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Research Article

Designing a BTP-Centric Integration Mesh for Shop-Floor IoT, MES and ERP in Discrete Manufacturing

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ABSTRACT

The development of Industry 4.0 has led to the expansion of the connection between shop-floor systems, manufacturing execution systems (MES) and enterprise resource planning (ERP) systems. The growing trend in discrete manufacturing companies is the implementation of digital transformation in manufacturing processes to realize operational excellence, real-time decision-making and flexibility. The given paper introduces an in-depth framework of designing a Business Technology Platform (BTP)-based integration mesh that can integrate IoT devices, MES and ERP to facilitate the flow of data and automate processes and improve analytics. The suggested architecture also utilizes microservices, event-based communication and cloud integration to curtail a resilient, flexible and scalable infrastructure. Integration patterns, security considerations and main design principles are discussed. The outcomes of simulation show that it leads to improved efficiency on production, minimized latency in information flow and increased visibility of the manufacturing value chain. The solution is proposed in between the technology of operation (OT) and information technology (IT), which facilitates smart decisions and predictive maintenance.

Keywords: BTP, Integration mesh, Shop-floor IoT, MES, ERP, Discrete manufacturing, Industry 4.0, Data integration, Cloud computing

1. Introduction

1.1. Background

A major change that digital technologies should bring to discrete manufacturing industries is the shift to their digital variant, through the implementation of Internet of Things (IoT), cloud computing and advanced analytics. Whilst manufacturing operations have traditionally been based on siloed manufacturing systems, shop-floor control or what is now known as Manufacturing Execution System (MES) and Enterprise Resource Planning (ERP) operate on a separate basis[1-3]. Such segregation usually leads to sluggish information flow, the lack of visibility regarding the current state of production and the lack of efficiency in decision-making. In fact, as an example, the production managers will not be able to get access to the machine performance data instantly and ERP systems will not be able to reflect the inventory and resources use in their actual state. These loopholes prevent prompt reaction to the deviations in operation, efficient planning of production processes or proactive maintenance. Accomplishment of such disparate systems integration is therefore pertinent in forming an integrated manufacturing environment where IoT devices, MES and ERP platforms data are integrated in order to be harmonized and real-time available. Integrated systems facilitate the exchange of information to enable predictive maintenance, which can identify the possible equipment failures before they happen, better production planning through proper scheduling and allocation of resources and improve the efficiency of the entire operations. In addition, the combined digital platforms will enable making decisions based on data and improve the responsiveness of manufacturers to new market requirements, minimize downtime and ensure the products remain the same. Since discrete manufacturing is shifting toward Industry 4.0 paradigms, the beneficial implementation of integrated, real-time solutions becomes more than important with regard to its potential to achieve competitiveness, agility and sustainable growth.

1.2. Importance of designing a BTP-centric integration

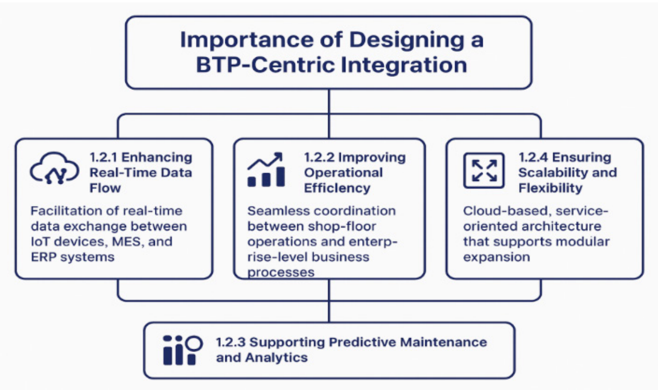

Figure 1: Importance of Designing a BTP-Centric Integration.

