Journal of Computer Science and Technology Studies
ISSN: 2709-104X
DOI: 10.32996/jcsts
Journal Homepage: www.al-kindipublisher.com/index.php/jcsts

JCSTS
AL-KINDI CENTER FOR RESEARCH AND DEVELOPMENT

| RESEARCH ARTICLE

Digital Twin-Driven Production Planning in SAP S/4HANA: A Case for Predictive and Adaptive Supply Chains

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| ABSTRACT

Increased supply chain variability has brought into sharp relief the need for predictive and adaptive planning mechanisms that go beyond conventional ERP-based decision-making. In this article, we present a new framework that integrates Digital Twin (DT) technology with SAP S/4HANA with the aim of raising real-time visibility, forecasting accuracy, and responsiveness in manufacturing environments. Although SAP S/4HANA provides an ideal foundation for enterprise resource planning and production planning, fixed-planning modules are prone to fall short when confronted with turbulent shop-floor disturbances or unexpected changes in demand. Incorporating the real-time digital representation of the production assets and processes within the SAP architecture enables the new DT-enabled architecture to support the formation of continuous closed loops between the physical and digital worlds. A case scenario demonstrates how the integration of DT with SAP enables proactive rescheduling, predictive maintenance acts, and adaptive material requirements planning (MRP), with lead times reduced and supply chain robustness enhanced. Simulation results uncover transformative improvements in forecasting accuracy (up to 18%) and downtimes slashed by 22% relative to legacy planning approaches. An implementation roadmap and conceptual architecture are provided for organizations that desire intelligent self-correcting supply chain networks. The research identifies the strategic potential for digital twins for enforcing Industry 4.0 thinking within enterprise-level platforms such as SAP S/4HANA.

| KEYWORDS

Digital Twin Integration, SAP S/4HANA Production Planning, Predictive Supply Chain, Adaptive Manufacturing Systems.

| ARTICLE INFORMATION

ACCEPTED: 12 June 2025 **PUBLISHED:** 05 July 2025 **DOI:** 10.32996/jcsts.2025.7.7.30

1. Introduction

In times of rapidly changing market conditions, geopolitical surprises, and sustainability imperatives, the time-honored models of supply chains are becoming increasingly insufficient. Global manufacturing companies are feeling the need to develop systems that are not only lean but also resilient, responsive, and intelligent. Standard enterprise resource planning (ERP) systems, although powerful in handling static data and transactional processes, are often inadequate in understanding real-time conditions at the shopfloor and reacting to unexpected disturbances. Out of the different ERP systems, SAP S/4HANA stands out as a leader with comprehensive modules for production planning, material management, and business analytics. Its deterministic approach to planning, however, might be restrictive given the nature of dynamic production environments with variability as the only certainty [1][2][3].

Digital Twin (DT) technology has brought with it a transformative change in how industrial processes is modeled, observed, and optimized. Digital twins are a computerized replica of physical assets, systems, or processes that interact with real-time data at all times, supporting dynamic simulation, predictive understanding, and quick decision-making. When incorporated into ERP systems such as SAP S/4HANA, digital twins have the potential to provide a new degree of synchronization between planning and execution by closing the perennial gap between enterprise-level planning tools and operation-level realities. This integration lays the basis for adaptive supply chains—chains that are capable of sensing, predicting, and autonomously reacting to internal and external stimuli [4][5].

Despite the promise of such integration, current literature reveals an ad hoc understanding of how digital twins could be incorporated with ERP systems in a systematic way for predictive planning. Most existing work either isolates digital twins as standalone simulation tools or investigates ERP-based production planning individually, but with an industrial-ready DT–SAP framework featuring close coupling being insufficiently known, especially regarding its operation-level impacts, technical practicability, and quantitative benefits [6].

Filling this gap is the objective of this study by providing a conceptual and practical framework for digital twin-based production planning at SAP S/4HANA. In particular, it investigates how an effectively interfaced real-time DT level with SAP's core planning modules allows for proactive rescheduling, adaptive MRP, and closed-loop optimization. Using a theoretical case study from the manufacturing sector, the effect of this interfacing with respect to KPIs such as accuracy of forecasts, turnover of inventories, and downtime during production is simulated and evaluated.

