Global Academic Journal of Economics and Business

Available online at https://www.gajrc.com
DOI: https://doi.org/10.36348/gajeb.2026.v08i05.077

OPEN ACCESS



ISSN: 2706-9001 (P)
ISSN: 2707-2584 (O)

Review Article

Digital Twin and Industrial IoT Integration for Real-Time Monitoring and Intelligent Control in Manufacturing Execution Systems (MES): A Critical Review

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Article History
Received: 18.08.2026
Accepted: 20.10.2026
Published: 24.10.2026

Abstract: Digital Twins & IIoT support monitoring, diagnostics, scheduling and controlled execution by connecting actual process data with virtual representations and associated execution contexts. This important integrated literature review identifies those connections' role in supporting these operations and synthesizes 35 relevant peer-reviewed journal articles written since 2020. Articles included are a variety of types, including conceptual analyses, computational studies, laboratory experiments and industrial trials. The synthesis differentiates evidence of capability from evidence of operation and identifies three applications that were common among all the articles surveyed: monitoring, diagnosing bottlenecks in production processes, coordinating production and logistics processes, and scheduling production based upon product-condition. There was no evidence from the surveys that would indicate the current level of development regarding implementing fully autonomous control at a manufacturing facility. Successful integration of DTs and IIoT will require a reliable collection of plant floor data, common understanding of events, sufficient model accuracy for decision making, and clear definition of the authority to execute. The authors propose an execution-oriented architecture where MES or a designated orchestration service verifies production plans and local controllers continue to have real-time control over machines and remain responsible for independent safety functions. The proposed control cycle includes maintaining a fresh view of system states, assessing uncertainty related to states, evaluating constraints on planned activities, and defining appropriate fallback behaviors. The primary areas requiring additional research include assessments of synchronization across systems, issues with model maintenance and reuse within multiple DTs, coordination of multiple DTs operating in a distributed environment, and long-term evaluations in industrial settings.

Keywords: Digital Twin, Industrial Internet of Things, Manufacturing Execution System, Real-Time Monitoring, Intelligent Control, Semantic Interoperability, Digital Thread.

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Citation: Qureshi, F. A. (2026). Digital Twin and Industrial IoT Integration for Real-Time Monitoring and Intelligent Control in Manufacturing Execution Systems (MES): A Critical Review; *Glob Acad J Econ Buss, 8*(5), 1934-1948. https://doi.org/10.36348/gajeb.2026.v08i05.077

1 INTRODUCTION

Manufacturing Execution Systems (MES) manage and monitor all day-to-day aspects of manufacturing including Work Orders, Routing, Resource Assignment, Quality Records, Work-in-Progress, and Product Genealogy. However, MES make decisions based on recorded production states that can fall behind what the actual condition of the equipment is. For example, a machine can still be marked "available", yet its processing time can increase, or an order can be released prior to the availability of necessary materials for downstream processes. This discrepancy between operational observations and model supported execution decisions is being addressed through both MES Integrated Digital Twins and Virtual-Physical IIoT Integration.

A manufacturing Digital Twin is a physically maintained representation of either a single asset or a process that is continuously updated with the current state of the related physical object. It's the mechanism for integrating the physical world into an IT environment through which decisions regarding the physical world can be made. While the method used to create a Digital Twin (i.e., twinning rate, state representation, etc.) and whether there is a flow of data from the Digital Twin back to the physical world, matters more than how closely it looks like the physical world [3]. Similarly, reviews of digital manufacturing environments and industrial applications also place heavy emphasis on models, data, and services [4, 5].

In this review, we define Automatic Physical-to-Digital Updating as supporting Observation of the physical world. We define Closed Loop Operation as having a controlled feedback loop for making decisions. Therefore, simply providing a Live Dashboard does not guarantee Predictive Fidelity nor Control Authority over the physical world.

Other recent reviews focus on different aspects of manufacturing Digital Twins. For example, Böttjer *et al*., review unit level implementation and point out several limitations associated with manufacturing Digital Twins such as lack of physical fidelity, poor interoperability and difficulty validating in a realistic manner [6]. Kerrouch *et al*., identified several issues associated with implementing Production-Twins at the component level [7]. Villegas *et al*., provided an overview of various manufacturing applications, their corresponding levels of maturity, and their relationships to technology [8]. Finally, Zhang *et al*., discussed hybrid Digital Twins where models are fused together using physics-based modeling, data-driven methods, and simulation models [9]. Table 1 identifies the overlap between our review and those previously mentioned. Specifically, since each reviewed article discusses one or more of the topics listed above, this comparison reflects differences in emphasis rather than suggesting that articles referenced were deficient in other areas.

The primary question asked in this review is how to convert a synchronized representation of a manufacturing system into an authorized production intervention. As previously stated, an MES provides order, routing, material, resource, and quality data needed to evaluate candidate actions. IIoT provides the observations that feed into a digital twin model to estimate the current state of a system or to predict candidate actions. The ability to convert MES data and IIoT observations into actionable knowledge requires establishing a common understanding among identifiers, timing, and constraints associated with producing goods.

Adding additional data or increasing model complexity does not inherently translate into a higher likelihood that candidate actions will improve productivity or feasibility.

This paper addresses this issue through three parts:

1. Thematic Synthesis of DT-IIoT-MES Integration Mechanisms;
2. Differentiation Between Demonstrated Capability vs Strength of Validation;
3. Conceptual Architecture for Authorizing Decisions Regarding Execution Using Explicit Decision Checks & Fallback Behavior.

Finally, this paper proposes an architectural framework for implementing DT-IIoT-MES systems along with a proposed adoption model. At no time was the proposed architecture validated as an integrated system within this research effort.

1.1 Aim and Research Questions

The goal of the investigation is to determine what circumstances exist for DT (Digital Twin) and IIoT (Industrial Internet of Things) integration that will enable dependable MES (Manufacturing Execution System) monitoring and smart execution. The study investigates four research questions.

RQ1: Which architecture mechanisms can link IIoT data inputs/observations, twin state, and MES execution definitions?

RQ2: In what way will these mechanisms be able to provide diagnostic capabilities, schedule production, coordinate logistics, and provide feedback controls for execution?

RQ3: Under what constraints will the integration hinder its ability to deploy in terms of

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synchronization, interoperability, model drift, cybersecurity, and decision governance?

RQ4: To transition from pilot decision support to scalable, audit-executable execution, what validation and implementation priorities should be addressed?

