central reliability expert providing strategic guidance.

Additionally, each department holds daily stand-up meetings designed to address ongoing challenges and prioritize them efficiently. Despite each department having its distinct priorities and overlap in objectives, there was a lack of a clearly defined vision for fostering synergies between teams to effectively tackle real-time challenges. Figure 2 shown below explains the overlap in priorities and the engagement across teams. Information technology (IT) team catered to all departments and had a relationship with across departments. Most departmental actions were reactive, focusing on past data and events without a strategic framework for immediate decision-making.

This gap highlighted a significant **oversight in facilitating real-time decision**-making processes aimed at reducing scrap and boosting operational efficiency. Emphasizing these areas could bridge existing gaps, fostering a culture of proactive, data-driven innovation.

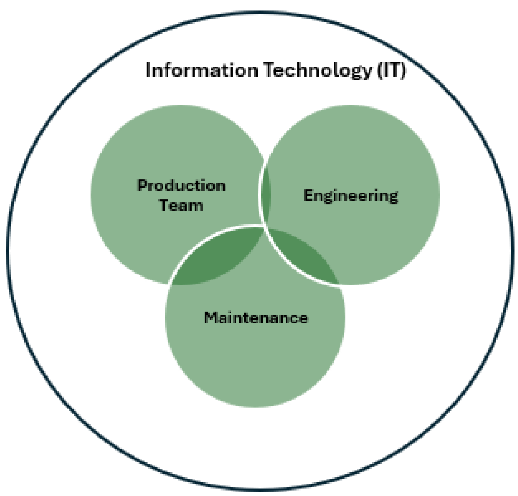

Figure 2. Team objective overlap and the integration between teams

4.2. Lacking vision

A clear vision is crucial when implementing industry4.0 initiatives because it provides direction, motivation, and a framework for making decisions. Firstly, a well-defined vision establishes a clear purpose, helping individuals and teams understand what needs to be achieved and why it's important. This clarity aligns all actions towards a unified goal, minimizing confusion and enhancing focus. In the context of implementing Industry 4.0, vision plays a critical role as it establishes a strategic framework through which organizations can navigate the complexities and challenges associated with this transformation. According to the study, one of the primary barriers to effective Industry 4.0 implementation is a "lack of vision and leadership from top management," which is emphasized as a fundamental challenge that can halt progress in its tracks ((Bakhtari et al.,2020).

The study conducted across fifteen manufacturing sites highlighted that, although teams had specific objectives and demonstrated a strong appetite for progress, there was a glaring absence of a unified vision towards fully embracing Industry 4.0. Each department, from engineering and operations to IT and maintenance, efficiently met their immediate goals—such as ensuring machine connectivity, adhering to production schedules, and deploying technological solutions. However, the lack of an overarching vision hampered their ability to synergize efforts and effectively address real-time challenges.

This missing vision meant that while the organizational appetite for innovation and improvement was apparent, teams struggled with direction and lacked a cohesive strategy for implementing Industry 4.0 principles. Consequently, actions tended to be reactive, centered on past data without a strategic framework for immediate decision-making. Bridging this gap through a well-defined vision could align departmental priorities, foster proactive, data-driven processes, and pave the way for seamless integration of Industry 4.0 technologies across the organization (Table 1).

Based on the observation conducted across various sites and as detailed in Table 1, each department's objectives, their eagerness for innovation, and the critical missing vision are thoroughly analyzed alongside the encountered challenges. While the drive and readiness to embrace Industry 4.0 are evident across engineering, operations, IT, and maintenance teams, the absence of a cohesive vision is apparent. This lack of strategic alignment and direction hinders departments from fully realizing the potential of Industry 4.0, highlighting the necessity for a unified vision to guide targeted initiatives and ensure progress is tangible and sustainable.

Table 1. Analysis of Department Objectives and Vision Gaps in Industry 4.0 Adoption

Department	Objectives	Appetite	Missing Vision	Challenges
Engineering	Ensure machine connectivity and oversee projects to maintain continuous machine operation.	High readiness for innovation	No centralized vision for aligning engineering efforts towards Industry 4.0.	Reactive operations, focusing on past data for connectivity issues.
Operations	Meet production schedules efficiently and actively reduce scrap.	Strong desire for process optimization	Lack of direction on how operations fit into the greater Industry 4.0 framework.	Difficulty in implementing real-time data solutions for operational efficiency.
Information Technology	Deploy technology and tailor system solutions to meet departmental needs.	Eager to facilitate interconnectivity	Missing strategic alignment with overall Industry 4.0 goals.	Disconnected from a unified vision, addressing ad-hoc requirements.
Maintenance	Assist operations and engineering, focus on preventing machine breakdowns.	Interested in predictive maintenance	Lacks vision for predictive analytics-based preventive maintenance.	Reactive maintenance strategies not fully leveraging real-time data.

4.3 Execution Strategy

A lack of knowledge in implementing solutions is a significant barrier to transforming a Manufacturing Execution System (MES) into an intelligent, real-time decision-making platform. This knowledge deficit affects several crucial areas in an execution strategy essential for embracing Industry 4.0.

A fundamental challenge is that understanding the technology and its implementation is often missing. Without this understanding, formulating a clear and strategic vision becomes difficult, leading to fragmented and misaligned departmental efforts. In terms of technology integration, these knowledge gaps can result in improper implementation, causing compatibility issues and preventing the full utilization of advanced analytics.

Furthermore, company representatives fear both a potential increase in system complexity and the implementation of immature technologies, which could result in unstable systems. Due to their interconnectedness, these systems might compromise functional product safety and process quality, eventually leading to production downtimes.

Inadequate knowledge also hampers collaborative team dynamics, as interdepartmental cooperation relies heavily on a shared understanding of technological innovations**.** The ability to break down strategies into executable tasks is also lacking, preventing efficient conversion of strategic goals into **actionable plans.** Qualification of employees for process planning and coordination responsibilities requires adequate training and development approaches. Additionally, the challenge of maintaining long-term employee loyalty against the backdrop of a skilled worker shortage highlights the necessity for continuous engagement and development (Kiel et al.,2017).