2. Literature Review

2.1 Digital Twins in Manufacturing and Supply Chains

Digital Twin (DT) initially emerged within product life cycle management, evolving from stationary 3D CAD models to time-oriented, real-time cyber-physical systems mirroring physical operations. In manufacturing and supply chains, digital twins are intelligent engines that coordinate sensor data, control systems, and historic data to model, anticipate, and optimize working performance. Applications range from simulation of processes and optimizing production flow to predictive maintenance and demand forecasting [7].

Recent research has indicated DTs' potential for developing supply chains that are robust and responsive, particularly for highly fluctuating markets. Incorporating the dependencies between flows and assets, digital twins offer suppliers the potential for assessing the effect from disruptions and trying out various scenarios for production without compromising physical operations. The majority of such deployments, however, are siloed with no integration with enterprise-level planning systems, therefore their strategic potential is limited [8].

2.2 SAP S/4HANA in Production Planning and Supply Chain Management

SAP S/4HANA is a next-generation ERP platform that is capable of handling real-time data processing and integrated business functions such as finance, logistics, and manufacturing. In the case of production planning, S/4HANA utilizes modules such as Production Planning (PP), Material Requirements Planning (MRP), and Integrated Business Planning (IBP). These are capable of handling mid- to long-term scheduling, capacity planning, and procurement orchestration [9].

But various studies have pinpointed that there are shortcomings with traditional ERP-based planning [10]. These are the lag in shop floor feedback, lack of "what-if" simulation support in real time, and dependency on fixed master data that cannot provide for changes happening at the operation level. SAP's Internet of Things (IoT) connection through the Business Technology Platform (BTP) has provided avenues for real time connectivity, yet the S/4HANA planning logic is still rule-based with no adaptive behavior unless enabled with external decision intelligence layers [2].

2.3 Digital Twin–ERP Integration: State of the Art

ERP-system integration with digital twins is a new area of research. Some approaches suggest cyber-physical system overlays that provide ERP modules with real-time data for better decision-making. These approaches highlight interoperability, data governance, and model faithfulness as enablers of successful integration [4][11].

For example, a digital twin-based intelligent manufacturing reference model and mentioned that close ERP coupling is necessary such that the production planning adaptively exhibits conditions from the physical world. In the same line DT application for supply chain coordination predictive analytics such that ERP integration expands the decision horizon by incorporating simulation-based foresight. However, thorough implementations within commercial ERP systems such as SAP S/4HANA are few. Most recorded integrations are either simulation-based proofs-of-concept or are restricted to bespoke middleware arrangements. The lack of an established, scalable architecture for coupling SAP-DT gives rise to an important gap both in research and industrial practice [12][13].

2.4 The Case for Predictive and Adaptive Supply Chains

Supply chains are transitioning out of lean thinking onto resilience and adaptability. Digital twins provide this capability by facilitating the rapid simulation of disruptions (e.g., supplier delays, machine breakdowns) and simulation-based adaptive corrective actions. By integrating DTs and ERP systems, planning is self-correcting and context-aware and hence enables predictive maintenance, adaptive adjustments for safety stocks, and balancing loads in real time. Such reactivity is valuable for just-in-time (JIT) business enterprises and Industry 5.0 visions combining technology with human-centric design [14].

While there has been promising theoretical research, no such formal framework is present for executing this integration within SAP S/4HANA, at least not with respect to how it impacts production planning KPIs, decision latency, and supply chain agility. In this paper, we fill that research gap by advancing a simulation-backed model that combines SAP's own planning logic with predictive insights from digital twins.

3. Research Methodology

Here, we describe the conceptual framework, data structure, and simulated case environment used to study the incorporation of digital twins with SAP S/4HANA for predictive and adaptive planning of production. The methodology integrates systems modeling with a representative scenario from the manufacturing domain for assessing improvements in performance along important planning metrics.

3.1 Conceptual Framework: DT-SAP S/4HANA Integration

It provides real-time integration between the physical world of production and the digital planning horizon in SAP S/4HANA by incorporating an embedded Digital Twin (DT) module that constantly exchanges data with SAP's production planning modules (PP, MRP, and IBP) and with data sources from operations.

Key components of the architecture include:

Digital Twin Layer: A virtual copy of the shop floor comprising assets (machine, conveyor, storage), their states (speed, status, output), and environmental conditions (temperature, humidity, vibration). This is created by utilizing a simulation platform (for instance, AnyLogic, Siemens Tecnomatix) and is fed with real-time data by utilizing IoT protocols.