2 REVIEW METHODOLOGY

2.1 Review Design and Source Selection

The first part of this section describes how this study was conducted (it is a Critical Narrative Review and Integrative Thematic Synthesis). It also explains the diversity of the studies included in the review by describing types of evidence used in the reviewed studies (reviews, conceptual models of Digital Twins; computational simulations of Digital Twins; laboratory implementations of Digital Twins; industrial uses of Digital Twins). In contrast to many other reviews, it does not attempt to identify all possible ways that Digital Twins can be implemented, nor will it provide a single overall summary of what is believed to be the "best" way to implement them. Instead, its goal is to provide a basis for comparing the various approaches that have been proposed to develop and use Digital Twins in manufacturing environments. Therefore, it did not need to pool the results from multiple studies to arrive at a final answer. The list of references included in the review are 35 journal articles published during 2020–2026.

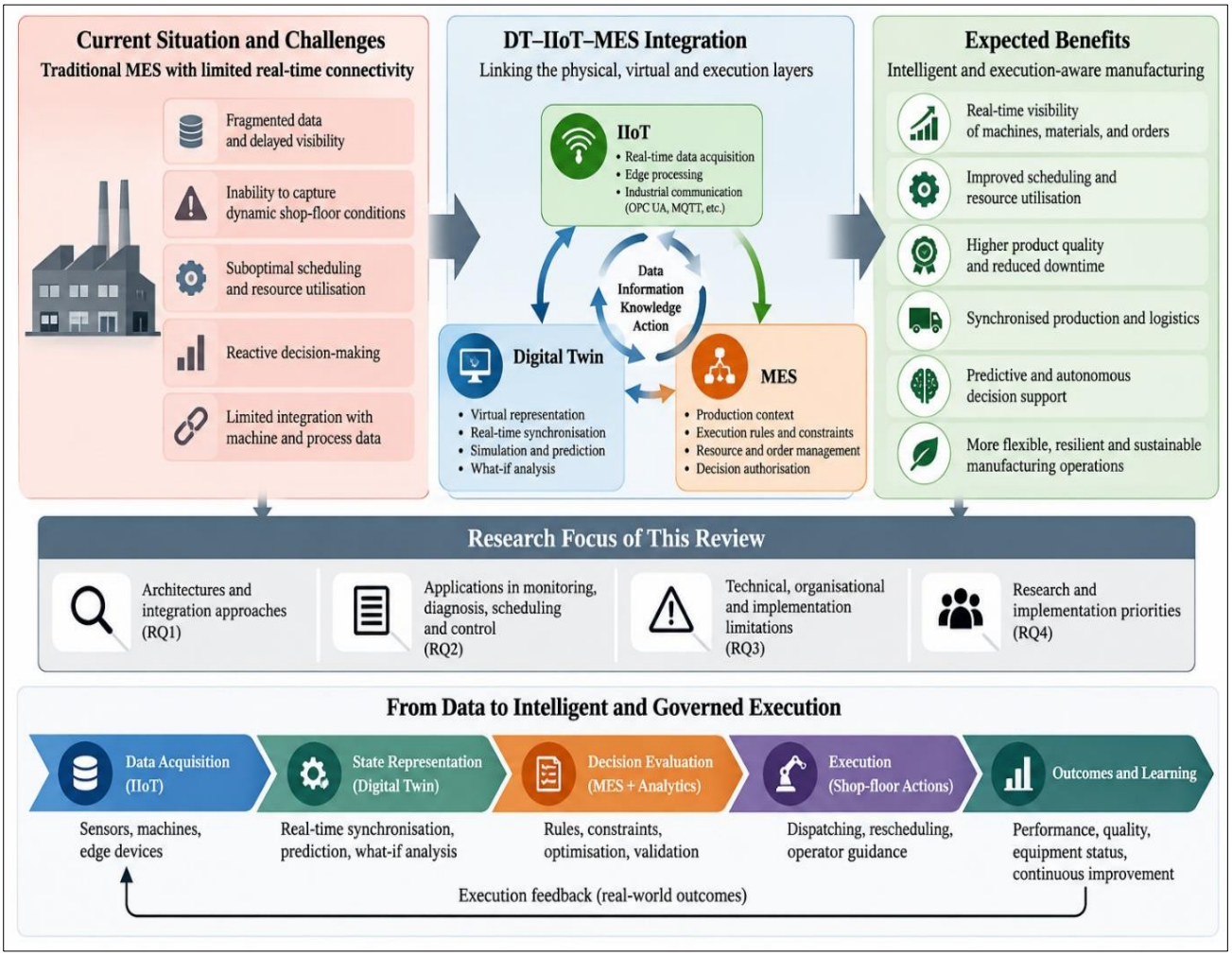


Figure 1: Conceptual overview of DT–IIoT–MES integration and the review scope. Benefits shown are intended outcomes, not measured effects

The references in this review were identified through a process called purposive sampling. First, the authors began by conducting a literature search on manufacturing twins, Industrial Internet-of-Things (IIoT) and Manufacturing Execution Systems (MES); they then extended their search to include additional work that focused on topics directly related to these areas including synchronization, digital threads, scheduling, maintenance, and feedback control. On October 7th, 2026, the authors performed a targeted update of the review, which involved searching the publisher web sites, the author's institutional research databases and the DOI records for each reference. The searches were limited to combinations of keywords that would likely result in references related to the use of Digital Twins in

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manufacturing settings such as "Digital Twin" AND "Manufacturing Execution System," "Digital Twin" AND "Manufacturing Synchronization," "Digital Twin" AND "Production Scheduling." Because the recent literature has provided important insights into how Digital Twins are being applied in manufacturing systems, the authors restricted their original literature search to publications that appeared during 2020–2023. Those same references were used to provide background information relative to concepts and practices associated with the development and use of Digital Twins.

