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Cloud-Based Manufacturing Execution Systems for Real-Time Production Optimization

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Abstract: This paper presents a comprehensive investigation into cloud-based Manufacturing Execution Systems (MES) and their role in real-time production optimization within the broader context of Industry 4.0. Drawing upon recent advancements in advanced planning and scheduling (APS) technology, the study addresses the limitations of traditional on-premises MES, particularly those linked to hierarchical automation pyramids and fragmented data flows. By consolidating theoretical frameworks and empirical findings from case studies in the automotive and electronics sectors, the paper highlights how cloud-based platforms facilitate dynamic scheduling, reduce cycle times, and enhance overall equipment effectiveness (OEE). Key enablers include the integration of Internet of Things (IoT) devices, modular microservices architectures, and standardized communication protocols—capable of delivering actionable insights to stakeholders in near real-time. Emphasis is also placed on practical deployment considerations, covering gradual (phase-based) versus comprehensive (big-bang) implementation strategies, data security, and organizational readiness. The research concludes with a set of recommendations for enterprises of varying scales to maximize the benefits of cloud-driven MES/APS solutions while mitigating operational, security, and cost-related risks. In doing so, it contributes to an emerging body of knowledge on the design and execution of agile, data-centric production systems that align with contemporary market demands for responsiveness and flexibility.

Keywords: Cloud-based MES, Advanced Planning and Scheduling, Industry 4.0, Real-time Production Optimization, IoT Integration, Data-driven Manufacturing

Introduction

Digitalization has become a pivotal driver of transformation in modern industrial production, fostering more efficient and flexible manufacturing processes [1, 2]. As global markets demand increasingly shorter lead times, higher product variety, and stringent quality standards, the need for real-time production management has grown significantly. Traditional manufacturing setups often rely on the hierarchical automation pyramid, wherein data flows and decision-making processes are typically siloed and lag in responsiveness [3]. In contrast, Industry 4.0 initiatives emphasize seamless data exchange, robust connectivity, and intelligent automation across all production levels.

Cloud-based Manufacturing Execution Systems (MES) and Advanced Planning and Scheduling (APS) solutions have emerged as promising answers to these challenges [4]. By leveraging remote computing resources, SMEs can access advanced analytics, on-demand scalability, and cost-effective integration without the high capital expenditures typically associated with on-premises systems [5]. Likewise, large manufacturers benefit from reduced infrastructure maintenance and faster deployment cycles when adopting cloud-driven platforms.

Nevertheless, legacy hierarchical architectures, commonly encapsulated by the notion of the automation pyramid, face intrinsic limitations in handling dynamic, real-time data streams, thereby hindering agility in complex production environments [2]. Cloud technologies circumvent these constraints by enabling flexible, service-oriented architectures that flatten the traditional pyramid. As a result, critical data and decision-making capabilities can be distributed across the network, improving transparency, responsiveness, and overall operational efficiency [1].

The overarching aim of this study is to conduct a comprehensive analysis of contemporary cloud-based MES solutions, identifying the trends, advantages, and limitations they present for continuous, real-time production optimization. To achieve this goal, the research will focus on the following objectives:

1. Identify key elements and functional capabilities of cloud-based MES systems.
2. Compare implementation strategies in SMEs versus large enterprises.
3. Assess economic and technological benefits as well as major barriers (security, reliability, and cost).
4. Formulate recommendations for designing and deploying cloud-based MES/APS.

Current literature on Industry 4.0 and the future of manufacturing highlights the imperative role of MES and APS systems in driving digitalized production [1, 4]. These platforms serve as central hubs for coordinating production planning, monitoring shop-floor operations, and facilitating vertical as well as horizontal data integration.

Recent studies underscore how cloud-based MES solutions align with Industry 4.0 principles by streamlining real-time information exchange and lowering the barriers to advanced analytics adoption [2, 3]. By shifting data storage and computing power to cloud infrastructures, manufacturers can scale production control capabilities rapidly, while also reducing on-premises IT complexity. However, the uptake of such solutions, especially among SMEs, remains limited due to persisting security concerns, uncertain cost structures, and the lack of uniform implementation standards [5]. In addition, many enterprises face organizational hurdles, including inadequate internal expertise and resistance to change, which further complicate the transition to cloud-based manufacturing systems.