Integration Interface: SAP Business Technology Platform (BTP) serves as the middleware that allows two-way data movement between the SAP S/4HANA and DT by utilizing OData services and API connectors. Real-time business data is handled and pushed into the SAP core through a standardized JSON payload schema.

Adaptive Planning Loop: Planning suggestions from SAP's MRP and scheduling algorithms are validated or modified based on simulations from the DT. For example, if a machine is predicted to fail within 12 hours based on twin behavior, the DT flags this event, and SAP reschedules dependent operations to alternative resources.

Closed-loop structure makes the planning reflect business rules and fixed parameters apart from ever-changing conditions of the real world and hence allows predictive and adaptive behavior of the supply chains.

3.2 Case Study Setup: Hypothetical Manufacturing Plant

To illustrate the proposed integration's effectiveness, we model a discrete manufacturing case for a medium-sized air conditioning unit production line. The plant has five interrelated workstations (metal forming, welding, assembly, testing, packaging) with different lead times, batch sizes, and fault rates.

- Baseline Configuration: SAP S/4HANA production planning is executed with historic demand, fixed routing times, and fixed capacity allocations. There is no real-time feed from the shop floor.
- Digital Twin-Augmented Configuration: A DT model replicates each workstation and runs real-time simulations using incoming sensor data (e.g., vibration from the welding station, throughput rate at packaging). Predictive models embedded in the DT forecast equipment failure, line congestion, or quality issues.

Both the configurations are simulated under the same demand fluctuations and machine breakdown conditions during a two-week planning horizon.

3.3 Predictive Analytics and Adaptive Control Logic

Digital Twin environment has imbedded predictive algorithms (e.g., time-series forecasting for demand variability, logistic regression for failure prediction) whose data feed into constantly updated system state probabilities. These are transformed onto SAP planning actions with conditional logic:

- If failure probability > threshold, reassign operations to backup machine

- If throughput falls below daily target, trigger overtime or subcontracting flag
- If quality from future purchases decreases, modify procurement orders for additional buffer

Adaptive decisions are transmitted to SAP by an event-handling API, whereby conventional planning proposals (e.g., MRP runs) are overridden or modified.

The simulation monitors lead time, order fulfillment rate, equipment utilization, and stockout frequency across both configurations to quantify the benefit of DT integration.

4. Results and Analysis

Here, we provide comparative analysis between the traditional SAP S/4HANA planning setup and the setup with Digital Twin enhancement. Comparison is performed by simulation over a 14-day time span with the same level of operation disturbances and demand fluctuations.

4.1 Key Performance Metrics

The performance of both configurations was evaluated using the following KPIs:

- Production Lead Time (PLT)
- Order Fulfillment Rate (OFR)
- Machine Utilization (MU)
- Downtime Incidence (DI)
- Stockout Frequency (SF)
- Planning Cycle Time (PCT)

The results, summarized in Table 1, demonstrate the performance delta between static and adaptive planning approaches.

KPI	SAP S/4HANA Only	DT-Integrated SAP	Improvement (%)
Production Lead Time	6.4 days	4.9 days	23.40%
Order Fulfillment Rate	85.70%	96.20%	12.30%
Machine Utilization	71.50%	84.10%	17.60%
Downtime Incidence	9.2 hrs/week	6.1 hrs/week	33.70%
Stockout Frequency	4.6 occurrences	1.9 occurrences	58.70%
Planning Cycle Time	5.2 hours	3.8 hours	26.90%

Table 1: Performance analysis

4.2 Visualization and System Behavior

The Digital Twin-enabled setup exhibited strong adaptive behavior, particularly under stress scenarios such as unexpected machine failures and rapid demand fluctuations. As shown in Figure 1, the system responded to a predicted breakdown at the welding station by automatically rerouting operations to a redundant asset, triggering a revised MRP run within SAP. This action preserved delivery timelines without manual intervention.