- **Enhancing real-time data flow:** The promotion of real-time data exchange among IoT equipment, MES and the ERP systems is also one of the major benefits of a BTP-based integration. Conventional point to point or siloed systems tend to be hit by the delay in delivery of vital production and operation information. With the help of SAP Business Technology Platform (BTP) as the central place of integration, the organization is able to have the data flow at all the levels of manufacturing, in a continuous and instantaneous manner. This guarantees that the managers, engineers and the automated systems will access the relevant up to date information that will help to make decisions quickly, take proactive actions and make the production environment responsive in general.
- **Improving operational efficiency:** It can be integrated through BTP to provide a smooth coordination between the enterprise duration business processes and shop-floor business operations. MES is capable of adapting production timetables dynamically with the help of real-time IoT data, whereas the ERP systems can reflect the correct availability of the resources and inventory. The alignment minimizes wasted time, resources as well as optimum throughput. The centralizing and standardization of data exchange in a BTP-based architecture simplifies processes, minimizes the workload in terms of the bottleneck in the operational processes and increases manufacturing processes in terms of productivity and cost saving.
- **Supporting predictive maintenance and analytics:** A BTP-based integration permits the integrating and examination of high-speed information in machines, sensors and enterprise systems. This can be used to predictive maintenance with a unified dataset and the manufacturers can predict equipment functions when the equipment is about to fail and can plan at the maintenance proactively and avoid unexpected downtimes. Moreover, embedded analytics can give operational information on the production patterns, resource utilization as well as quality measures and support ongoing improvements efforts and information-based decision making throughout the enterprise.
- **Ensuring scalability and flexibility:** The world of manufacturing today needs systems that can be expanded to accommodate new devices or new production lines or even a changing business need. BTP offers a service-oriented and cloud-based tool, which can be used in a modular fashion and not interfere with the current workflows. Its integrated suite enables organizations to rapidly add or modify services, integrate new technological innovations like edge computing or AI and change with the market conditions. This scalability will guarantee long-term sustainability and place manufacturers in a better position to adopt Industry 4.0 paradigms.

1.3. Mesh for Shop-Floor IoT, MES and ERP in discrete manufacturing

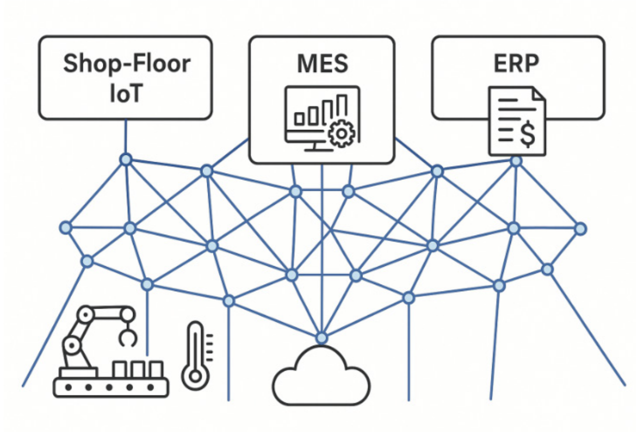

Figure 2: Mesh for Shop-Floor IoT, MES and ERP in Discrete Manufacturing.

The smooth interaction of Time series shop-floor IoT devices, Manufacturing Execution Systems (MES) and Enterprise[4,5] Resource Planning (ERP) platforms are essential objectives of the unified, live view of the manufacturing operations in discrete manufacturing. The best framework towards achieving this goal is a mesh-based integration architecture that generates a network of interrelated elements in which they communicate in a decentralized but coordinated way. IoT devices, in turn, sensors, actuators and edge computing nodes are installed in such a mesh, constantly gathering operational data related to machines performance, environmental factors and production parameters. This information is passed by standardized protocols to the MES layer that is then interpreted by the production scheduling, quality control and monitors the work-in-progress. The MES in its turn aligns with the ERP systems making sure that the enterprise-level processes (procurement, inventory management and finance) are updated to reflect the real situation on the shop floor. Through the adoption of mesh architecture, communication takes place on an event driven and asynchronous fashion, which allows the communication to be real-time responsive and minimizes the reliance on the sequential and point to point integrations that is usually subject to latency and data inconsistency. Besides, the mesh approach is scalable and flexible and the addition of new devices, production lines or enterprise modules does not have to affect current workflows. SAP Business Technology Platform (BTP) is a cloud-based integration platform, which becomes the foundation of the mesh, delivering middleware, API management and data orchestration functions and harmonizing heterogeneous data formats and protocols. This can guarantee as well as identify steady, trustworthy as well as safe data share at all manufacturing operation tiers. Finally, the IoT, MES and ERP integration using a mesh architecture provide manufacturers with the ability to gain end-to-end operational visibility, perform predictive maintenance, optimize the use of resources and promote advanced analytics, which makes it one of the strong enablers of Industry 4.0 and digital manufacturing transformation.