In light of these observations, this study endeavors to build upon the existing body of knowledge, offering a systematic investigation into the technical and managerial facets of cloud-based MES/APS. By documenting both theoretical and practical insights, the research aims to address the current gaps and contribute meaningful perspectives on the evolving landscape of real-time production optimization.

1. Conceptual Foundations of Cloud-Based Manufacturing Execution Systems (MES)

A central challenge in contemporary manufacturing environments is the fragmented nature of production data and the resultant lack of real-time transparency. This issue is closely tied to the conventional, strictly layered approach referred to as the "automation pyramid," where each hierarchical level—from field devices and programmable logic controllers (PLCs) to supervisory control and data acquisition (SCADA), MES, and ultimately enterprise resource planning (ERP)—operates with limited vertical and horizontal data exchange [6, 7]. Although this pyramid structure has historically provided clarity and control, it poses significant constraints in a dynamic, highly interconnected industrial setting.

Specifically, the inability to achieve seamless, immediate visibility of shop-floor operations hampers strategic decision-making and diminishes responsiveness to market fluctuations [3]. When data resides in isolated silos, attempts to optimize scheduling, resource utilization, and quality management become increasingly complex, driving up operational costs and time-to-market. Consequently, manufacturers are actively exploring alternatives that bypass these traditional limitations and foster real-time interoperability across the entire value chain [2].

Building on this problem, the evolution of Manufacturing Execution Systems (MES) offers promising solutions. Historically, MES were developed as proprietary, on-premises software solutions, with system ownership, maintenance, and upgrades managed internally—often involving significant upfront capital and extensive IT resources [8].

Although on-premises MES systems still offer advantages such as dedicated security controls and customization, they are increasingly being supplemented or replaced by cloud-based architectures [2].

Cloud-based MES leverages remote infrastructure to deliver greater scalability, improved accessibility, and lower operating costs [9]. The hallmark of these systems is the "pay-per-use" model, whereby companies pay for actual consumption of resources (computing power, storage, or analytics modules) rather than investing in substantial hardware and software infrastructure from the outset. This shift not only democratizes access to advanced production control and monitoring tools—particularly relevant for SMEs with limited capital [5]—but also allows large enterprises to deploy and update systems more nimbly across geographically distributed facilities.

Cloud services intrinsically support high levels of modularity and interoperability. By adopting well-defined application programming interfaces (APIs) and communication protocols, MES modules and microservices can be easily added, upgraded, or replaced without substantial downtime [9]. This ensures more efficient lifecycle management while accommodating evolving production requirements.

Numerous research prototypes and commercial platforms exemplify the transformative potential of cloud-based MES [10]. For instance, pilot implementations featuring embedded Internet of Things (IoT) sensors (e.g., retrofitted legacy machines) provide automated data acquisition and bidirectional communication, enabling real-time feedback loops that lead to dynamic scheduling, predictive maintenance, and just-in-time inventory control. These pioneering solutions validate the feasibility of integrating cloud resources, edge computing devices, and advanced planning and scheduling algorithms within an overarching MES framework [2].

Whereas traditional MES solutions commonly interact with fixed hardware and monolithic software structures, cloud-based APS or Cloud-based Advanced Planning and Scheduling (CAPS) systems tap into distributed computing resources and shared data repositories to orchestrate production more dynamically [1]. In a classic on-premises deployment, performance bottlenecks, resource underutilization, and maintenance overhead can inhibit continuous optimization. By contrast, CAPS leverages automated scalability—scaling up or down in near real-time—thereby enabling companies to handle demand fluctuations more responsively [2].

Despite the compelling benefits, adopting cloud-based MES raises important questions regarding data security, privacy, and system reliability [11]. Manufacturers must consider strict access controls, encryption protocols, and ongoing threat monitoring to protect sensitive production data. The implementation of robust identity and access management (IAM), alongside compliance with established security frameworks (e.g., ISO/IEC 27001), can help mitigate risks. Additionally, hybrid solutions—where critical data remains on-premises while non-sensitive operations reside in the cloud—provide a balanced alternative [2].