Moreover, while one of the goals of enabling technologies is to maximize the availability of manufacturing assets, it is equally important to consider the availability of the enabling technologies themselves (Lee et al.,2020).

This deficiency impacts the development of continuous learning programs, leaving employees unprepared for efficient real-time data interpretation. Additionally, it affects strategic investments, where decision-makers may misallocate resources due to a failure to align with Industry 4.0 objectives.

To address these challenges, organizations must invest in education and training, develop a comprehensive understanding of new technologies and implementation strategies, and foster a culture of knowledge sharing. By overcoming these deficiencies, companies can effectively execute strategies that align their MES upgrades with Industry 4.0 goals, ensuring sustained competitive advantage.

4.4 Infrastructure challenges

Implementing an intelligent Manufacturing Execution System (MES) capable of real-time decision-making introduces several infrastructure challenges that organizations must navigate to fully embrace Industry 4.0.

One primary challenge is the integration of new technologies with existing legacy systems. Many organizations operate with outdated infrastructures that may not be compatible with the advanced analytics and real-time data processing required for Industry 4.0 adoption. This can result in significant compatibility issues, necessitating costly upgrades or complete overhauls of existing systems to ensure seamless data flow and integration. Furthermore, the increased system complexity associated with implementing intelligent MES systems can lead to potential instability. As these systems become more interconnected, ensuring the reliability of technologies becomes crucial to maintaining functional product safety and process quality. Any instability could result in production downtimes and compromise the overall system efficiency and safety.

Another significant infrastructure challenge is related to ensuring the availability and reliability of enabling technologies themselves. With the emphasis on maximizing the availability of manufacturing assets, organizations must also focus on the robust deployment of enabling technologies to prevent bottlenecks and disruptions.

Establishing an infrastructure for effective communication between the manufacturing company and its strategic suppliers is also crucial (Alami and ElMaraghy,2021). This involves developing reliable channels for information exchange to ensure that all stakeholders are aligned, facilitating real-time data sharing, collaboration, and coordination across the supply chain. This communication infrastructure is essential for synchronizing operations, improving supply chain efficiency, and responding swiftly to any changes or disruptions.

Addressing these infrastructure challenges requires strategic planning, significant investment in upgrading technologies, and a comprehensive understanding of the necessary integration requirements. Organizations need to develop clear strategies for seamless technology integration, invest in scalable infrastructure, and foster a culture of continuous improvement and learning to adapt to new challenges effectively.

4.5 Decoupled systems / conventional MES system

In many traditional manufacturing environments, critical systems such as Enterprise Resource Planning (ERP), Supervisory Control and Data Acquisition (SCADA), Laboratory Information Management Systems (LIMS), and Quality Management Systems (QMS) operate in isolation. These siloed or decoupled systems create operational inefficiencies, data delays, and inconsistent decision-making frameworks across the enterprise. For instance, production data collected at the machine level might not flow instantly to quality or planning departments. As a result, deviations or equipment inefficiencies are often discovered only after a batch is completed, leading to downtime, rework, and compliance risks. The lack of integration also prevents holistic performance monitoring—each system optimizes only its local processes, not the enterprise-wide outcome.

In pharmaceutical and life sciences manufacturing, this decoupling poses a serious regulatory and operational risk. Regulatory submissions (e.g., FDA or EMA) require traceable, validated electronic records across the entire product lifecycle. When MES, QMS, and ERP systems are disconnected, maintaining data integrity and audit trails becomes tedious and error-prone.

As shown in Table 2 below, each plant typically operates through multiple interconnected levels that communicate data across the production hierarchy. However, while data exchange between these layers exists, troubleshooting remains largely reactive rather than proactive. This approach often results in unplanned downtime, production losses, and increased scrap generation — all of which contribute to higher operational costs.

Table 2. Different levels in the plant floor

Level	**Automation Pyramid**	**Key Systems/Functions**
Level 0	Process	Sensors, actuators, physical equipment
Level 1	Intelligent Devices/Basic Control	PLCs, RTUs, controllers
Level 2	Supervisory Control	SCADA, HMI
Level 3	Manufacturing Operations	MES, historians, maintenance, batch management
Level 3.5	DMZ/Integration	Event brokers, firewalls (OT-IT bridge)
Level 4	Business/Enterprise	ERP, logistics, planning

An Intelligent MES addresses this challenge by acting as the central integration layer connecting plant-floor automation (OT) with enterprise information systems (IT). It unifies operational data, automates handoffs between processes, and enables real-time visibility and closed-loop feedback. Through standardized interfaces and data models (e.g., OPC UA, ISA-95, and API-based connectors), it transforms decoupled, production-oriented workflows into a synchronized digital ecosystem.

5. Methodology: Migrating towards Intelligent MES with real time decision making (Industry5.0)

There are five building blocks that lead to intelligent MES system (Figure 3).

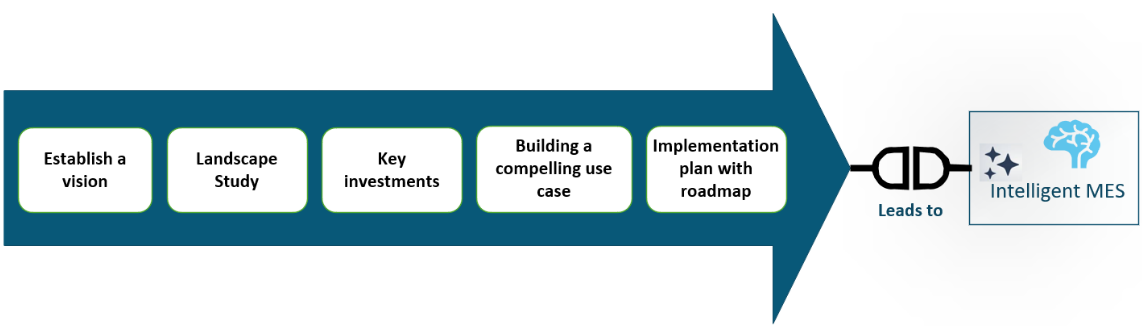

Figure 3. Steps needed to build an intelligent Manufacturing Execution system

As shown in Figure 3 above there are five main components that need to be implemented to build an intelligent Manufacturing Execution system (MES) system. They are as follows:

1. Establishing a Vision
2. Landscape study
3. Key investments
4. Building a compelling use case

5. Implementation plan with road map

5.1. Establishing a vision

Crafting a clear and compelling vision is often perceived as elementary; however, it is a fundamental step where many organizations encounter challenges when charting a path toward an intelligent Manufacturing Execution System (MES). Vision is a cornerstone in the development of an MES with real-time decision-making capabilities, acting as a vital blueprint that directs strategic efforts. Support from senior leadership is vital in making this a reality. This vision not only provides clarity and direction but also aligns the actions of diverse teams, serving as a guiding star throughout the entire development and implementation process. By integrating key elements—such as comprehensively understanding the specific problems to be addressed and planning for scalable growth—the vision evolves into a robust framework. This ensures that all initiatives are purposefully geared toward achieving transformative improvements, resulting in a more agile, efficient, and intelligent manufacturing operation.