Table 1: Positioning of the review relative to selected manufacturing digital-twin reviews

Review	Main emphasis	Relevance to MES execution	Focus of the present synthesis
Jones *et al*., [3]	Twin characteristics and information relationships	Defines state and updating requirements	Validity of the state used for an execution decision
Leng *et al*., [4]	Twin-based manufacturing system design	Connects twins with production-system architecture	Decision authorization across interfaces
Böttjer *et al*., [6]	Practical unit-level twin applications	Clarifies fidelity and validation challenges	Transfer from asset capability to MES action
Kerrouchi *et al*., [7]	Production-twin implementation challenges	Organizes barriers around twin components	Consequences of barriers for execution reliability
Villegas *et al*., [8]	Applications, maturity, and technological capabilities	Relates capabilities to manufacturing domains	Assurance required for increased decision authority
Zhang *et al*., [9]	Hybrid models and fusion paradigms	Informs model selection and integration	Decision-specific fidelity and maintenance needs
Present review	DT–IIoT–MES mechanisms and evidence	Connects sensing, inference, authorization, and outcomes	Conceptual architecture and validation priorities

A journal article was considered eligible if it described a manufacturing-related or cyber-physical production-related concept, methodology or application and addressed at least one of the review questions. Journal articles that discussed non-manufacturing applications provided only geometric visualizations of Digital Twins (i.e., images of virtual objects), represented solely conference proceedings, containing references that could not be verified were excluded from consideration. Reviews were allowed because they serve as conceptual evidence and allow comparisons among studies, but not because they represent independent examples of industrial success. Being published in a high impact factor journal was not sufficient to conclude that an implementation is operational.

As mentioned earlier, the second part of this study did not involve performing a complete search through Scopus or Web of Science. Consequently, there are no complete export files from either of those databases, no record of when duplicates were removed, and no log file documenting how each reference was screened. For this reason, a PRISMA flow diagram showing how many references were screened, how many exclusions were made and claiming systematic completeness based on screening activity cannot be produced. Although registering the protocol prior to initiating screening would increase the level of transparency regarding screening criteria and procedures (and thus enhance the potential for others to reproduce this study), limiting reproducibility is the lack of documentation regarding screening activity.

2.2 Synthesis and Evidence Appraisal

The synthesized articles are organized into categories that represent the various components (connectivity and data quality; representation and synchronization; MES and digital thread integration; monitoring and diagnosis; scheduling and control; and trust, human factor, and scale) of the overall system. The authors stated system boundaries, information flow, decision processes, and validation procedures are also compared for each article. A qualitative evaluation is performed to determine if the proposed architecture has been demonstrated in practice, as well as to differentiate simulated performance from real-world laboratory or industrial evidence.

The assessment was done subjectively using no formalized risk of bias scores; independent duplicate screening; nor an estimate of inter-rater reliability. Publisher abstracts and metadata supported both bibliographic and scope-based verification. When only these items were available then they were not utilized to derive inferred but unreported quantifiable results, durations of reported deployments or detailed validation activities. Tables 2 and 3 compare representative systems with corresponding MES implications (Table 2), as well as provide comparisons of studies that have validated settings that can be determined based

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on the published documentation. Table 3 is intended to be illustrative of how one might perform such an extraction at the study level.

Because the studies have differences in terms of production context, baseline conditions, model scope and performance metrics, no pooling of the reported results occurred. Therefore, improved simulated waiting times do not necessarily indicate sustained improvements in industrial throughput or economic benefits. The proposed implementation safeguards and areas for future research identified by this review are part of its synthesis, rather than being considered experimental results proven by all referenced studies.

3 THEMATIC LITERATURE REVIEW AND CRITICAL ANALYSIS

3.1 Connectivity and Operational Data Quality

The acquisition in IIoT decides what changes in the physical world are observable by the next level models. Tapia *et al.,* describe an open-source scalable platform for machine-tool real time monitoring as presented in [10]. Jiang *et al*., place the digital twin at the intersection of heterogeneous IIoT devices with applications and services [2], the Digital-Twin-as-a-Service Architecture described by Aheleroff *et al.,* enables modular delivery of services [11].

These architectures provide the frameworks for addressing access and organization; the production application is responsible for determining the meaningfulness and useful age of each data point it receives.

The signals that are acquired have different timing requirements. For example, some machine variables may update multiple times per second (e.g., vibration), while others such as order status and inspection results are typically event driven.

Edge processing can help filter observations, align timestamps, and maintain local availability when communications fail. However, filtering can also lose important transient behaviors, and batching observations can delay apparently current dashboard updates. Therefore, sampling rates, communication latencies and decision-making latencies should be reported separately.

Data quality for MES integration encompasses identity, units, timestamp origin, validity, and production context. A consistent mapping from a machine identifier to an MES resource must exist and a quantity must remain constant with respect to unit and material identity across the entire interface. Late, duplicated, or out-of-order events must be explicitly handled. In addition, design recommendations include having commands carry unique identifiers and ACKs to prevent retries creating duplicated production actions. Connectivity should be measured based upon the correctness of the resultant state and not solely based on whether messages were delivered successfully.

3.2 Twin Representation and Synchronization

A practical digital twin must provide enough detail (fidelity) so that it can support the decision being made by the twin. According to Jones *et al.,* State and relationship with the twinned entity are two main aspects that define a "twin" [3]. A simple, three-dimensional model that is updated rarely might be more useful for dispatching than a complex, reliable model that is updated after every significant event. On the other hand, models related to geometry or control processes may have some requirements that are not supported by a queuing-based scheduling model.

Fan *et al*., create a conceptual structure (visualized architecture) that supports flexibility in manufacturing [12], and Ding and Fan create a web-based integration framework using Automation ML and Asset Administration Shell concepts [13]. Onaji *et al.,* evaluate a case study-based manufacturing framework [14].

The most critical issue associated with determining what actions are required to be taken in response to process data is to determine how those data take on meaning regarding their application to the process. For example, a machine that is idle could be starving for work, blocked waiting for a piece of equipment to complete a task, out-of-service due to maintenance or simply waiting on an approved order for work to begin; all of which will call for different types of reactions.

Automated discovery of manufacturing systems can reduce the amount of manual effort needed to build models [15]. However, this still leaves the requirement to ensure that the observed behaviors of the model reflect the physical world's routing and resource constraints. Böttjer *et al*., indicate that there continue to exist large differences between demonstration of units and their practical use in industry [6]. Zhang *et al.,* expand upon the previously described model by creating hybrid representations that combine multiple sources of knowledge that were never represented before [9]. In the current synthesis, hybridization is valuable if the additional model improves one or both of decisions and adds value to the cost of maintaining them.

State synchronization quality should be measured when considering an action. Indicators such as State Age, Timestamp Uncertainty, Missing

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Event Rate and Prediction Residuals are recommended. One statement about a system operating in "real-time" is not acceptable. The allowed latency is dependent on the type of process and the decision horizon; A new schedule created from updates to the schedule and rapid controls of machines cannot assume common thresholds for latency.