An equally significant dimension involves assessing the total cost of ownership (TCO) for cloud-based MES compared to traditional setups. Although capital expenses (CAPEX) are typically lower due to reduced hardware procurement, operational expenditures (OPEX) may accumulate over time [5]. Still, the scalability inherent to the cloud allows manufacturers to align IT spending more closely with fluctuating production demands, reducing the risk of paying for idle infrastructure. In addition, simplified maintenance and automatic software updates can substantially decrease internal resource allocation for system administration, further enhancing cost-effectiveness [8].

Table 1. Comparative analysis of key features: traditional MES vs. cloud-based MES [2, 5-9, 11].

Parameter	Traditional MES	Cloud-Based MES
Initial investment	High CAPEX for hardware and licenses	Lower upfront cost; pay-per-use model
Flexibility/configuration	Often rigid; customizations are time-consuming	Highly configurable, modular microservices
IT infrastructure	On-site servers and dedicated IT staff required	Remote infrastructure, minimal local server usage
Real-time availability	Limited by internal network and server capacity	Scalable on-demand, continuous updates in near real-time
Data security	Physical control of servers but fragmented updates	Centralized security patches, encrypted data exchange
Deployment timeline	Lengthy installation, testing, and rollout	Faster deployment; reduced integration overhead

The comparative overview in Table 1 underscores how cloud-based MES solutions deliver a more agile framework for modern manufacturing processes. While traditional MES often rely on substantial upfront investments, cloud-hosted platforms enable an incremental payment model that is more feasible for both SMEs and global enterprises seeking to optimize cash flow [9]. Additionally, configuration and customization in cloud-based systems frequently follow a microservices architecture, reducing implementation risks and creating pathways for continuous improvement [2].

Nevertheless, organizations must acknowledge and address legitimate concerns regarding data security, latency, and dependency on third-party service providers. Managed correctly, these risks can be mitigated through multi-layer cybersecurity measures, robust service-level agreements (SLAs), and the utilization of hybrid approaches where mission-critical data remains on-premises [11]. Ultimately, the shift to cloud-based MES represents not merely a technological upgrade, but a strategic decision demanding alignment with organizational goals, careful risk assessment, and thorough cost-benefit analysis [5].

2. Technological Solutions and Tools for Cloud-Based Production Optimization

Effective real-time planning and scheduling in manufacturing increasingly depends on reliable, high-frequency data flows and robust computational resources [1, 12]. A principal question is how to harness cloud services to organize scheduling (e.g., job dispatching and resource allocation) with minimal latency and maximum responsiveness. Additionally, the timely collection of operational data—such as production status, machine conditions, and quality metrics—relies on Internet of Things (IoT) technologies [2]. Modern sensor networks and microcomputers (e.g., Raspberry Pi, BeagleBone boards) facilitate continuous shop-floor visibility, serving as critical enablers for cloud-based Advanced Planning and Scheduling (APS) or Cloud-Based APS (CAPS) solutions. Identifying the right technological stack, therefore, becomes vital in ensuring that manufacturing systems can adapt to dynamic market requirements without sacrificing operational stability or data integrity.

In an Industry 4.0 ecosystem, the integration of MES, Enterprise Resource Planning (ERP), and APS modules is paramount for end-to-end visibility. Traditionally, this integration occurs through on-premises interfaces that rely on legacy protocols or custom middleware [12]. However, the rise of cloud computing has shifted the paradigm toward service-oriented architectures (SOA) and microservices. In these architectures, each subsystem (e.g., MES or APS) can be deployed in separate cloud environments or within a hybrid arrangement, communicating via well-defined APIs [1].

For instance, Cloud MES platforms typically store production data and order-related information centrally, making it accessible to cloud-based APS engines that schedule tasks in real time. By linking APS capabilities directly to both real-time shop-floor feedback (from MES) and higher-level business data (from ERP), manufacturers can optimize resources, manage bottlenecks, and update production plans more dynamically [2, 3]. This vertical and horizontal integration not only improves agility but also fosters deeper analytics, including predictive modeling of demand and machine usage.

A key facilitator of such cloud-driven integration is the application programming interface (API). Rather than hard-coded data exchange, APIs allow for modular interactions among software components, enabling microservices to scale or evolve with minimal disruption [13]. Given the diversity of software landscapes in modern manufacturing, SOAP (Simple Object Access Protocol) and REST (Representational State Transfer) have become de facto standards for secure, interoperable communication. SOAP offers more formal structures and built-in error handling, while REST tends to be lighter weight and more flexible for web-based applications.