I. To set the vision one need to understand what Problems the Organization is aiming to Solve:
   - Real time decision making: Reduce production loss, improve yield, efficiency and reduce cost.
   - Production Efficiency and Bottlenecks: The vision should address challenges such as inefficiencies in the production process, bottlenecks affecting throughput, and the need for optimized resource allocation. By setting clear objectives, the organization can focus on automating manual processes, reducing waste, and improving the overall flow of production.
   - Quality Assurance: In terms of quality, the organization aims to minimize defects, enhance product consistency, and maintain compliance with industry standards. Incorporating real-time quality control and predictive maintenance into the MES can help address these issues, resulting in higher customer satisfaction and reduced costs.
   - Cross-Landscape Integration: Across different landscapes—such as supply chain management, inventory control, and demand forecasting, the vision should address the silos that lead to fragmented data and decision-making. An intelligent MES with real-time capabilities can facilitate seamless data integration, delivering a holistic view of operations.

II. How the above problems are interconnected and where we find the most bang for the buck:

The problems in production, quality, and across landscapes are highly interconnected (Mohanvel, Subash,2025):
   - Impact on Production: Inefficiencies in production can lead to delays and increased costs, directly affecting quality and delivery times. If one aspect of the process fails, it can impact the entire system.
   - Quality Issues: Poor quality can result in rework or recalls, affecting production schedules and costing the organization significantly. Real-time data analysis can preemptively identify quality issues, thereby reducing these risks.
   - Data Silos: Lack of integration across landscapes, such as logistics and supply chain, may lead to misinformed decision-making. Real-time, interconnected data from an intelligent MES enhances visibility across the organization, allowing for proactive, informed decision-making.
     For example, in a manufacturing plant, connectivity issues with the equipment could impact on the quality of the product, resulting in increased losses and affecting the delivery of the product. This, in turn, impacts on customer satisfaction when delivery dates are not met. Thus, an engineering department issue at the site can have a direct or indirect impact on the customer. This aspect is often lacking in the industry today, as attention towards cross-department or passive impact is not typically considered.

5.2. Building a compelling use case

When migrating toward an Intelligent MES, developing a compelling and well-defined use case is critical for ensuring success and building trust in the system. The key lies in leveraging the connected framework to address high-priority business challenges and creating scalable pathways for future problem-solving. **Many organizations fall short in this area**, as the true return on investment is lost when implemented solutions fail to achieve adoption or reuse.

It is vital to recognize that every customer environment is unique, each shaped by its distinct processes, constraints, and operational nuances. Instead of applying a one-size-fits-all approach, begin with a comprehensive study of your own landscape—analyzing existing bottlenecks, inefficiencies, and improvement opportunities. Dive deep into the specific operational realities and pain points that define your industry and organization.

By developing use cases that are directly aligned with these insights, organizations can create focused, value-driven solutions that precisely address real-world challenges. This tailored approach not only enhances the technical effectiveness of the system but also strengthens stakeholder engagement by demonstrating a genuine understanding of their unique operational context.

Ultimately, such a strategy ensures that the implementation of an Intelligent MES results in tangible business outcomes, driving sustained improvements in performance, compliance, and decision-making. **Table 3** highlights a few representative customer/business use cases and their measurable business impacts. These use cases must be carefully defined and validated before system deployment to ensure that the Intelligent MES delivers the full potential it promises.

Table 3. Uses cases for the intelligent MES system

Use Case	**Challenge in Traditional MES**	**Intelligent MES Capability with use cases**	**Business/Operational Impact**
Scrap Reduction	Lack of real-time insight causes late detection of quality deviations or parameter drifts.	Integrates real-time process analytics, machine vision, and AI-driven quality monitoring to identify anomalies early.	Minimizes rework and material waste, improves Right-First-Time yield, and strengthens process capability.
Downtime Reduction	Equipment breakdowns often discovered only after failure, disrupting production schedules.	Uses predictive maintenance models that analyze sensor data (vibration, temperature, pressure) to forecast potential failures.	Reduces unscheduled downtime, improves asset utilization, and supports continuous production flow.
Integrated Maintenance and Timely Intervention	Maintenance activities performed on rigid time schedules rather than actual equipment condition.	Enables predictive-based maintenance by correlating MES data with asset health indicators and production throughput.	Ensures maintenance is performed "at the right time", balancing availability with reliability; minimizes unnecessary interventions.
Performance Optimization	Disconnected systems provide limited visibility into real production efficiency (OEE, throughput, cycle time).	Provides unified KPIs with drill-down analytics across lines, shifts, and products; supports automated root cause insight.	Improves productivity and facilitates continuous improvement cycles through data-driven decisions.
Quality & Compliance Automation	Manual batch documentation and delayed deviation handling in pharma and regulated industries.	Auto-captures process data and generate electronic batch records (EBR) compliant with GAMP 5 and 21 CFR Part 11.	Reduces human error, ensures traceability, and enhances audit readiness.
Supply chain	Unable to accurately predict when production will be completed; only rough estimates are provided.	Accurately predict production completion timelines and offer alternative options to enhance customer satisfaction and ensure optimal utilization of the production line.	Increased revenue and reduced operational costs.