3.3 MES Integration and the Digital Thread

Twin frameworks have been directly linked to MES (Manufacturing Execution System) functions by Negri *et al*., [1], based upon their role as intermediate layers connecting analytical models to the execution environment. While a twin could recommend a technically viable operation, the executing services would need to verify many additional details such as the current status of an order, routing rules, materials being eligible, quality hold issues and available resources before they are allowed to make changes to a production system. These verification processes are critical in defining when an operation's recommendation can be executed into a production change.

Digital thread-based collaboration among manufacturing systems was explored by Liu *et al*., [16], as well as twin-based support for collaborative production through blockchain technology by Tao *et al*., [17]. More recently, Ding *et al*., [18], integrated Process Orchestration, Smart Contracts, and Manufacturing Twins. All three of these papers focused on developing ways for multiple distributed entities to collaborate and coordinate. However, no one paper established that all plants would need to implement blockchain technology; instead, traditional transactional interfaces will likely be adequate in environments where there is centralized control over who has access and what data is shared.

Distributed MES execution and on-the-fly replanning were demonstrated by Vyskočil *et al*., [19], using a laboratory Industry 4.0 test bed. Although the authors demonstrated the ability to achieve real-time replanning, larger scale operational durability remains to be evaluated. Regardless of how the orchestration occurs (centralized vs. decentralized), common identifiers, versioned process definition and consistent event semantics are still required.

State and intended execution behavior must also flow from the twin to MES. Constraints and orders feed into the model. Predictions regarding future constraints and candidate actions influence execution behaviors. Then, actual results must be tied back to the specific action taken. This will allow the ability to distinguish between errors within the model, obsolete data, missing constraints, and failure to successfully complete the planned actions. Although read-only implementations can provide visibility into the activities occurring at each point within a plant's operations, they do not represent closed-loop functionality.

3.4 Monitoring and Diagnostic Intelligence

Xu *et al*., develop a data-driven twin for machine- and system-level monitoring of the production line [20], the system perspective is important, since local utilization is an ambiguous measure; high levels of activity can be associated with downstream congestion, while low levels of activity may indicate upstream starvation. Thus, the connection of machine observations to material flow and order progress prior to an MES interpreting them as actionable exceptions is required for monitoring.

Kumbhar *et al*., have linked bottleneck detection, diagnosis, and improvement [21], together, Toothman *et al*., have developed a framework for the implementation of prognostic and health management [22], which motivates decisions about the execution of tasks (such as stopping production) based upon usable capacity and condition (and not simply whether a machine is stopped or operating). A condition estimate however must include uncertainty and an identifiable forecast period. An anomaly score by itself cannot define when to stop production, when to inspect a batch, etc.

Caiza and Sanz implemented an immersive twin connected to an MES using OPC UA, AR and VR in an Industry 4.0 laboratory [23], this provides evidence of combined monitoring/interaction in a controlled setting. However, it does not provide evidence that immersive visualization will necessarily contribute to the success of MES integration or that the advantages of immersion will carry over into factory settings. Evaluations of interfaces require consideration of diagnostic time, interpretation errors, and intervention quality in addition to technical connectivity.

3.5 Scheduling and Production Logistics

The authors link their scheduling approach to the actions that an MES could take based on the predicted states of the machines. Serrano-Ruiz *et al.,* discussed the use of smart manufacturing scheduling in [24], and Pandhare *et al*., used equipment degradation in their study on using twins for robust scheduling [25]. Their research was conducted in a laboratory environment that included an assembly line that had been intentionally degraded and faulty. Their results show the benefit of health-based scheduling when using the methods described, but do not suggest that these methods will increase overall productivity at all factories.

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Pan *et al*., discussed how to synchronize production and logistics in real-time using a multi-layered computer architecture [26], and Su *et al.,* developed production – intralogistics coordination (PIC) using a twin-controlled mechanism to develop PIC; the results were demonstrated using computational experiments [27]. These two studies highlight one major issue regarding treating material and/or machine readiness as separate issues from other aspects of the operation. Therefore, while computational models may improve wait times and reduce instances of tardiness, it remains necessary to perform additional operational testing prior to providing site specific business forecasts.

There are three scheduling implementation questions identified in this article. They include:

1) Does the proposed schedule remain viable after considering current material status, availability of tools, product quality requirements, and need for scheduled maintenance?
2) Can data processing and approvals occur within sufficient time so that the decision does not become invalid (stale)?
3) Is the cost associated with adjusting schedules less than the potential benefits realized?

These factors including replanning frequency, degree of schedule instability, and operator acceptability should also be assessed with respect to the defined optimization objectives.

3.6 Intelligent Decisions and Feedback Control

Xia *et al*., proposed two examples of how a virtual environment can support smart manufacturing; training a deep reinforcement learning (RL) agent within a simulated twin environment by Xia *et al*., [28], and reviewing further smart manufacturing applications (e.g., optimization and maintenance), such as those studied by Soori *et al*., [29]. While training/evaluating in a virtual environment can help minimize the risk associated with physically exploring through trial and error; there are significant challenges related to model mismatch (the difference between how the model is used during training/testing vs. deployment) and unobserved disturbances when deploying a trained RL policy in real-world settings. As a result, any learned policy will need to have actions limited in scope, explicitly check for feasible operations, and define a mechanism for withdrawing from operation.

Sjöberg *et al*., [30], examined online calibration and feedback control for ensuring geometry assurances for sheet metal assemblies. This work presents an industry specific example of linking model updates with control actions. It cannot serve as evidence that an enterprise Manufacturing Execution System (MES) could replace low level process control systems. In this architecture, the MES has authority over what production tasks are authorized and sequenced, whereas Programmable Logic Controllers (PLCs) and other designated control systems provide the necessary timing for executing machine actions. Any independent safety functions should be able to operate without reliance upon the availability/prediction of the twin. Figure 2 shows a separation of services including analytical services, execution governance, and physical action. The term "intelligent control" refers to both supervised rescheduling/constrained execution decision making as well as application specific feedback control. Establishing a clear definition helps prevent describing a scheduling recommendation as equivalent to a validated continuous controller.

3.7 Interoperability and Human Collaboration

Cimino *et al*., provide a simulation-based twin for human-robot interaction for an automotive manufacturing process, focusing on both syntactic and semantic interoperability [31], while Ciampi *et al*., use a twin and physics-informed neural networks combined with mixed-reality interfaces to support the reconfiguration of production systems; they used this framework on a university research platform (a mock production-line) [32], these two examples relate integration to operator/worker participation and the completion of the physical tasks. The environments and goals for each example differed from one another and therefore the results produced by each example cannot be considered identical measures of industrial readiness.