2. Literature Survey

2.1 IoT and MES integration

Implementation of Internet of Things (IoT) and Manufacturing Execution Systems (MES) can attract much attention in recent studies[6-9]. The IoT devices, sensors, actuators and smart machines help to gain real-time data collections off the production lines, which will provide a fine-grained understanding of how the production is working. This data combined with MES will be used in monitoring production, predictive maintenance, quality management and manufacturers act fast upon deviation or equipment failures. Nonetheless, a number of challenges remain such as the absence of standardized communication protocols, low-interoperability of heterogeneous devices and network latency-related problems that can undermine the real-time responsiveness. Other studies have also noted the difficulty in taking into account the high frequency IoT streams of data into conventional MES architectures without affecting the system performance. All in all, the IoT-MES integration has been viewed as an important measure towards manufacturing smartness, although it must be thorough to both operational and technical limitations.

2.2. MES and ERP connectivity

The linkage of MES and Enterprise Resource Planning (ERP) systems is essential in relating the shop floor activities with higher business goals. Making one comparison between the two, unlike MES that is concerned with real-time production management, ERP involves planning, resource allocation and financial control. Literature highlights the suitability of the service-oriented architectures (SOA) and middleware solutions as facilitators of the smooth data flow between the systems. The literature shows that a good integration of MES-ERP provides a level of schedules, inventory and fulfilment of orders and this has resulted in a high level of efficiency and decision-making. Nonetheless, there are other challenges such as lack of consistency of data models, delay in implementing transactional updates and ensuring data integrity within complex enterprise environments. Researchers have proposed that standard interfaces and clearly defined integration layers are useful in getting over these challenges, but in practice it has been found that scalability and adaptability are found to be missing.

2.3. BTP and cloud-based integration

SAP Business Technology Platform (BTP) and some other cloud-based applications have become potent industrial integration workhouses and offer integration as a service (iPaaS) functionality. The authors of literature prove that BTP makes it possible to connect IoT devices, MES and ERP seamlessly as it uses standardized APIs, existing integration flows and cloud-native services. The advantages of cloud-based integration will be the increased scalability and centralized management of data, improved data consistency and quick implementation of new workflows. Besides, cloud systems can be used to perform sophisticated analytics, machine learning and predictive data due to the aggregation of data with various sources. But in the past projects, some issues are reported to confront data security, user compliance with the industry and reliance on network availability. Utilization of BTP integration solutions has been identified as promising in the development of highly interwoven production environments that are nimble.

2.4. Challenges in discrete manufacturing integration

There are various issues experienced in discrete manufacturing systems when consolidating the environment of IoT, MES and ERP systems. Diverse data formats of old machines, different communication protocols and vendor-specific interfaces make it difficult to aggregate data and process real-time information. Time-sensitive operations are also subject to network latency and bandwidth and threats are also experienced on cybersecurity due to intellectual property as well as operational continuity. Moreover, the older MES and ERP systems are not always flexible enough to support the new IoT products or services in the cloud environment, which provides a new bottleneck in end-to-end integration. In literature, this achievement of a single digital thread through which the accuracy and traceability of data and operational transparency across the enterprise is ensured is also a challenge. To deal with these issues, it is important to have strong middleware, standardized protocols and good planning of the architecture that would create smooth integration without interrupting the current production processes.

2.5. Gap analysis

An analysis of the current literature reveals that the insights of integration activities have been primarily made in the form of point-to-point integration between individual systems as opposed to end-to-end integration. Though the integration of IoT-MES and MES-ERP have been thoroughly researched alone, there is a lack of studies that cover a centralized framework of integration that exploits cloud computing systems such as SAP BTP. In particular, we know of a limited exploration of a BTP-based mesh of integration which allows data transfer between IoT, MES and ERP in real-time, scalable, secure and standardized. This discontinuity supports the potential creation of frameworks that do not only tie systems that are physically apart but also provide real-time decision-making, predictive analytics and adaptive manufacturing workflows. Filling this gap in the literature may greatly help to increase agility, efficiency and intelligence of discrete manufacturing firms.

3. Methodology

3.1. System architecture

- **IoT layer:** The layer is the IoT that establishes the integration mesh because it captures real-time information on the shop floor[10-12]. It consists of edge devices, sensors, programmable logic controllers (PLCs) and gateways used to track the status of the machines, environmental conditions and production parameters. The layer guarantees a high-frequency data capture with timely decision-making and predictive maintenance, which is necessary. IoT layer also assists preprocessing of initial data at the edge to minimize latency and network load to facilitate better and efficient integration with the higher layers.