Start Small and Then Scale:

Starting with a pilot use case allows the organization to test the intelligent MES on a smaller scale, addressing key pain points without overwhelming complexity. For example, implementing predictive maintenance in one facility helps validate the technology and processes. It's not a plug and play as mentioned in paper (Mohanvel, 2025) and needs to understand how it can be done. Once the use case is implemented and proven, the system can be scaled to other parts of the operation, adapting and refining according to specific needs and feedback.

Using the five key steps outlined, create a vision that aligns with all departments and stakeholders involved, engaging them in the pursuit of this vision.

5.3. Landscape study

Conducting a comprehensive landscape study is essential to understand the current composition of the operational environment. This study begins with identifying the elements that constitute the present landscape—ranging from the infrastructure and technological frameworks to the processes and personnel involved—across different departments such as engineering, operations, maintenance, infrastructure, quality, and warehouse. It's crucial to discern which components have the potential to scale, as well as those that do not, enabling informed decisions about future growth and enhancements. Another option could be to perform the study based on the use case from section 4.2. This could reduce the or tailor the cost as per the need.

Furthermore, assessing real-time connectivity within this landscape, department by department, is vital to determine the efficiency and responsiveness of operations throughout the plant Establishing which elements within each department offer seamless connectivity can highlight areas ripe for enhancement. Additionally, identifying critical equipment, such as specialized machinery in engineering or inventory systems in the warehouse, and evaluating their connectivity and integration into the broader system helps prioritize upgrades and improve operational synergy. Through this detailed examination across all departments, organizations can effectively strategize and transform their landscapes to foster innovation, drive sustainable growth, and ensure cohesive operational success (Table 4).

As explained in Figure 4, in a typical manufacturing site, there are several departments as explained in Figure 1 spread across the landscape and the entire landscape needs to be studied.

Table 4. Topics to be studied and scored

Area	**Topic of study**	**Importance**	**Review scale of 1 to 10**
Infrastructure	Access Points for Wi-Fi Connection	Installed to ensure robust Wi-Fi connectivity across the manufacturing site to support mobile interfaces and system integration.	1….10
Infrastructure	PLC Integration with Critical Equipment	Programmable Logic Controllers (PLCs) are integrated with critical equipment to monitor and control manufacturing processes in real time.	1….10
Infrastructure	Data access to all PLC	Can all PLC data be tapped in to and are all the critical data points accessible	1….10
Infrastructure	Servers	On-site servers are installed to support the systems architecture, with scalability features to manage increasing data loads and future expansion.	1….10
Infrastructure	Operating Systems	Various operating systems are employed across the infrastructure to ensure compatibility and seamless operation of the digital manufacturing systems.	1….10

Operations	Raw Material Tracking	Systems are in place for the precise tracking of raw materials throughout the production process, ensuring efficient inventory management and quality control.	1….10
Operations	Employee Engagement Towards Change and knowledge	Initiatives are implemented to enhance employee participation and adaptability in embracing new technologies and process improvements, supporting continuous innovation and operational excellence.	1….10
Security	Security	Security protocols are in place to protect data integrity and manufacturing systems against unauthorized access or cyber threats, safeguarding critical operations.	1….10
Operations	Current Practices in Operations and quality	The current operational practices focus on enhancing production efficiency through digital manufacturing techniques and lean management strategies. These practices aim to reduce waste, improve quality, and streamline processes.	1….10
Operations	Challenges	Challenges include adapting to rapidly changing technological trends, ensuring cybersecurity, maintaining consistent employee engagement, and managing the scalability of systems to accommodate growing data and process complexity.	1….10

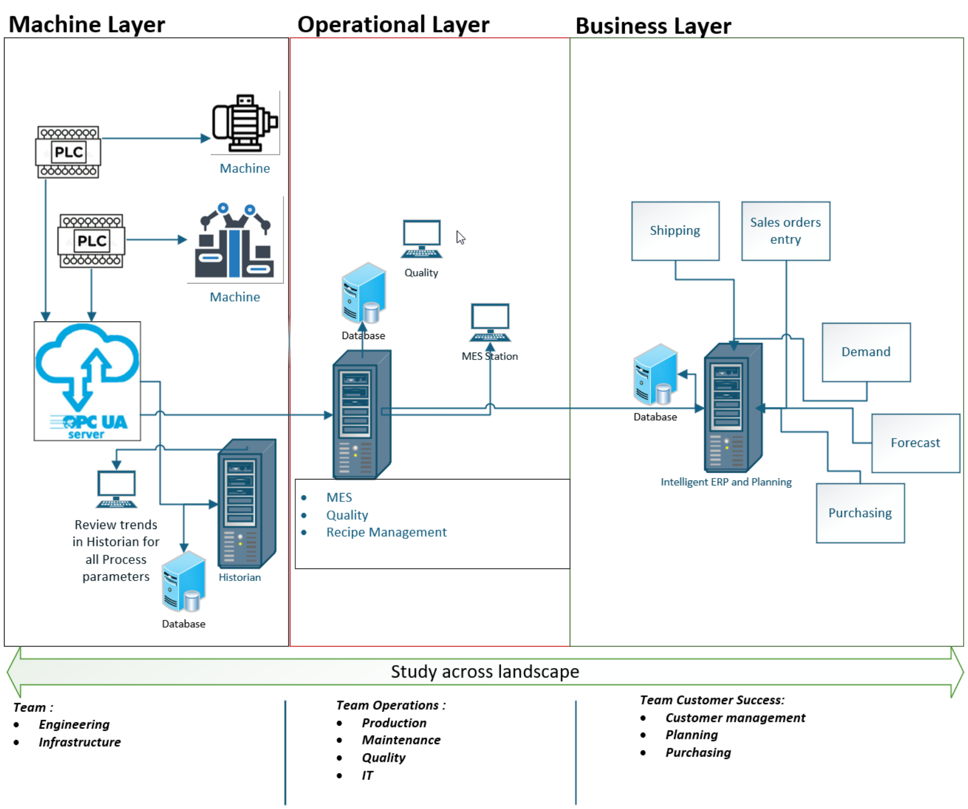

Figure 4. A typical customer landscape in manufacturing and the study that needs to be done

As you can see in Table 4, it highlights the various topics to be studied. These may vary by organization and plant, and one can tailor them to their needs. To perform the study effectively, focus first on evaluating the digital manufacturing infrastructure, which includes assessing the access points for Wi-Fi to ensure robust connectivity that supports mobile interfaces and system integration essential for continuous operation. Examine the integration of Programmable Logic Controllers (PLCs) with critical equipment to ensure they provide real-time monitoring and control of manufacturing processes. Additionally, assess whether data from the PLCs are fully accessible and can be reliably utilized. This evaluation should also determine the potential need for middleware solutions such as Kepware or an OPC server to facilitate seamless data connectivity and interoperability. Analyze the performance and scalability of on-site servers to accommodate increasing data loads and future expansion needs, while also evaluating compatibility across various operating systems to ensure seamless operation of digital systems. Score each of these infrastructure components on a scale of 1 to 10 based on effectiveness and capability, where a score of 10 indicates optimum performance (Figure 4).