In parallel, messaging protocols like MQTT (Message Queuing Telemetry Transport) are increasingly adopted at the edge layer, especially for low-bandwidth IoT devices. This approach further promotes decoupled system design, simplifying deployment and updates across distributed manufacturing locations [2].

Modern cloud ecosystems offer diverse deployment choices. Commercial providers such as Amazon Web Services (AWS), Microsoft Azure, and Google Cloud provide pay-as-you-go computational resources and specialized services—ranging from IoT device management to machine learning modules [1]. These platforms usually incorporate robust security frameworks and scalability options that cater to both small-batch production and large-scale, multi-site operations.

Alternatively, some organizations opt for private or hybrid clouds, leveraging on-premises data centers for sensitive workloads and integrating public cloud resources for burst capacity or advanced analytics. While public clouds often yield efficiency gains due to economies of scale, stringent industry regulations or cybersecurity policies might prompt certain manufacturers—particularly those dealing with proprietary information or defense contracts—to maintain partial data on internal servers [9].

Achieving a continuous flow of shop-floor data can be challenging in facilities with older equipment. Retrofitting—the addition of sensors, controllers, and networking capabilities to existing machinery—addresses these constraints [2]. Affordable microcomputers like the Raspberry Pi, Arduino-based boards, or industrial variants (e.g., industrial PCs) enable data collection (e.g., temperature, vibration, throughput rates) and streaming to cloud services in real time. By integrating these edge devices with existing PLCs or SCADA systems, manufacturers can incrementally transform their legacy setup into a digitally connected environment, feeding accurate data to APS engines.

Notably, this retrofit strategy often costs significantly less than machine replacement, rendering it especially attractive to SMEs. Once retrofitted, machines can be monitored for predictive maintenance, anomaly detection, and advanced optimization algorithms—expanding a company's competitiveness without major capital expenditures [2, 12].

Enterprises must determine the most suitable deployment model by evaluating key factors such as performance, stability, scalability, and support service-level agreements (SLAs). Cloud-based APS solutions generally excel at handling large data volumes through distributed computing architectures—scaling storage and compute nodes on demand [14]. In contrast, on-premises APS may become limited by local hardware constraints during periods of high-volume production scheduling or complex optimization scenarios.

Stability in cloud environments relies on geographically redundant servers and automated failover mechanisms. Meanwhile, on-premises systems often face constraints of physical infrastructure and in-house expertise. The cloud also simplifies updates and maintenance by allowing providers to roll out incremental patches and software improvements, ensuring that organizations operate on the most recent versions of APS modules [9]. However, the dependency on external providers and potential latency issues must be carefully managed through robust internet connectivity and well-negotiated SLAs.

Determining the success of cloud-based scheduling hinges on quantifiable metrics:

1. Resource Utilization Rate: Measures how effectively computational and production resources (machines, labor, etc.) are used. High utilization often indicates fewer idle assets and leaner operations.
2. Manufacturing Cycle Time: Shorter cycle times are a direct indicator of efficient scheduling and real-time adaptability [14].
3. Quality Yield or Scrap Rate: In systems with continuous monitoring and swift feedback loops, early detection and corrective actions can reduce scrap, translating into cost savings [12].
4. On-Time Delivery Percentage: Demonstrates the alignment between actual production performance and scheduled commitments, capturing the effectiveness of planning tools and real-time adjustments [1].

3. Practical Cases and Implementation Recommendations

Despite the technological advantages offered by cloud-based APS and MES, transitioning from traditional on-premises solutions presents several challenges. Chief among them is the need to reorganize existing workflows and integrate new technologies without disrupting core production processes [1]. Companies often have to undertake substantial reconfigurations of their IT infrastructure, migrating data, and customizing software to preserve functional continuity and data integrity.

Moreover, data security remains a persistent concern, particularly for industries handling sensitive intellectual property or personal information. Cloud-based solutions require robust encryption, identity management, and compliance frameworks to mitigate risks of unauthorized access and data breaches [11]. On top of technical complexities, organizational readiness is essential: management buy-in, employee training, and process standardization all play critical roles in ensuring a smooth transition [5].