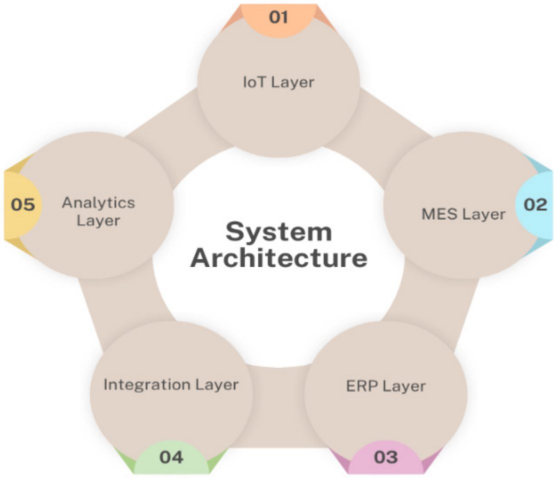

Figure 3: System Architecture.

- **MES layer:** The MES layer is to deal with the implementation and control of manufacturing processes. It will have functionalities of production scheduling, shop-floor monitoring, quality control and work-in-progress tracking. The incorporation with the IoT layer can allow MES to obtain real-time machine and process data allowing dynamical scheduling and prompt reaction to the operational anomalies. The layer will provide a communication mechanism between both the physical production scenario and enterprise-level planning, so that manufacturing operations are optimized to provide efficiency, quality and utilization of resources.
- **ERP layer:** ERP layer deals with business processes that are enterprise-wide and they are resource planning, procurement, inventory management, sales and finance. ERP systems have an opportunity to coordinate the production schedules and supply chain operations by linking to the MES layer to ensure that the necessary stocks are ordered in good time and the consequences of a stockout or overproduction are minimized. The ERP layer gives the business an overall picture of the business performance and gives the strategy the opportunity to be based on operational realities ensuring the production activity forms part of overall business objectives.
- **Integration layer:** The connective tissue in the architecture is the integration layer which is driven by SAP BTP middleware. It consists of API management, micro services and event-based communication systems to enable smooth data transfer between IoT, MES and ERP layers. This layer provides the means of interoperability of heterogeneous systems, message routing and data consistency of the enterprise. It also provides scalability, integration workflow reuse as well as fast deployment of new business processes through the use of cloud-based integration functionality.
- **Analytics layer:** The analytics layer uses all the data that is gathered and combined by all the other lower layers to give actionable information. It entails check-in dashboards concerning critical measures of performance, forecasting analytics to prevent breakdown or production bottlenecks in machines and strategic decision-making through reporting. This layer will assist in optimizing the processes with the assistance of analysing past and current data and reducing downtime, planning maintenance measures before it begins, launching continuous improvements and raising overall operational efficiency and business value.

3.2. Integration patterns

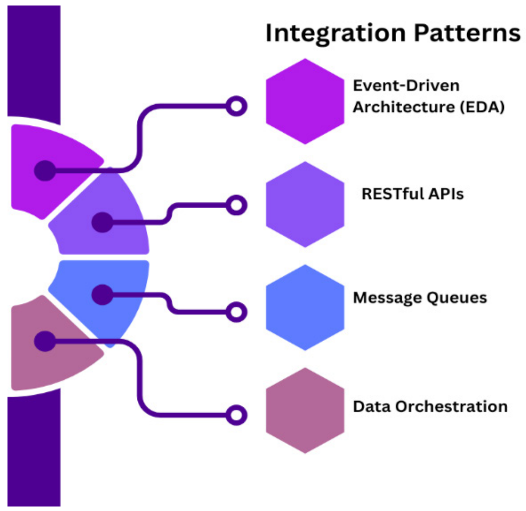

Figure 4: Integration Patterns.

- **Event-Driven Architecture (EDA):** The Event-Driven architecture (EDA) is a design philosophy in which systems interact by generating and receiving events, which allow flow of data to interact asynchronously. The proposed BTP-based mesh of integration offers EDA, enabling the IoT devices, MES and ERP systems to respond to real-time events, including change of machine status, production completions or changes in inventory. This method minimizes the strict interconnection among systems, increases responsiveness and enables scaling as new services will be able to subscribe to events without interfering with the current workflows. EDA is well applied in factory settings where agility in responding to events in the factory is paramount to its efficiency and decision making.
- **RESTful APIs:** RESTful APIs offer the standard interface to communication between heterogeneous systems. REST APIs provide MES, ERP and cloud services with a reliable and structured method to communicate with each other: REST APIs allow exchanging data in a reliable and well-defined format, like JSON or XML, using HTTP protocols and clearly defined endpoints. RESTful API in the BTP integration mesh streamlines integration, facilitates interoperability and enables third-party applications or analytics tools access data on the operations safely. They are also scalable and flexible as the additional services or devices can be added without significant alterations to the current architecture.
- **Message queues:** Message queues are middleware elements that support credible transport of messages amongst systems. They temporarily hold the messages until the receiving system is in a position to process the messages and none of the data is lost in case of a peak load