Simultaneously, review operational efficiency by investigating the precision and effectiveness of raw material tracking systems for inventory management and quality control. Additionally, assess the impact of initiatives aimed at enhancing employee engagement in adopting new technologies, thereby supporting continuous innovation and operational excellence. Evaluate the current operational practices that focus on efficiency through digital manufacturing techniques and lean management strategies with the goal of waste reduction and quality improvement, scoring each operational aspect from 1 to 10 to reflect their impact on overall productivity.

Security should be a priority, so assess the strength of protocols in place for protecting data integrity and safeguarding against unauthorized access and cyber threats, scoring the robustness of security measures on a 1 to 10 scale. Lastly, analyze the main challenges such as adapting to rapidly changing technological trends, ensuring cybersecurity, maintaining consistent employee engagement, and managing the scalability of systems in handling data and process complexity. Detailed analysis across these areas, combined with their scoring, will provide a comprehensive evaluation of the current state of digital manufacturing systems and highlight areas for improvement, thereby enhancing infrastructure and operational efficiency in the manufacturing environment.

5.4. Key Investments

Based on the comprehensive review and scoring of the digital manufacturing areas mentioned in table 2, targeted key investments can be strategically made to support enhancements in several critical areas:

1. **MES system with capabilities:** Having an MES system is a foundational element, and understanding its capabilities is key. It is essential to ensure that the system can interact with PLCs, collect data effectively, and connect seamlessly with external systems and ERP platforms for real-time data exchange(OpenAI, 2023). The MES should also be capable of transmitting data in real time to historians or data lakes for analysis and long-term storage. However, having an MES system alone does not make it intelligent—it serves as a critical building block within the broader digital ecosystem.
2. **Wi-Fi Connectivity Enhancement**: Investment in upgrading access points to the latest standards can ensure robust and seamless Wi-Fi connectivity. A score below optimal would indicate the need for higher capacity access points or additional coverage to support expanding mobile interfaces and system integration. Focus on technology that supports high data throughput and low latency, critical for real-time operations.
3. **PLC Integration and Equipment Monitoring**: For areas with lower scores in PLC integration, allocate funds to upgrade or replace existing PLC systems with next-generation models that offer enhanced processing power and connectivity. This ensures real-time control capabilities and scalability to handle more complex manufacturing processes.
4. **Server and Systems Scalability**: If server performance scores are lacking, investments should be directed towards scalable server architectures that can handle increased data loads. Consider hybrid cloud solutions that offer flexibility and expandability without significant upfront costs, ensuring future growth and data scalability.
5. **Operating Systems Compatibility**: Investments in standardized operating systems across the manufacturing infrastructure could greatly enhance compatibility and streamline operations. If scores indicate fragmented systems, funds should be allocated to unify platforms, reducing operational complexities and improving system efficiency.
6. **Operational Efficiency through Technology**: Low scores in raw material tracking and inventory management may necessitate investments in advanced tracking technologies, such as RFID systems or AI-driven analytics platforms, which enhance precision and automation capabilities in inventory management.

7. **Employee Engagement and Training**: To address engagement scores, allocate resources for comprehensive training programs focusing on new technologies and continuous improvement processes. Develop workshops and incentives that foster adaptability and innovation amongst employees, aligning with the latest technological developments.
8. **Security Enhancement**: Investments in advanced cybersecurity solutions are crucial where security protocol scores fall short. Upgrading to AI-powered security systems can detect and mitigate threats in real-time, ensuring data integrity and system protection against cyber threats.
9. **Addressing Operational Challenges**: For areas revealing significant challenges, investments should focus on implementing agile methodologies and flexible technologies, allowing the organization to respond swiftly to technological changes. Supporting scalability in systems design will address data and process complexity challenges, enhancing overall operational resilience.

By strategically investing in these key areas, based on the scores and detailed analysis, a more robust and efficient digital manufacturing environment can be established, driving increased productivity and operational excellence.

5.5. Implementation plan with roadmap to build the intelligent MES

This five phase Implementation plan is designed to strategically elevate the current manufacturing systems architecture (explained in Table 2) by embedding intelligence and adaptability using cutting-edge technologies such as Artificial Intelligence (AI), advanced data analytics, and real-time connectivity. The transformation will focus on aligning operational practices with a vision-oriented approach, fostering cross-departmental collaboration, and integrating sophisticated AI frameworks to achieve a comprehensive, data-driven, and agile manufacturing environment.