An illustrative case from the automotive sector demonstrates the potential benefits and hurdles of migrating to a cloud-based APS/MES environment. Liu et al. [1] describe the development and implementation of a Cloud-based Advanced Planning and Scheduling (CAPS) system for an automotive parts manufacturer. By consolidating data from heterogeneous production lines onto a centralized cloud platform, the company achieved significant improvements in on-time delivery and cycle-time reduction.

- Integration challenges: adapting existing enterprise resource planning (ERP) and MES modules to align with the new APS cloud infrastructure required extensive custom API development and testing.
- Key outcomes: enhanced visibility across multiple shop floors, faster decision-making due to real-time data availability, and substantial cost savings on IT infrastructure.

A separate case discussed by Peßl and Rabel [2] highlights how retrofitting legacy equipment serves as a stepping stone toward cloud adoption. In this example, a mid-sized manufacturing plant installed IoT sensors and microcomputers (Raspberry Pi) on aging machinery to collect real-time data on machine health and throughput. The data was subsequently streamed to a cloud-based MES, enabling advanced analytics and more dynamic scheduling.

- Integration challenges: aligning newly collected sensor data with existing MES frameworks sometimes introduced data mapping and synchronization issues. Additionally, staff required training to interpret the new dashboards and analysis reports.
- Key outcomes: gradual transition minimized downtime, increased operational transparency, and provided a proof-of-concept for broader cloud adoption.

Beyond these specific cases, several recurring challenges impede seamless integration [3, 5]:

1. API configuration: ensuring secure and robust communication protocols (e.g., SOAP, REST) between older ERP/MES modules and modern cloud platforms.
2. Data migration: safeguarding historical data consistency and ensuring minimal data loss during the transition.
3. Employee training: developing the competencies necessary to manage, maintain, and derive value from cloud-based systems, including real-time dashboards and predictive analytics.

Drawing from these and other industrial case studies, a set of best practices emerges for cloud-based APS/MES adoption:

1. Phase-based (stepwise) implementation

- **Advantages:** allows organizations to gradually build competencies, reduce financial risk, and adapt workflows incrementally. This approach suits SMEs that may lack extensive IT resources or face cultural resistance to drastic changes [12].
- **Drawbacks:** slower realization of full system benefits and potential for system fragmentation if multiple legacy modules persist without eventual consolidation.

2. **Big-bang implementation**
   - **Advantages:** streamlines deployment by rapidly replacing aging infrastructure, accelerating modernization, and aligning the entire organization around a unified platform.
   - **Drawbacks:** higher initial costs, greater risk of operational disruptions, and steeper learning curves for employees [9].

In practice, many manufacturers opt for a hybrid approach, beginning with key modules (e.g., scheduling, data acquisition) in the cloud, then progressively integrating remaining functionalities [2].