or network discontinuities. With IoT-MES-ERP integration, decoupling between data producers and consumers with message queues contribute to the reduction of system latency, workload balancing and system overload. Sensors or shop-floor machines send high-frequency events to it that require this mechanism to manage, preserve the integrity and order of information.

- **Data orchestration:** The data orchestration is a real-time transformation, routing and combination of heterogeneous data across data sources. In the mesh based on BTP, it will provide the opportunity to streamline the process of data flow between the Internet of Things devices and MES through to the ERP systems and make sure that all of the systems will be presented with the necessary information in the form they need. Conditional workflow execution, addition of surrounding data with more information and coordination of cross-layered processes are also enabled by orchestration. The trend is vital in the success of end-to-end visibility, operational efficiencies and business insights in contemporary manufacturing ecosystems.

3.3. Security and compliance

Security and compliance come as an essential element in a BTP-based mesh of integration among IoT, MES and ERP systems[13-15], intended to guard delicate operational and business data and guarantee compliance to the industry regulation. API authentication has been handled with the use of OAuth 2.0 which is an authorization architecture that has gained popularity in allowing domestic accessibility without revealing user data. OAuth 2.0 enables any system or user to acquire the tokens that give them limited rights to access certain resources so that only the trusted applications and staff might communicate with APIs. The mechanism is crucial to multi-layered architectures, where many services are asynchronous and there should be access control imposed uniformly across IoT devices, MES apps and ERP. Also, end-to-end encryption is applied to protect information when transmission across devices, cloud services and enterprise applications occurs. With the use of encryption standards like TLS (Transport Layer Security), the integrity and confidentiality of data transfer are ensured over a public or a shared network and data is not intercepted, tampered with or disclosed without the permission of any sensitive information in the manufacturing side. In addition to these, the role-based access control (RBAC) refers to user permissions where roles are set depending on the job of the user and this will guarantee that people can only access specific data and functionalities, which are relevant in their jobs. An example of this might be where production supervisors are able to see real time activities on the shop-floor, but cannot modify financial records within ERP, whilst IT administrators can access the system level more widely to monitor and maintain it. OAuth 2.0, encryption and RBAC make a set of solutions in the form of a multifaceted security framework that overcomes the problems of authentication and authorization, as well as reduces the possible risk of vulnerabilities based on cloud-based and internet of things (IoT) industrial settings. Moreover, adherence to the compliance requirements, including GDPR, ISO 27001 and industry-specific policies, is enforced by the means of auditing, logging and monitoring systems that inform about access, data modifications and other actions carried out by the system. All these security and compliance options are more likely to shield the organizational assets and at the same time giving confidence to the stakeholders that the integrated manufacturing ecosystem actually functions in a reliable and secure manner.

3.4. Implementation steps

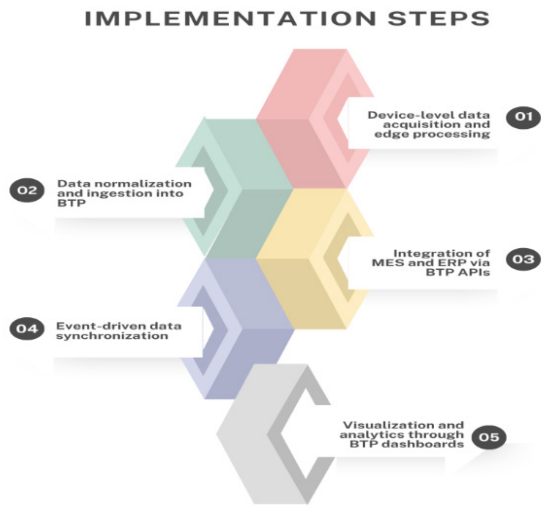

Figure 5: Implementation Steps.