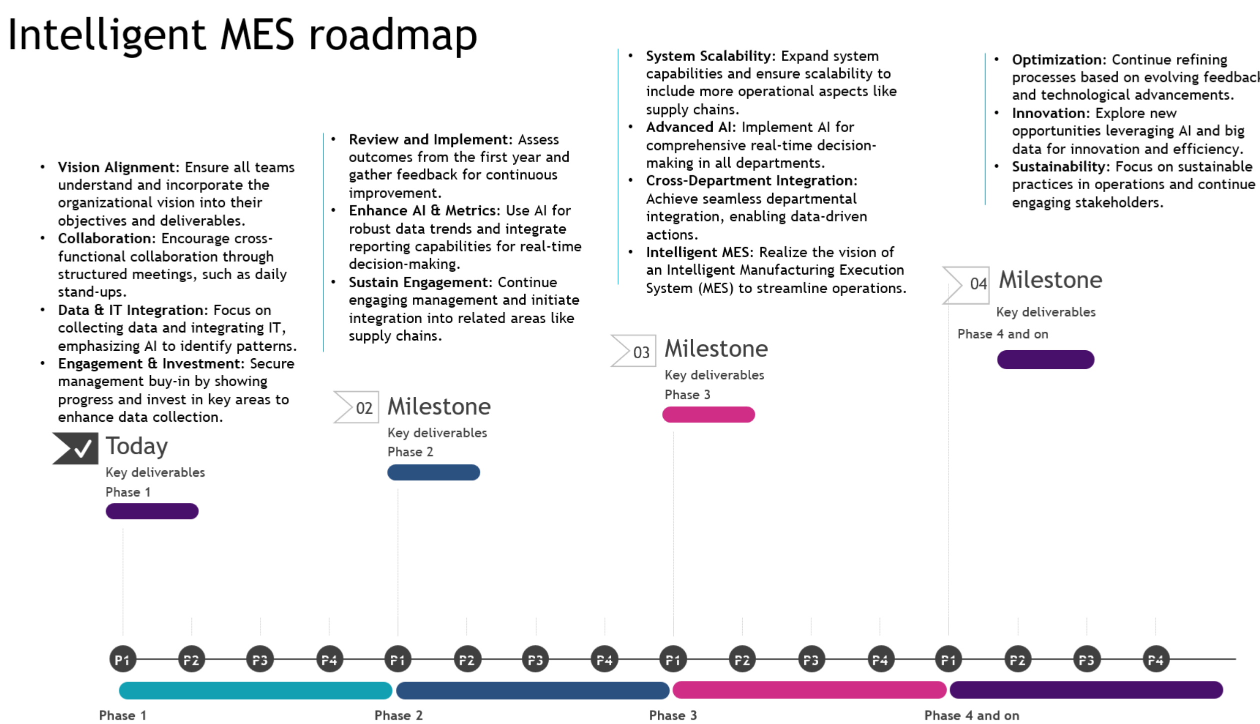

Figure 5. Phased approach road map in building an Intelligent MES

Initiating the phased approach:

The journey towards establishing an Intelligent Manufacturing Execution System (MES) underscores the critical need for collaboration across teams, systems, and processes, as illustrated in Figure 5. The inaugural year sets a strong foundation, emphasizing the alignment of vision, fostering collaboration, and integrating data-driven technologies to propel this transformation.

Phase 1 deliverables:

- **Investment in the right areas with use cases:**

Based on the study performed as per table 4 mentioned above the right investments needs to be made. Data is foundation and needs to focus on areas based on the study to start the investments. This is a very tricky area as without proper attention the spend could be quite high. So, one need to be very careful and ensure the investments are picked from the compelling use cases that the business needs to solve. For example it could be that the scrap generated during the start up is high and how to address it could be a use case. Now one needs to the study this in detail and understand all the connecting elements like the machine, where the raw materials are stored, how the level area monitored, is the data accessible and then provide the list where then the management can decide if the spend is worth it. Also the investments need to be in a structured way so that the growth can be achieved as the intelligent MES moves to next stages. For example if you have a machine that need to be connected and its infrastructure is old and cannot be connected , solution needs to be defined so that all machines having such issues can also be addressed. It could be buying a Kepware server or an Ignition platform for example to cater to the need. But the key message is that the solution can scale and reinvestment should be avoided.

- **Vision Alignment and Departmental Objectives:** During the first year, a pivotal focus is ensuring that the overarching vision for intelligent MES is not only clearly understood but also integrated into the fabric of each team's objectives and deliverables. This involves breaking down the vision into departmental goals that resonate with daily tasks and long-term ambitions.
- **Fostering Cross-Team Collaboration:** Cross-functional collaboration is essential. Through regular daily stand-ups and weekly meetings, major functions within the sites converge to tackle cross-departmental impacts. This collaborative forum allows teams to address immediate operational issues, such as high start-up scrap rates, by examining engineering and maintenance challenges collectively rather than in isolation.
- **Data Collection and Pattern Recognition:** A significant effort will be made to collect data from various critical sources on the shop floor, including equipment, production lines, quality metrics, and maintenance data. This comprehensive data collection serves as the cornerstone for deriving actionable patterns, enabling the correlation of operational performance with maintenance schedules, equipment efficiency, and quality control measures. The objective is to cultivate a cultural shift towards real-time problem-solving, using these insights to swiftly address issues and optimize production processes.
- **Integration of IT systems and AI Capabilities:** Integrating the IT system like Production, maintenance, Quality and Supply chain is pivotal, as AI plays a crucial role in pattern recognition and generating insights. The strategic use of AI is central to advancing real-time capabilities and fostering a proactive operational environment.
- **Investment in Data Collection Technologies:** Investment in critical technology areas, such as Programmable Logic Controllers (PLCs) and Wi-Fi access points, is vital for enabling robust data gathering and seamless connectivity. These investments lay the groundwork for a comprehensive data framework that supports intelligent operations.
- **Management Engagement and Buy-in:** Regular engagement with management is necessary to showcase progress and secure continued support. By demonstrating measurable achievements and alignment with strategic goals, teams can ensure ongoing buy-in, which is critical for the sustained momentum of the initiative.