Users need to know whether the output they receive is based upon observation, prediction, suggestion, or approval to act. All outputs should include reasons and uncertainty, and users do not have to look at the raw data to see them. Users may also need to know the process for overriding the system when it does not work correctly (who can override, how will the system get back into a known correct working state, will the override be retained for further analysis). These are possible governance mechanisms and not potential benefits that result solely from the addition of an interactive, user-experience-enhanced interface.

3.8 Trust and Lifecycle Governance

Attaran *et al.,* provides recommendations on how to implement the solutions outlined above. The author suggests the need for the use of physical models as well as logical models. The authors recommend using both physical and logical models when possible. However, they do not provide specific guidance on how to select which models to use.

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This is because selection of models depends on multiple factors including; cost, complexity, time available, degree of uncertainty, etc. Additionally, there may be additional costs and/or technical issues related to integrating multiple models into one system. The authors do acknowledge these issues and suggest that "integration" will likely require significant investment in resources and time.

Finally, the authors conclude by stating that successful implementations will depend on a combination of business acumen and technical expertise. They further state that companies wishing to achieve success through digital transformation will have to find ways to address some of the challenges mentioned above (i.e., managing large numbers of models, finding qualified personnel to manage those models, etc.).

Table 2: Comparative synthesis of DT–IIoT–MES integration functions and execution implications

Integration function	Article	MES contribution	Critical limitation
Connectivity and edge acquisition	[2-10]	Timely resource and event state	Timestamp consistency, stale data, heterogeneous interfaces
Representation and synchronization	[3-13]	State linked to production objects	Decision-specific fidelity and semantic consistency
Monitoring and diagnosis	[20, 21]	Actionable flow and condition exceptions	Local indicators can misrepresent system performance
Scheduling and logistics	[25-27]	Plans reflect material and capacity constraints	Uncertainty, solving time, and schedule stability
Distributed execution and digital thread	[16-19]	Traceable coordination and replanning	Identifiers, ownership, and version consistency
Learning and feedback control	[28-30]	Candidate policies and calibrated actions	Model mismatch, constraints, and failure handling

4 Comparative Appraisal of the Evidence

Table 3 separates studies by way of their form (i.e., experimental / simulation based vs. field-based) and describes the type of "validation" environment in which they were conducted. It does not provide any quantitative measure of quality. In terms of relevance to actual operational environments, an industrial example may have greater immediate applicability. However, this does not necessarily mean that the data collected for such a study are equally applicable over time, as well as being transferable from one process environment to another. On the other hand, an experimentally based study can determine whether a particular mechanism exists, even though it has no direct relation to potential costs associated with integrating the new technology into an existing manufacturing operation.

Table 3: Validation settings and inference limits of selected implementation studies

Study	Validation setting	Capability examined	Limit of inference in this review
Vyskočil *et al*., [19]	Laboratory Industry 4.0 testbed	Distributed MES and on-the-fly replanning	Factory-scale response and durability need further evaluation
Caiza and Sanz [23]	Festo-based Industry 4.0 laboratory	Immersive MES–DT monitoring and interaction	Controlled integration is not multi-site effectiveness
Pandhare *et al*., [25]	Laboratory assembly line with induced degradation	Health-aware production scheduling	Transfer depends on equipment and degradation patterns
Su *et al*., [27]	Computational experiments	Production–intralogistics synchronization	Modeled outcomes require operational confirmation
Cimino *et al*., [31]	Automotive assembly application	Twin-supported human–robot collaboration	A specific case does not establish cross-site generality
Ciampi *et al*., [32]	Production line within a research platform	Reconfiguration and hybrid model support	Proof of concept is not sustained commercial deployment

Different conclusions may be drawn from the body of evidence presented. For example, if we define "integration" as the ability of components to successfully communicate and coordinate each other's activities under defined conditions, then laboratory examples clearly demonstrate that DT-IIoT architectures can enable communication and coordination. Examples of simulations exploring how DT-IIoT enabled systems respond to modeled disturbances are similarly valid. Conversely,

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industrial applications represent testing the feasibility of implementing a similar DT-IIoT-enabled architecture in each production context. However, none of these individually provides conclusive proof that DT-IIoT architectures will be able to maintain their efficacy across various combinations of production processes, vendors, etc.

Additionally, all the examples discussed optimized different performance metrics (e.g., material flow coordination, scheduling quality, product geometry, etc.), thus making comparisons between them using a single metric (e.g., percent increase) somewhat meaningless. Similarly, this review did not attempt to evaluate the relative effectiveness of the various DT-IIoT architectures reviewed nor did it imply that there was some type of "pooled effect" resulting from their use. Rather, the most reasonable conclusion is that DT-IIoT integration provides various types of execution-related capabilities that will vary depending upon both the level of synchronization achieved through DT-IIoT interfaces and the accuracy of the models used to guide those interfaces; as well as the limitations imposed by the receiving production system.

5 DISCUSSION AND CONCEPTUAL ARCHITECTURE

5.1 Execution Authority and Architectural Boundaries

Figure 2 illustrates the proposed execution-centered reference architecture. Data passes through acquisition and semantics integration into a physical model; analytical services use this model with production context as input from MES and other systems in the enterprise to determine the best alternative; once determined, the selected alternative must have been feasible and authorized by the execution authority prior to being sent to the appropriate operating system; outcomes then feed back to the current model state and the ongoing process of maintaining models.

The above architecture provides the answer to RQ1 in defining the necessary interfaces which provide identity preservation, timing, meaning and authority. Therefore, it is possible to have each individual functional unit running on separate products within a single MES application. If the production rules enforced by a single orchestrating service clearly define ownership and transactional boundaries, there will be no need for ERP or other applications such as PLM, Maintenance or Quality Systems to generate conflicting, un-coordinated orders.

As illustrated in RQ2, the literature describes several paths from observing to diagnosing problems, to scheduling, to coordinating logistics and to providing specialized feedback control. However, to maintain trustworthiness (assurance), these various paths are based on differing levels of assurance. For example, while an alert indicating that something has gone wrong during diagnosis can contain some degree of uncertainty regarding what went wrong and when it occurred; an automated release of materials to the shop floor cannot include similar uncertainty. As a result, we believe that the technical capabilities of a model must be evaluated independently from the level of authority assigned to the outputs generated by the model.