- **Device-level data acquisition and edge processing:** The initial stage of the implementation is an actual gathering of real-time information transferred directly through IoT device, sensors and PLCs spread throughout the production environment. Processing of edges is done locally at gateways or edge servers to filter, pre-process as well as aggregate data then transmitted to the cloud. This lowers down latency, reduces network traffic and only the relevant information will flow. The system is capable of identifying anomalies, generating local alerts and ensuring efficiency of operations by computing near the source, before the data is transmitted to the MES or ERP layers.
- **Data normalization and ingestion into BTP:** After gathering, the data of heterogeneous sources will have to be standardized in a homogeneous format to facilitate easy integration. Neutralizing of the data makes the data and output of the IoT device compatible with the output of the MES and the ERP records. Once it has been transformed, the normalized data is consumed by the SAP Business Technology Platform (BTP) via secure APIs or integration flows. By doing this, it will ensure that every system level functions on a single data set, which ensures integrity of the data and facilitates proper analytics.
- **Integration of MES and ERP via BTP APIs:** BTP APIs and middleware services are used in combining the MES and ERP systems. The process in this step includes the configuration of RESTful endpoints, microservices and connectors to be used in two-way exchange of data. Systems are synchronized with production schedules, inventory status and resources are planned such that the ERP system is used to capture real-time shop-floor operations whilst the MES systems are used to respond to operations directives at the business level. The API based integration is scalable and flexible, thus it is simpler to expand the workflows or add new applications subsequently.
- **Event-driven data synchronization:** In order to be responsive in real-time, event-based synchronization

framework is adopted between the IoT, MES and ERP layers. Generated events, usually as a result of machines, sensors or business processes, are collected and transmitted as messages by message queues or event brokers. This allows systems to respond immediately to vital changes, including production delay, quality variation or stock outage. The event-driven architecture ensures a minimal latency; in addition, it does not heavily depend on polling mechanisms and the business system is always aligned to the operational system.

- **Visualization and analytics through BTP dashboards:** The last action is devoted to using the integrated data to take action. SAP BTP dashboards offer real-time graphics of metrics of production, operational KPIs and indicators of business performance. Predictive analytics, trend analysis and reporting tools enable managers and engineers to make effective decisions, predict equipment failures and streamline production processes. This layer will help sustain improvement efforts and an increase in the efficiency of the entire work by taking into account both historical and real-time data.

3.5. Tools and technologies

The recommended mesh of the BTP-centric integration is based on a set of special tools and technologies at varying layers to allow connecting as smoothly as possible, run and process data in real-time and act on the analytics[16-18]. On the IoT layer, industrial communication systems like OPC-UA and MQTT are used to support dependable and standardized data communication between edge devices, sensors and programmable logic controllers (PLCs). The interoperability of heterogeneous industrial equipment using OPC-UA is a secure and platform-independent implementation and the lightweight, low-latency messaging that can be used with MQTT in high-frequency sensor data. The initial data processing, filtering and aggregation are done at the edge devices so that the networks do not clog with data and higher layers can receive the information before it spoils. The MES layer uses SAP Manufacturing Execution (SAP ME) or hand-made MES systems to control the production, namely, scheduling, shop-floor control and quality control. Communication with IoTs ensures that the state of machines and processes is available in real time so that MES can change workflows dynamically and respond to deviations. SAP S/4HANA is the ERP system that operates at the enterprise level and is used in the management of core business processes which include procurement, inventory, sales and finance. MES links with ERP would provide operational choices that would be aligned with the strategic business goals to enhance efficiency and utilization of resources. The implementation of the integration layer is in the form of SAP BTP Integration Suite that provides cloud-native intermediation, API administration and occasion-based communication. This suite permits to standardize, scale and secure data transfers over the IoT, MES and ERP systems and assist in real-time synchronization and orchestration of workflows. Lastly, the analytics layer using SAP Analytics Cloud to offer interactive dashboards, reporting and predictive analytics. This platform provides actionable insight based on historical and real-time data of all the layers to support decision-making, optimization of operations and continuous improvement. All these tools and technologies are built upon a unified ecosystem, which facilitates the efficient, scalable and secure industrial integration.