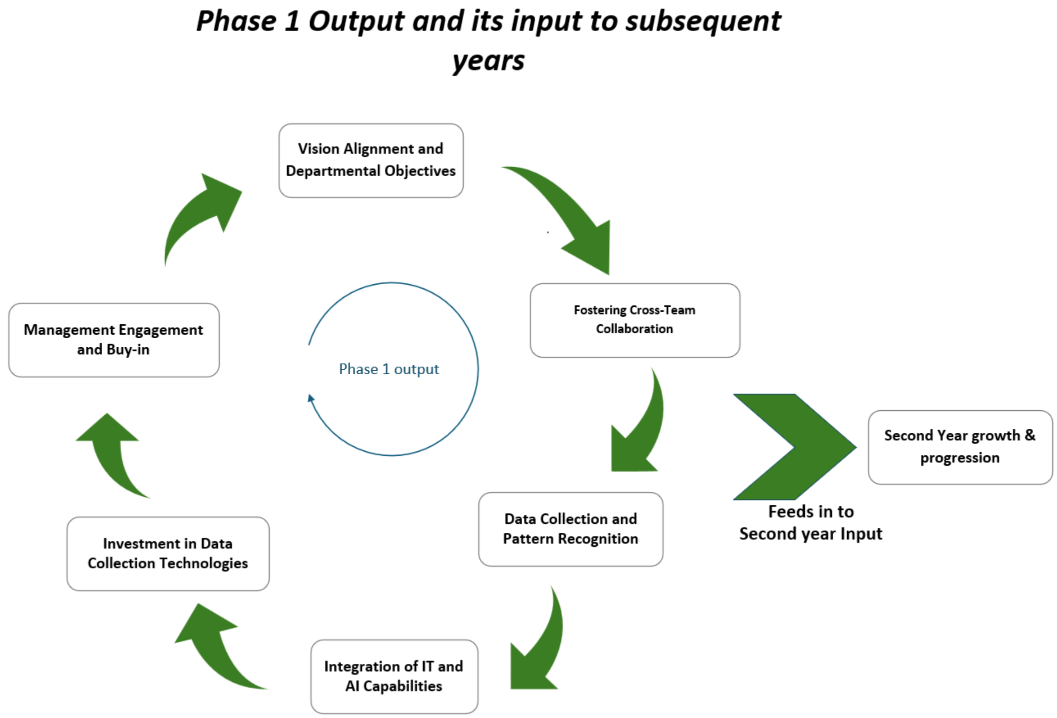

Figure 6. First year output feeding into second year growth and progression

Phase 2 deliverables:
As one can see in Figure 6 the phase 1 output is measured, which directly feeds into phase 2. The first step is to assess the feedback as it provides critical input for the second phase.

The strategic roadmap begins with assessing first-phase outcomes, gathering feedback, and implementing targeted improvements to align efforts with the organization's long-term vision. Building on this foundation, data-driven metrics will be established to evaluate team progress, identify growth opportunities, and ensure system robustness for continuous performance tracking. As the initiative advances, AI-driven reporting capabilities will be integrated to deliver predictive insights that empower real-time, proactive decision-making. Emphasis will be placed on validating **AI model outcomes to ensure they are well-trained, reliable, and accurate, while fostering trust within the team through transparency and consistently reliable results.** Continued strategic investments will be aligned with organizational goals, **supported by clear progress tracking and active leadership engagement to maintain executive buy-in**. In the next stage, integration efforts will expand across critical areas such as Maintenance , Quality and supply chain management, supported by a robust AI framework and centralized data lake that enables seamless data exchange within the MES ecosystem as shown in figure 8. Ultimately, these phases will culminate in the realization of an intelligent, self-optimizing MES—driven by AI and real-time insights—empowering teams to make confident, data-backed decisions that fuel continuous improvement, innovation, and operational excellence.

The process will begin with assessing first-year outcomes, gathering structured feedback, and implementing targeted improvements to strengthen alignment with the organization's strategic vision. Progress will be continually measured through robust metrics derived from real-time data, ensuring teams remain focused on key performance goals while identifying new opportunities for optimization.

A major emphasis during this phase will be on integrating all critical functions—including production, quality, maintenance, and engineering—into a unified, intelligent ecosystem as shown in Figure 7. By connecting these departments through a scalable architecture, supported by cross-functional data sharing and AI-driven analytics, the organization will enable seamless communication and end-to-end visibility across operations. Real-time data will fuel proactive, AI-assisted decision-making, allowing departments to anticipate issues, optimize resources, and coordinate actions cohesively. For example, production can align schedules with maintenance forecasts, quality teams can intervene early through predictive analytics, and engineering can leverage feedback loops to enhance system design and equipment performance.