5.2 Decision Checks and Fallback Behavior

Figure 3 illustrates the Architecture in a conceptual sense as a series of steps from sensing to synchronization, interpretation, recommendation, validation, execution, and learning. Before any action must meet four conditions related to state freshness, valid models, production limits, and access rights. The conditions are specific to each type of review decision; thus, no universal threshold values were suggested by the review.

An Analytical Service that monitors all data for staleness or finds that it is modeling beyond the range of its previously validated operation will withhold making an automated recommendation and will prompt a review. Local control shall remain active only within the bounds of the approved operating range. An action on a piece of equipment (and/or materials) cannot be reversed once initiated, therefore rolling back a program does not reverse movement of equipment or materials processed.

Recovery alternatives include safely transitioning the equipment to a known stable condition, completing a compensatory transaction, or authorizing a rework procedure.

The primary limitations identified for RQ3 are interrelated. Inaccurate semantics result in a potentially fresh but inaccurate state; poor timing results in an otherwise accurate model being invalidated; and unimplemented authorization policies render an otherwise possible technical action unacceptable. Thus, merely increasing communication speed is likely to have little impact on improving reliability of execution.

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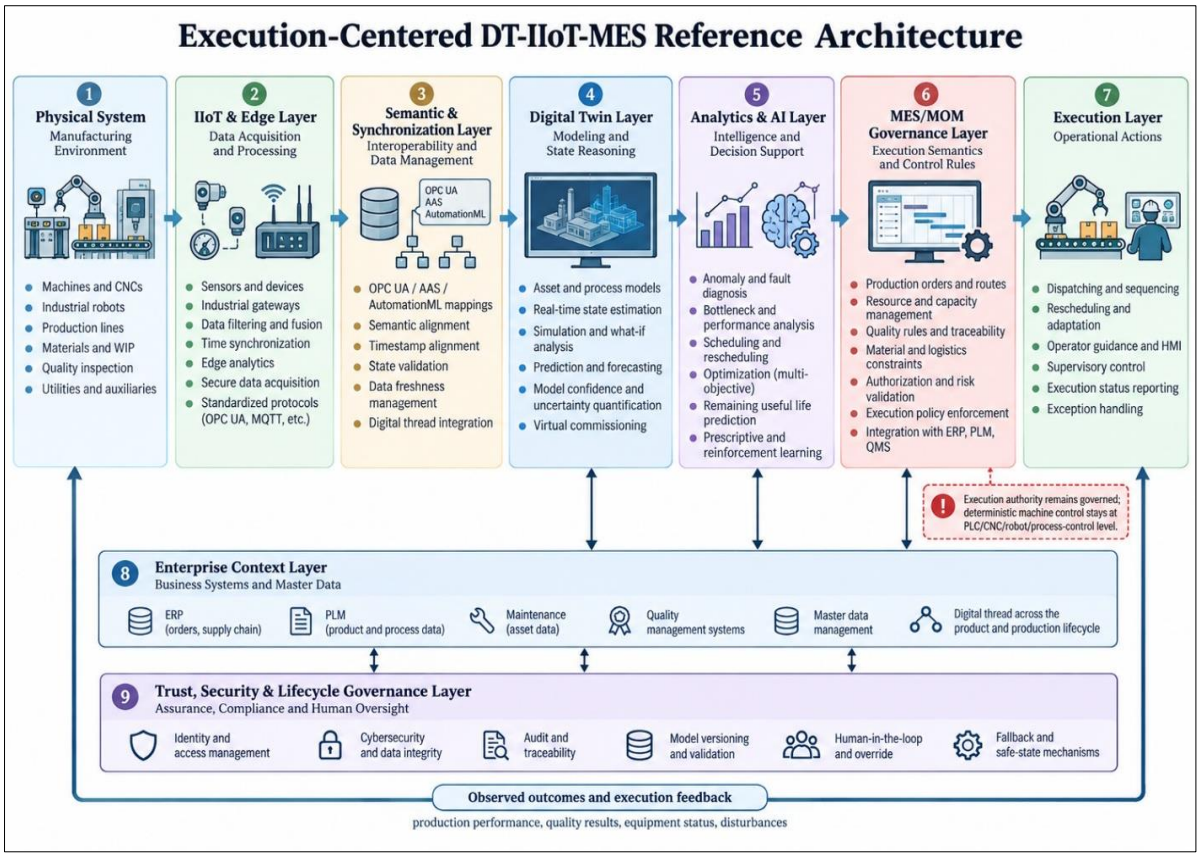


Figure 2: Proposed execution-centered DT–IIoT–MES reference architecture. Production authorization is distinct from local machine control and independent safety functions