4. Results and Discussion

4.1. Simulation setup

The proposed simulation environment that the integration mesh built around BTP aims to simulate is supposed to be based on the realistic manufacturing setting of an industrial environment, permitting evaluation of the system functioning, data flow, as well as efficiency of integration. Within the given configuration, 50 IoT devices are placed at simulated production floor which consists of sensors, edge devices and programmable logic controllers (PLCs). The devices produce real-time data concerning the status of machines, the parameters of the processes and environmental factors, which allows tracking the operation of performance with precision. All IoT devices are connected on the same standard protocols i.e. OPC-UA and MQTT protocols which provides interoperability and low-latency message throughput. In the simulation, the MES layer comprises of five instances that are the various production lines or plant areas and they handle various tasks, including scheduling tasks, tracking of work-in-progress, quality assurance tasks. These MES instances are fed with high frequency data streams of the IoT devices hence able to dynamically remodel production schedules and react on anomalies in near real time. On the enterprise level, three ERP modules are modelled to take into consideration the key business processes, such as procurement, stock control and finance. These ERP modules communicate with MES layer to ensure that the operation on the shop-floor is in line with enterprise resource planning to ensure that materials, workforce and capital used are efficiently utilized. The complete system is intended to support a message rate of 10,000 messages in an hour, which is a representation of high-throughput manufacturing situation. This rate data is used to check the capability of the system to ingest, transform and synchronizes real-time data simultaneously in many layers with low latency and data integrity. Simultaneously, the simulation will include the integration layer, which is an SAP BTP-based platform to control the event-driven data flow, API-based connectivity and information coordination of the data between the IoT, the MES and the ERP platforms. These conditions being recreated when simulating the system can reveal the following: (a) scalability, responsiveness and performance of the system with realistic industrial workloads; (b) the performance and viability of the proposed integration architecture is achievable.

4.2. Performance metrics

Table 1: Performance Metrics.

Metric	Before Integration (%)	After Integration (%)
Data Latency	100%	27%
Production Efficiency	78%	92%
Data Consistency	80%	99%

- **Data latency:** The latency of data can be considered as the time spent on the passage of data across IoT devices to the MES and ERP systems to the analytics layer. Latency used to be high (100) before integration and it indicated that there were very high delays between isolated systems, manual data transfer and real-time synchronization. Latency was decreased to 27% after introducing the BTP-centric mesh of integration and it shows that event fusion architecture, API connectivity and edge processing could be effectively used to decrease latency. Reduced data latency allows prompt decision-making, improved anomaly detection and more prompt production changes, all of which is essential in ensuring efficiency and reducing downtime in production processes.

- **Production efficiency:** Production efficiency measures the ratio of productive production and planned capacity. Before integration, the efficiency was recorded as 78 because of slow flow of information, low coordination among MES and ERP and poor scheduling. Efficiency rose to 92 percent after integrations, a feature that underscores the importance of real time nature of exchanging data and having the entire operations under the same view. Through synchronized MES and ERP systems, production scheduling is able to be dynamically adjusted to machine status, availability of resources and order priority, to reduce idle products and enhance overall throughput. This is an enhancement that helps in reinforcing the importance of smooth integration as an immediate influence on operational performance and productivity.
- **Data consistency:** The data consistency refers to the accuracy, credibility and correspondence of the information at all levels of the system. The consistency used to be 80 in the pre-integration period, as there were inconsistencies due to multiple data entries and incompatible formats, as well as low update frequency between the MES and ERP systems. Once it was integrating, the data consistency increased to 99% showing that by centralizations of data orchestrations, standardization of APIs and real-time synchronization, all systems work with the same correct data. Large data consistency ensures quality reporting and analytics as well as minimizes mistakes during decision-making, managing inventory and production planning.

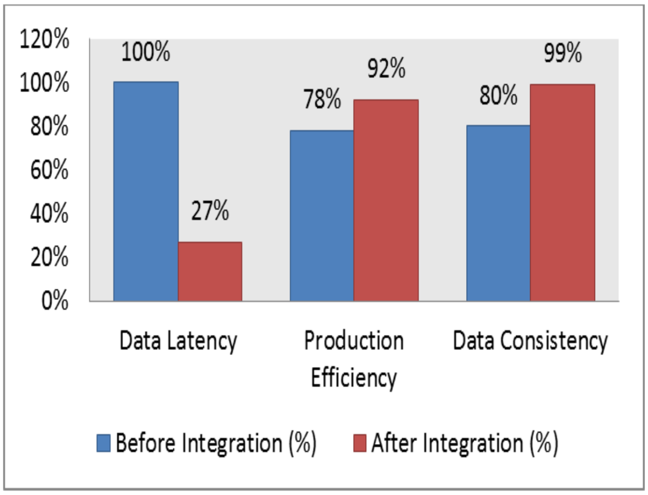

Figure 6: Graph representing Performance Metrics.