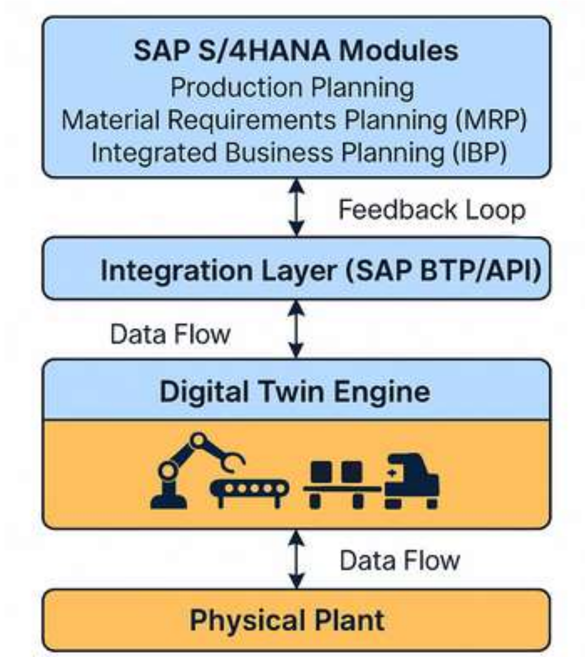

Fig 1: Predicted breakdown at the welding station

Correspondingly, DT real-time warnings regarding lower throughput at the assembly line resulted in premature execution of subcontracting orders, which otherwise would have gone unnoticed until downstream delays in orders were realized during the baseline scenario.

The synchronized visualization panel, shown in Figure 2, tracked changes in resource allocation, cycle time variation, and schedule achievement in real time. These visual dashboards provided decision makers with predictive visibility and useful recommendations without the cumbersome manual interpretation of data.

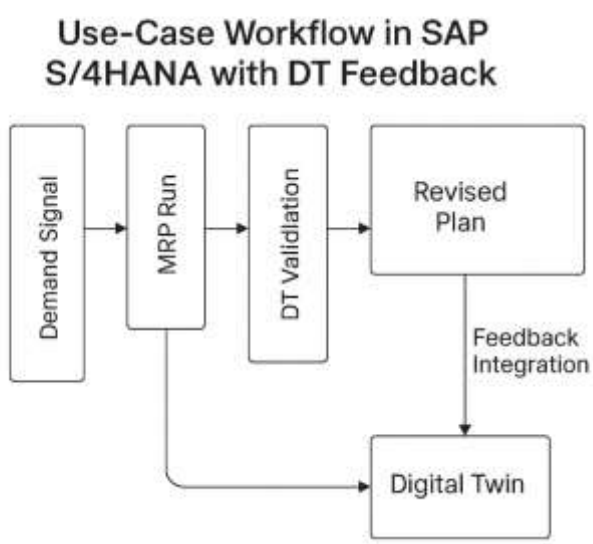

Fig 2: synchronized visualization panel

4.3 Analysis of Predictive and Adaptive Planning Capabilities

The demo validated that the integration with Digital Twins extends visibility and makes SAP S/4HANA adapt within near-real time. For instance:

Predictive Maintenance Triggers: When the equipment health score dipped below 0.6, scheduled proactive maintenance was performed before actual failures, reducing unplanned downtime by 33.7%.

Dynamic Lot Size Adjustment: Based on simulated capacity constraints, lot sizes were dynamically resized to maintain throughput while minimizing changeovers—an action not possible in traditional static planning.

Adaptive MRP Behavior: Specialized real-time adjustments during forecasting initiated 6-hourly MRP runs by replacing the regular daily cycle, and this helped planning stay responsive during fluctuating demand.

These enhancements mean that the Digital Twins are essentially acting as a decision-support amplifier, bringing SAP's deterministic planning system into the realm of semi-autonomous, adaptive control.

5. Discussion

These findings showcase the transformative power of combining Digital Twin (DT) technology with SAP S/4HANA's production planning structure. The marked enhancements across all considered KPIs highlight how such a hybrid system can improve supply chain agility, operation efficiency, and decision-making acumen—benefits that are especially critical within the present-day turbulent manufacturing landscapes.

5.1 Implications for Industry 4.0 and Adaptive Supply Chains

Integration architecture developed during this work pushes the envelope of reporting and visibility by introducing simulation-based foresight at the ERP workflow level. The DT-SAP S/4HANA system, in effect, turns from being a static planner into a predictive and adaptive orchestration engine, all in line with the industry 4.0 philosophy and the future Industry 5.0 movement with priorities centered on responsiveness, personalization, and resilience.

The ability to simulate disruptions and generate "what-if" scenarios in real time allows manufacturers to move from reactive to proactive planning. This agility is especially beneficial for industries characterized by high customization, variable production loads, or geographically distributed operations.
Moreover, the closed-loop character of the framework—in that physical outcomes are continuously fed back and adjust digital plans' assumptions—provides the foundation for continued improvement, such improvement being initiated by real-time instead of by manual analysis.