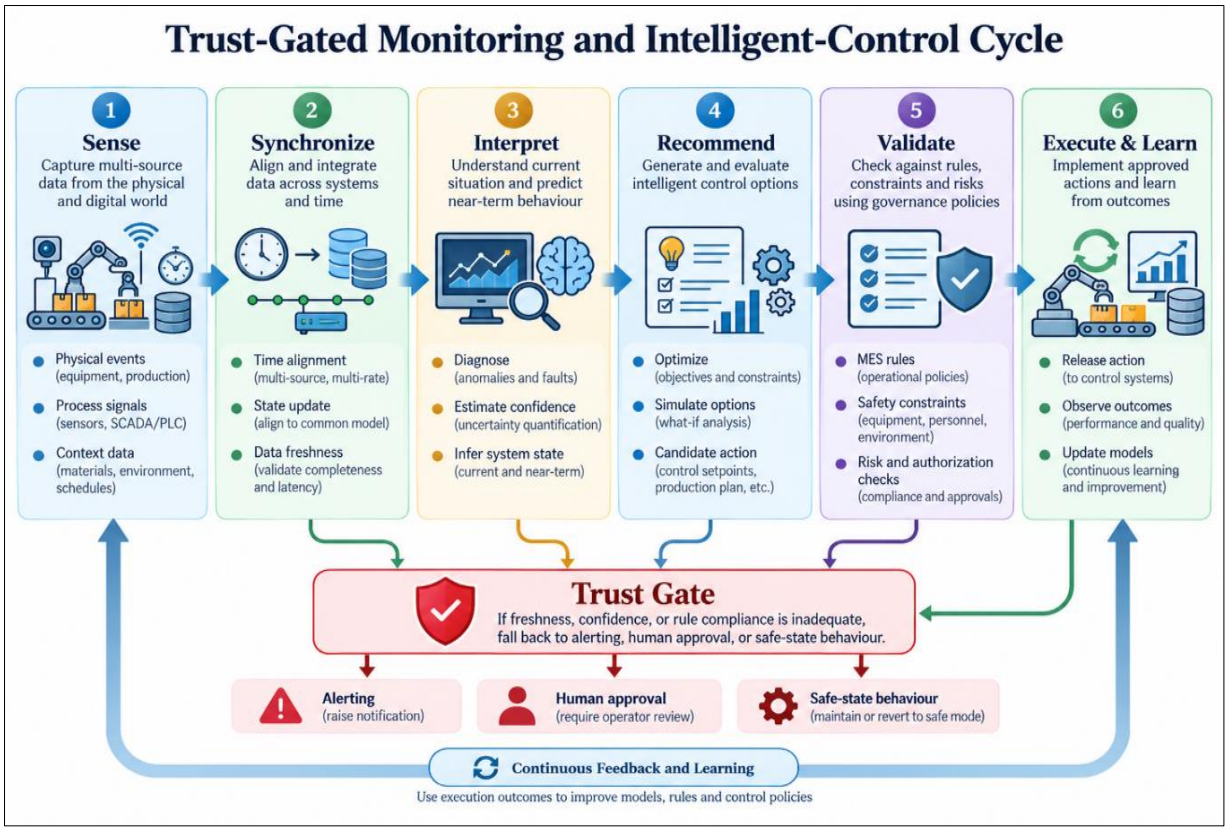


Figure 3: Proposed control cycle with decision checks and fallback behavior. Model updates and learned policies remain subject to validation and change control.

5.3 System Outcomes and Contribution Boundaries

Improvements made locally can move loss from one area to another. More use of machines could cause an increase in blocking; Rescheduling more often could make the downstream processes unstable; Condition based maintenance could be conflicting with the commitment to deliver. Therefore, this architecture will evaluate throughput, quality, on time performance, WIP and intervention burden all at once. Xu et al's view of system level monitoring as well as the monitoring of assets for production flow [20], support the necessity to monitor asset behavior in relation to production.

This study, relative to reviews listed in Table 1, places a focus on the execution boundary and what is required to demonstrate enough evidence that would give you increased decision making authority. This study does not claim a new control algorithm, nor a standardized maturity scale, nor does it show to have superior results than those systems which already exist. What this study contributes is the combination of model and interface requirements to produce a measurable test set of questions for implementation.

6 Research Gaps and Future Research

Table 4 takes the stated limitations of this study and converts these to possible questions (and some proposed data collection) to help form the basis for a comparative validation of synchronization and prediction methods in manufacturing systems. These proposed methodologies will provide direction toward the comparative validation of synchronization and prediction methods, but they do not represent claims regarding the current standardization of the listed metrics.

Research on synchronization must also determine how state age, clock uncertainty, and missing events impact specific decision-making processes. Therefore, all such experiments must intentionally introduce variability in one or more of these factors and document when recommendations may no longer be feasible or stable. In addition, predictive accuracy must be analyzed within the context of the appropriate time horizon with assessments of uncertainty and drift made at the point in time when there have been changes in equipment status or product mix.

To evaluate interoperability in terms of resource identifiers, operation states, quality holds, and product genealogy, researchers must test whether these remain consistent and meaningful across various vendors and brownfield equipment. Although OPC-UA, Asset Administration Shells, and Automation ML address aspects of communication and representation, adoption of these standards does not inherently establish equivalent business semantics. Therefore, conformance testing must include scenarios that violate consistency in units, delay events, change versions during use, and interrupt transactions.

To establish trustworthiness in autonomous decision making, it is essential to define constraints explicitly, and to assess how each candidate policy fails. Each candidate policy must therefore be tested for constraint violations, taking invalid-states-of-action as well as recovery performance into account. Human override should also be included in such experiments. Thus, the goal is to demonstrate that an action continues to be admissible under typical disturbances, rather than simply demonstrating increased average rewards or decreased modeled make spans.

For multi-twin coordination, issues related to model ownership, version compatibility, and conflict resolution procedures need to be addressed. Furthermore, researchers should investigate communication and computation costs associated with increasing numbers of assets. An example of a successful laboratory-based replanning experiment is insufficient by itself to resolve these scalability-related problems [19].

Finally longitudinal studies comparing a defined baseline to a staged implementation based on documented operating conditions can help build credibility to claims about long-term operational and economic benefits. Such longitudinal studies can collect useful data including observation duration, production mix, disturbance exposure, frequency of interventions (i.e., updates), model maintenance efforts required and uncertainty surrounding observed results. Also claims about operational and economic benefits should be separated from other contemporaneous investments in equipment or process improvements.

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Table 4: Research gaps, priority questions, and suggested validation evidence

Research gap	Priority question	Suggested evaluation evidence
Synchronization quality	How stale or uncertain can state become before the decision is invalid?	State age, jitter, missing-event rate, prediction error, sensitivity
Semantic interoperability	Do events and MES objects preserve meaning across vendors and legacy assets?	Cross-vendor mappings, conformance tests, schema errors
Trustworthy autonomy	Do candidate actions remain within operational and safety constraints?	Constraint violations, overrides, fallback tests, explanation usability
Multi-twin coordination	How are conflicting models and recommendations resolved on a scale?	Conflict frequency, compute load, version traceability, communication cost
Lifecycle governance	Who validates, changes, and retires execution models?	Change records, approval time, drift detection, audit completeness
Industrial durability	Do benefits persist as equipment, products, and staffing change?	Multi-month performance, uncertainty, interventions, maintenance effort

7 Practical and Managerial Implications

Figure 4 illustrates potential progression from Read Only Monitoring to Diagnosis, Recommendation Support, Rule Validated Rescheduling, and Selective Closed Loop Execution. Each step in this progression should be based upon reliability of operation and consequences associated with incorrect or missing information. This progression represents an implementation heuristic as opposed to an empirically validated measure of maturity. More autonomous systems do not necessarily result in more business value.

A manufacturer may begin by creating a limited number of decisions that have well defined input variables, constraints, and owners. A manufacturer should then examine how their automated recommendations relate to the current state of their decisions and investigate all differences. A manufacturer will know it is safe to expand the system's scope if the system has operated correctly and provided reliable recommendations through normal operating conditions (including some level of simulated disturbance) and if the benefits associated with automation exceed the cost of integrating and maintaining the system. All actions which affect the Quality Status, Material Disposition, Routing, or Process Parameters must explicitly require approval and provide a history of all approvals.