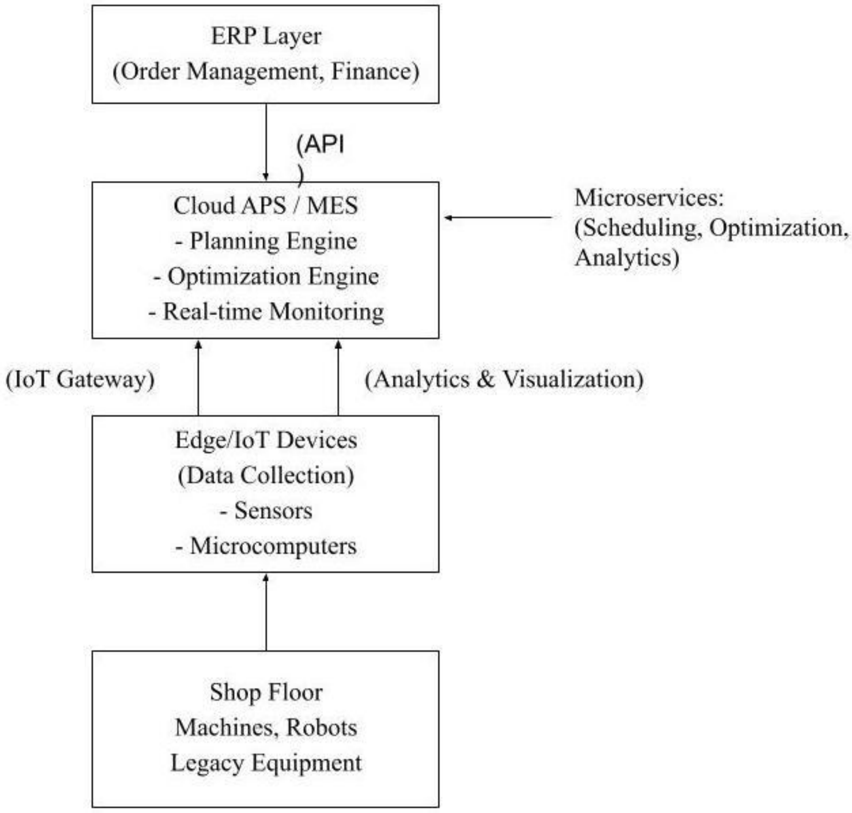

Figure 1. Overall architecture of a cloud-Based MES/APS system

In this architecture, sensors and microcomputers such as Raspberry Pi units are deployed on the shop floor to capture operational variables that include temperature, vibration, throughput, and downtime. Depending on the specific requirements, the captured data is either buffered locally or transferred directly to the cloud-based APS/MES. An edge or IoT gateway facilitates secure communication by implementing protocols such as MQTT or secure RESTful APIs, thereby enabling low-latency and reliable data streaming [2]. Once the data is in the cloud, the system hosts a planning module capable of receiving real-time shop-floor inputs and orchestrating resource allocation. An optimization engine then refines scheduling parameters, including shift assignments and job queues, by applying predictive or prescriptive analytics. Real-time monitoring further enhances responsiveness by supplying dashboards that decision-makers can use to adjust strategies on the fly [1]. At the higher managerial level, the ERP layer oversees customer orders, financial transactions, and inventory control, all of which inform decisions made within the APS. Standardized APIs ensure bidirectional data flow, thereby granting production planners immediate insight into order backlogs and resource availability [12].

The architecture's effectiveness derives from its flexibility, visibility, scalability, and security. By employing modular microservices, companies can integrate new functionalities or expand resources with minimal disruption. Immediate feedback from the shop floor to the APS drastically reduces response times in the face of unexpected events, such as machine failures or sudden demand surges. The cloud infrastructure can also handle large computational loads, a crucial asset when running complex scheduling or optimization algorithms [9]. Despite the distributed nature of the system, each module can operate under strict security protocols, an especially important consideration for highly regulated industries [11]. Overall, the cloud-based

MES/APS architecture, illustrated in Figure 1, embodies a scalable, secure, and data-centric framework for contemporary manufacturing contexts. By choosing either a stepwise or a big-bang transition to this architecture, organizations can calibrate the adoption of new technology to match their goals, available resources, and operational readiness [5, 12].

Conclusion

The analysis undertaken in this paper demonstrates the transformative potential of cloud-based MES solutions for achieving real-time production optimization. Traditional on-premises models, bounded by hierarchical data structures and rigid architectures, struggle to accommodate the dynamic shifts and high variability characteristic of modern manufacturing environments. By comparison, cloud-based systems offer high scalability, seamless interoperability, and advanced analytics—a triad that enables organizations to respond rapidly to fluctuations in product demand, machine status, and resource availability.

Key findings from both theoretical sources and industry case studies underscore the importance of robust integration strategies. Whether an enterprise adopts a stepwise or big-bang approach, aligning the transition process with specific operational contexts and readiness levels is critical. Furthermore, the successful application of IoT devices and microcomputers enhances data visibility on the shop floor, feeding advanced planning and scheduling engines with high-frequency, high-fidelity production data. This transition, while beneficial, does introduce challenges pertaining to data security, organizational training, and effective governance of hybrid IT infrastructures.

Ultimately, the deployment of cloud-based APS/MES emerges not merely as a technological shift but as a broader organizational evolution, requiring alignment of strategic objectives, stakeholder engagement, and continuous process improvement. By following the recommended best practices—ranging from phased retrofitting of legacy machinery to robust encryption and compliance measures—manufacturers can maximize the inherent benefits of cloud architectures. This research thus contributes actionable insights for enterprises aiming to enhance their operational agility, reduce total cost of ownership, and better position themselves in an increasingly competitive global marketplace.

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