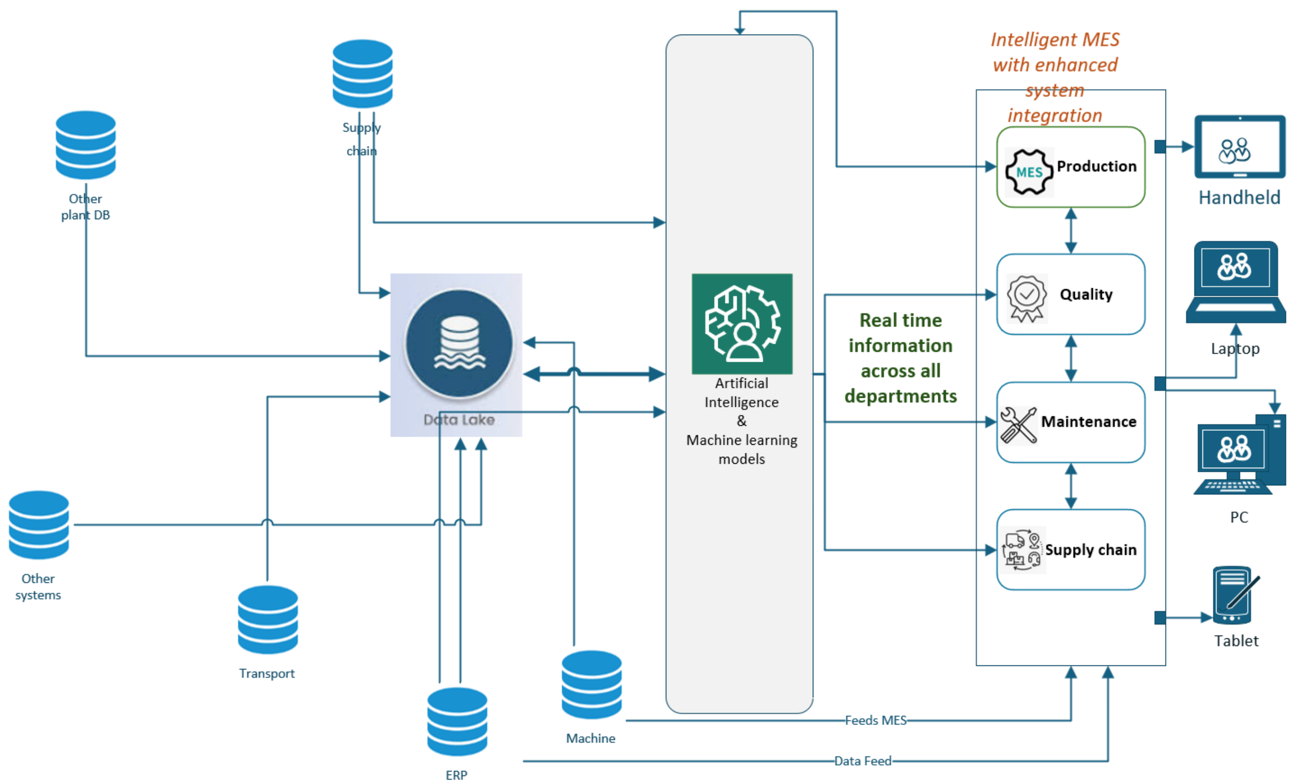

Figure 7. Intelligent MES architecture

As integration extends to other key systems such as the supply chain, the enterprise will transition toward a fully connected environment where AI supports synchronized decision-making across all operational layers. This convergence will culminate in the realization of an intelligent MES—an adaptive, self-learning system that empowers every department to make real-time, coordinated, and data-driven decisions. The result will be a resilient, insight-driven operation built on collaboration, agility, and continuous improvement.

6. Monitor Results/outcome with Continuous improvement

Continuous improvement (CI) has long been a cornerstone of high-performing manufacturing systems, rooted in methodologies like Six Sigma, Lean, and Total Quality Management (TQM). However, traditional CI programs often depend on retrospective data analysis and periodic reviews that limit the speed and scope of process optimization. An Intelligent Manufacturing Execution System (MES) transforms this paradigm by embedding real-time analytics, feedback loops, and adaptive learning mechanisms directly into the production environment.
An intelligent MES enables continuous improvement through three central capabilities: real-time visibility, predictive analytics, and closed-loop feedback. Real-time visibility provides plant operators and engineers with immediate access to key performance indicators such as equipment efficiency, production yield, and quality deviations. Rather than waiting for end-of-shift or end-of-day reports, teams can identify root causes within minutes of a variance, thereby reducing downtime and scrap rates. Predictive analytics enhances this by identifying patterns and correlations in production data that humans might overlook. For instance, subtle temperature fluctuations or micro stop patterns detected through sensor data can trigger automated insight recommendations before they manifest as defects.

The closed-loop feedback mechanism represents the most powerful enabler of continuous improvement within an intelligent MES. It allows the system to autonomously adjust parameters or recommend interventions based on data-driven learning. Over time, these continuous micro-adjustments accumulate to deliver significant improvements in overall equipment effectiveness (OEE), process stability, and regulatory compliance. When integrated with enterprise-level systems such as ERP and quality management software, the MES ensures that learnings at the operational level are institutionalized — driving organizational learning rather than temporary fixes.

In highly regulated industries such as pharmaceuticals and biotechnology, continuous improvement also intersects with compliance. The ability to maintain electronic batch records, audit trails, and process histories ensures that every improvement initiative remains traceable and validated, aligning with standards such as GAMP 5 and FDA 21 CFR Part 11. This dual focus on operational excellence and regulatory integrity positions the intelligent MES as both a productivity enabler and a compliance assurance tool.

Ultimately, continuous improvement in the context of an Intelligent MES extends beyond incremental optimization. It evolves into a culture of digital kaizen — where each data point contributes to smarter decision-making, every process cycle refines itself, and the boundary between execution and innovation becomes increasingly seamless. As industries advance toward autonomous manufacturing and Industry 5.0, continuous improvement will transition from a human-driven initiative to a system-embedded capability — one powered by data, intelligence, and real-time adaptability.

7. Conclusion

The evolution of manufacturing systems toward intelligence-driven, data-centric operations represents a fundamental transformation in the way modern industries approach efficiency, quality, and agility. This paper highlighted how an Intelligent Manufacturing Execution System (MES) serves as the cornerstone of this transformation by bridging operational data, analytical intelligence, and decision-making in real time. Through seamless integration of sensors, data platforms, and predictive analytics, intelligent MES solutions not only optimize shop-floor performance but also enable proactive responses to variations before they escalate into production issues.

The shift from reactive to predictive and autonomous operations creates a sustainable pathway for continuous improvement. Real-time visibility, coupled with closed-loop learning, allows organizations to refine their processes dynamically and build resilience against disruptions. Moreover, intelligent MES systems support regulatory traceability and data integrity, enabling highly regulated industries such as pharmaceuticals to maintain quality compliance without compromising productivity.

As manufacturing continues to align with the principles of Industry 4.0 and progresses toward Industry 5.0, the role of intelligent MES systems will further expand — moving beyond execution to actively orchestrating manufacturing intelligence. The convergence of artificial intelligence, machine learning, and digital twins will strengthen MES capabilities, transforming data into actionable insights and fostering a culture of operational excellence.

In essence, the Intelligent MES stands not just as a technological upgrade but as a strategic enabler of smart, adaptive, and continuously improving manufacturing ecosystems. By embedding intelligence into every operational layer, organizations can achieve enhanced efficiency, assured quality, and a sustainable competitive edge in an increasingly data-driven industrial landscape.

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Biography

Subash Senthil Mohanvel is a manufacturing technology leader specializing in ERP, Manufacturing Execution Systems (MES), quality management, and digital transformation within industrial environments. As Director of ERP Manufacturing, Quality & Planning, and Functional Design & Architecture at West Pharmaceutical Services in Exton, USA, he oversees enterprise-level system design, cross-functional integration, and the implementation of digital manufacturing strategies. His work focuses on enabling real-time decision-making through intelligent MES architectures, data-driven process optimization, and the adoption of Industry 4.0 and 5.0 technologies. With extensive experience collaborating across engineering, operations, maintenance, IT, and quality teams, he has led large-scale multi-site transformation initiatives that enhance system connectivity, improve operational efficiency, and drive predictive and autonomous capabilities on the shop floor. Subash's research and professional contributions center on bridging the gap between theoretical advances in smart manufacturing and practical industry deployment, empowering organizations to build scalable, intelligent, and future-ready execution systems.