The manager responsible for deploying the Twin Portfolio should determine who is responsible for defining the Data Semantics, Model Validation, Operational Approval, Cybersecurity prior to expanding the portfolio. All business cases related to deploying the Twin Portfolio must consider Interface Maintenance, Model Recalibration, Operator Training and Downtime related to System Changes. The use of Dashboards to monitor the performance of production equipment is not equivalent to demonstrating production benefit. Procurement and Internal Governance can facilitate the deployment of the Twin Portfolio by mandating documentation of Interfaces, Version Control over software and hardware components, Auditable actions including authorization and denial of access, and clearly defined fallback responsibilities.

8 Limitations

The review is both selective and interpretive. While the synthesis contains 35 references to manufacturing twin research, it is not a comprehensive catalog of all manufacturing twin research conducted. The lack of replicability within this study; inability to create reproducible data export files; and limitation on the ability to reproduce screening records limit the ability to replicate results from this study. Evidence used in this synthesis was also limited due to the availability of materials in only the English language, as well as access to publisher or institutional records.

A formal risk-of-bias assessment and/or independent screening did not occur. A verified Digital Object Identifier (DOI) and published record of an article does not confirm all the technical claims stated in the article. To evaluate some of the most recent contributions to literature, only an abstract and the publisher's description regarding experimental details were assessed. Because of these limitations, the review did not make unverified numerical comparisons and did not assume that any information that was not reported, such as validation or failure testing, had been absent from the entire study.

Due to heterogeneity among the reviewed articles, quantitative pooled conclusions cannot be drawn. Related reviews may include overlap of primary studies which would then constitute non-independent replication. Studies that have failed to demonstrate long term integration success may suffer from "demonstration" and "publication" biases favoring successful demonstrations over failed ones.

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Validation of the proposed architecture, decision checks, and adoption sequence will need to be completed prospectively. Coherence should not be misconstrued as demonstrated effectiveness.

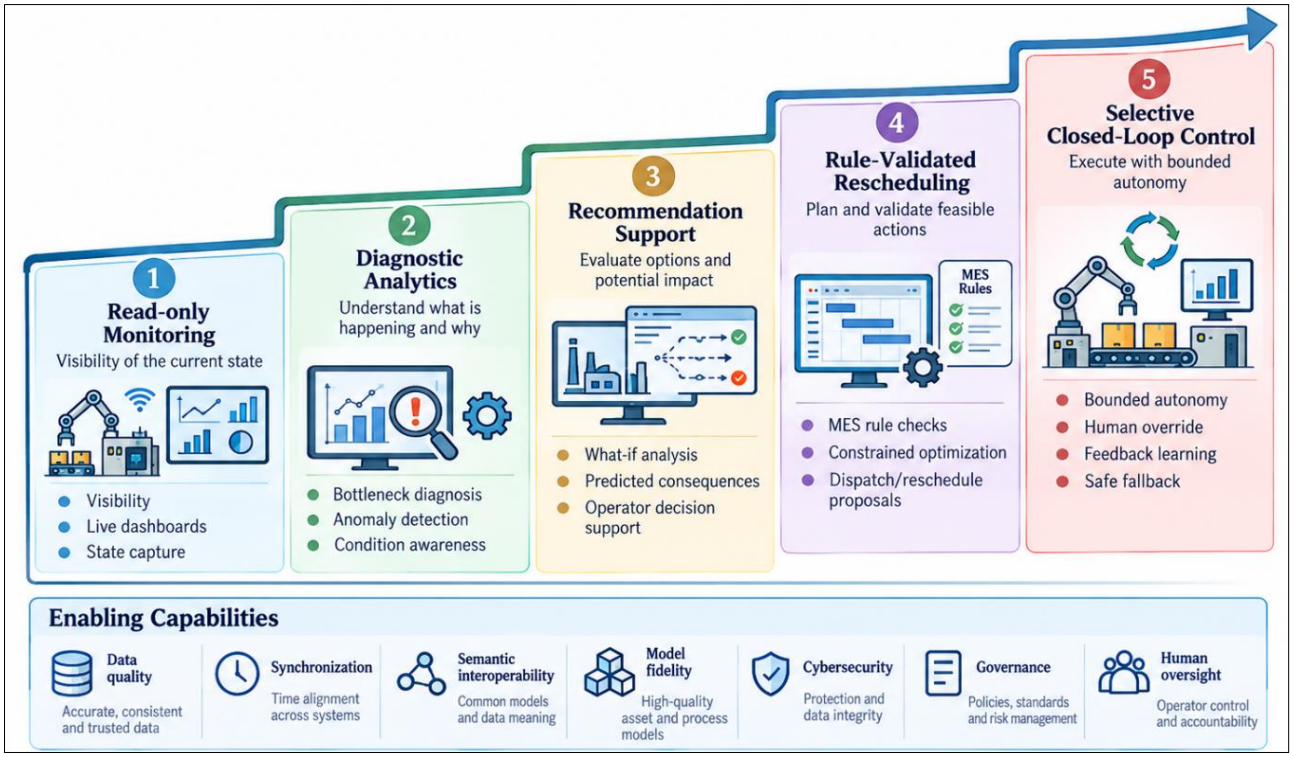


Figure 4: Proposed progression of DT–IIoT–MES adoption and autonomy. The sequence is a conceptual implementation guide, not a validated maturity scale or a guarantee of economic benefit

9 CONCLUSION

DT/IIoT integration will enable MES to make decisions based upon a current view of the shop floor. The mechanisms discussed in the literature (monitoring, diagnosis, production-logistics coordination, scheduling and special-purpose feedback control) depend on the quality of the data collected; the relevance of the models used for making decisions; and whether the systems executing those decisions have adequate resources to enforce operational constraints.

An architecture has been identified that includes explicit connection of analytics to execution authority as well as verification of state freshness, model applicability to decision, feasibility and authorization. Production changes are governed by MES or a designated orchestrator. Local controllers remain responsible for real-time control and independent safety considerations. Separation of responsibilities may provide a practical basis for evaluation of increased autonomous operation without presumptions that a twin is a safe and/or authoritative controller.

Additional research is needed regarding synchronization, semantic consistency, model drift, fallback operations and continued industrial success. The central challenge is to demonstrate that the validated action taken is still valid when executed.

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