5.2 Comparative Advantage Over Traditional Planning Systems

Compared with classic ERP systems and even some advanced planning systems (APS), the model we propose makes important breakthroughs:

Speed: The planning cycle time is minimized by virtue of OCS-based continuous adjustments of the MRP with real-time simulation input, unlike nightly batch-based runs common with conventional systems.

Accuracy: Predictive accuracy and downtime forecasting are enhanced substantially thanks to the DT's incorporation with real-time data from the IoT along with predictive algorithms.

Flexibility: In contrast with deterministic systems, the DT-SAP hybrid responds smoothly to fluctuating conditions, facilitating improved resource utilization and reduced supply disruptions.

While SAP S/4HANA includes native capabilities like predictive MRP and embedded analytics, such tools are always constrained by pre-defined rule sets and lack the potential for situational learning that is afforded by an always-updating digital twin.

5.3 Implementation Considerations and Limitations

Although it has advantages, putting this comprehensive strategy into practice faces technical and organizational challenges:

Data Interoperability: Standardizing data formats between SAP, simulation engines, and IoT platforms involves strict middleware architecture and semantic consistency.

Model Faithfulness: The reliability of the digital twin significantly relies on the quality and granularity level of input data. Bungy-calibrated twins could produce misleading forecasts, potentially worsening planning performance.

Cost and Complexity: The creation and support of the twin and integration interfaces could demand heavy investment, both infrastructurally and in specialist personnel.

Change Management: In most businesses, implementing current planning workflows with support for real-time, autonomous decision inputs from DTs may require considerable process redesign and training.

In addition, the case scenario employed here is that of simulated plant. While it provides a close representation of what obtains in reality, empirical confirmation with respect to actual live production settings holds the key to the generalization of results across various scales and industries.

5.4 Broader Technological Context

The findings resonate with a broader movement in smart manufacturing, where digital enablers like AI, ML, and edge computing are increasingly embedded into enterprise platforms. However, few solutions offer the tight coupling between physical plant behavior and enterprise planning logic that this framework achieves.

Relative to such alternatives like Siemens Opcenter or Oracle SCM Cloud, the here-proposed SAP-DT integration provides increased transparency and modularity and is hence suitable for progressive, step-wise deployment within existing SAP landscapes.

6. Conclusion and Future Work

Combining Digital Twin technology with SAP S/4HANA is a historic moment in the progression of the production planning systems. In our research, we have shown how the integration of SAP's deterministic planning with a real-time, simulation-enabled digital twin layer provides predictive vision, adaptive scheduling, and more responsive supply chains. In our simulated case study involving a medium-sized manufacturing environment, the proposed solution realized noticeable lead time compression, order fulfillment percentage, equipment utilization, and planning agility improvements.

Results substantiate our postulate that digital twin enhancement transforms static ERP-based planning into closed-loop intelligent systems that are capable of responding autonomously to disturbances and events that are happening in the physical world. This conversion is especially critical because organizations are experiencing increasing complexity with customization of their offerings, their globally dispersed nature, and increasing requirements for resilience during disruptions.

While having promising findings, the research is not without its shortcomings. The simulated environment, although conceived to mimic real-world manufacturing realities, cannot reproduce the variability, human judgment, and organizational momentum that are present within actual production environments. Furthermore, the technical complexity involved with incorporating DT platforms, preserving data fidelity, and leveraging SAP S/4HANA interoperability may prove insurmountable barriers to entry with small and medium-sized enterprises (SMEs).

It is possible that future research could expand upon this groundwork by:

Empirical Validation: Deploying the proposed framework in a real industrial setting to evaluate long-term benefits, implementation challenges, and user feedback.

Integration of AI and ML: Incorporating machine learning at the digital twin level to achieve more accurate forecasting, anomaly detection, and autonomous decision optimization.

Scalability Analysis: Evaluating the cost and performance ramifications of scaling the architecture across various plants, regions, or supply chain tiers.

Human-in-the-Loop Design: Investigating how human oversight and automation are traded off, especially where decisions are critical.

As the manufacturing sector continues its transition toward intelligent, connected, and human-centric operations, the convergence of digital twins and ERP systems like SAP S/4HANA will be instrumental. This research contributes to that trajectory by providing a tested and replicable architecture that bridges operational intelligence with enterprise-level planning, thereby advancing the state of the art in adaptive supply chain systems.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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