4.3. Discussion

The outcomes of the application of the BTP-centric integration mesh demonstrate the significant advances in the operational performance and the system responsiveness in the discrete manufacturing settings. Among the greatest consequences is the decrease in data latency that was 100 percent prior to integration hence 27 percent upon integration. This reduction indicates how efficient event-driven architecture, API-based connectivity and processing data at an edge can support near real-time information exchange between IoT devices, MES and ERP systems. This reduces latency will enable managers and automated systems to take more timely and informed decisions, become responsive to anomalies and reduce delays in the production processes. The second direct benefit of improved data flow is that it led to an increase in production efficiency; pre-integration, the company was at 78% but, after the integration, it rose to 92%. The integration mesh helps to maximize allocation of resources, minimize wastes and makes production schedules to be dynamic to evolve depending on the real-time machine and inventory status by ensuring a seamless synchronization between the shop-floor and enterprise planning. Real-time access to operating parameters also underpins predictive maintenance plans so that possible equipment failures can be monitored and dealt with before causing unexpected downtimes. This will preventive strategy will lower maintenance expenses, enlarge availability of the machines as well as general productiveness. Another benefit is that the event driven architecture of the integration framework provides better scalability and resiliency of the system. Adding new devices, instances of MES or modules to the ERP system do not affect the current working processes and the event-based data flow is asynchronous, which means that high-frequency information arriving in the IoT devices does not overload the system. Also, data consistency rose to 99, meaning that all levels of the system can work with the accurate and synchronized data which is a key to the quality reporting, analytics and compliance. Generally, the BTP-intensive integration mesh proves that a cloud-based, standardized and event-driven integration of industry not only disperses the efficiency and delays but also forecasts, operational robustness and expansive development of discrete production companies.

5. Conclusion

This study shows that BTP-centered integration mesh provides a powerful, versatile and extremely effective method of integrating IoT, MES and ERP in discrete manufacturing settings. The proposed framework facilitates smooth communication and real-time data flow among systems of heterogeneous nature by means of cloud-based middleware, event-driven architecture and standardized APIs, addressing the traditional challenges, i.e., latency, inconsistent data and interoperability. Application of the integration mesh has demonstrated significant data latency cut down thereby helping in increased responsiveness of production systems besides increasing production efficiency and throughput. Through its ability to give a managed picture of the operations between the shop-floor equipment and the enterprise planning systems, the architecture enables managers and automated systems to make decisions, maximize utilization of their resources and change production schedules dynamically according to conditions on the ground in real-time.

The ability to facilitate predictive maintenance and operational analytics is among the great benefits of the BTP-centric approach. Resting on the reliable and high-frequency data gathered by the IoT devices and refined with the help of the integration platform, the system will be able to identify any early signs of equipment malfunction or the process deviations, which in turn will decrease the level of unplanned downtime caused and the expenses of maintenance. Also, the consistency of data in both MES and ERP is greatly enhanced providing steady reporting, audit and adherence to regulations.

The event-based architecture also provides a high level of scalability and resilience since additional devices, production lines or even enterprise modules can be introduced to the system without affecting current operations. This elasticity plays a vital role in the contemporary production set ups that need to react rapidly to the fluctuating market needs and the dynamic technological environment.

In the future, the application of AI-based optimization algorithms to improve production planning, predictive maintenance and resource allocation will become a part of work. Addition of new machine learning models can give more efficient predictions, recommendations on optimization of processes and ability to make decisions automatically, which will increase efficiency and competitiveness. Cybersecurity is also one of the major areas of improvement, such as the provision of IT threat detection systems, secure data processing and high-level access control technology to secure sensitive information of industries and businesses. Additionally, the study will investigate more intimate connections with new paradigms of edge computing to perform the important data nearer to the production devices and decrease latency and enhance the system robustness. By covering all these aspects, the BTP-oriented integration mesh will be able to develop into a smarter, safer and more dynamic digital manufacturing ecosystem that can accommodate the goals of Industry 4.0. Finally, this paper confirms the practicality and utility of a cloud-based, integrated solution to linking IoT to MES to ERP systems and that it brings quantifiable reduction in the latency, efficiency and operational transparency and offers a way in which the future of intelligent manufacturing is likely to evolve.

6. References

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