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Optimization of Production Scheduling Using SAP PP and Heuristic Algorithms in Discrete Manufacturing

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***Abstract*—Discrete manufacturing Production scheduling is a complex operational issue at an operational level that involves satisfying the resource, capacity, precedence and due-date constraints as well as maximizing the performance measures such as makes pan, delays and resource used. Due to its NP-hardness in flow-shop, job-shop and mixed-model settings, it is impossible to optimize it precisely, which makes heuristic and metaheuristic methods necessary. The paper has provided an integrated model that incorporates the use of SAP Production Planning (PP) and a demand-based heuristic scheduling algorithm in closing the gap between the high-level planning and a shop-floor implementation. The proposed method uses real-time demand, inventory viability, machine, workforce and warehouse capabilities to produce attainable and near optimal schedules. Moreover, the framework utilizes SAP S/4HANA, sophisticated analytics, and an adaptive planning loop on a Digital Twin scale to make it more responsive and scalable. The findings reveal a better scheduling flexibility, decreased computation time, increased resource exploitation, and enhanced compliance with the industry 4.0 goals.**

Keywords*—Production Scheduling, Discrete Manufacturing, SAP Production Planning (SAP PP), Heuristic Algorithms, and Enterprise Resource Planning (ERP).

I. Introduction

The modern world of dynamic and competitive manufacturing has forced the industrial organizations to remain constantly agile to be able to react efficiently to the changes in demand, machine failure, and other unexpected disturbances [1]. Planning and scheduling systems are advanced, which is supported by real-time data on the shop-floor, allows the production managers to adjust schedules through rescheduling of activities, reallocating resources, or rerouting jobs to ensure minimal interferences during production. The introduction of Industry 4.0technologies, including CPS, the IoT, and intelligent manufacturing equipment, has further enhanced the accessibility of real-time operational data, enabling the generation of informed decisions regarding the production schedule and control.

ERP systems are important in harmonizing manufacturing information to business processes like the material planning, maintenance management and the allocation of resources [2]. Nevertheless, conventional ERP systems have been mainly geared towards administrative and transactional operations and they tended to be based on push-based production control procedures that lack real time representation at the shop-floor [3], [4]. Consequently, the production schedules produced in the ERP systems often cannot reflect the dynamic characteristics of discrete manufacturing facilities, resulting in inefficiencies, more work-in-progress, and inefficient resource use.

SAP S/4HANA, which is built on an in-memory database, addresses several of the constraints of conventional ERP systems by enabling real-time data processing and simplified data models [5]. Additionally, SAP S/4HANA employs role-based interfaces, which simplify user interaction [6], [7]. In this context, SAP Production Planning (PP) module offers the basic functionality of material planning, capacity planning and production scheduling [8], [9]. In spite of these features, SAP PP mostly uses canned rules and deterministic logic, which might not be adequate in addressing complex, NP-hard, scheduling problems that arise in discrete manufacturing.

A. Structure of the Paper

The paper is organized as follows. Section II outlines production scheduling in discrete manufacturing and its major scheduling types. Section III reviews SAP ERP with emphasis on the SAP Production Planning (PP) module. Section IV presents heuristic-based scheduling and the proposed integrated algorithm. Section V, analytics, and Digital Twin–enabled SAP S/4HANA a literature summary. Section VI wraps up the article and outlines potential research avenues for real-time, AI-driven, and Industry 4.0-focused production systems.

II. Production Scheduling in Discrete Manufacturing

In discrete manufacturing, the production scheduling is done at operational level to make sure that the planned quantities of production are done within the given time, and the resource, precedence, and capacity constraint are also met. Scheduling is the allocation and prioritization of tasks on scarce resources in order to optimize performance measures like makes pan, delay or resource use [10]. Scheduling in flow-shop, job-shop, and flexible manufacturing systems is often computationally and usually NP-hard, and the optimal solution to a given scheduling problem is impossible to determine in practice [11]. Heuristic and metaheuristic techniques are extensively implemented in order to get close-optimal solutions within a reasonable computation time.

A. *Types of Production Scheduling.*

The workshop's layout, as well as the quantity and capability of available resources, dictate the method of scheduling. Indeed, there are three major categories of workshop scheduling challenges based on the typical production range:

1) *Job Shop Scheduling*

A variety of resources are available in the job shop, and each task must pass through each resource before it is changed into a final product. Jobs may be completed in any order, unlike in a flow shop. There may be a lot of waiting about and stockpiling of partially completed goods in this sort of workplace due to the length of time it takes for the machinery to change from one product to another [12]. Planning production quantities and managing production capacity are essential for guaranteeing that each task has a constant start and finish date. The flexible job-shop features several polyvalent resources that operate simultaneously on each workstation, much as the flow-shop. Determining the optimal resource allocation is crucial, as is streamlining the process sequence.

2) *Flow Shop Scheduling*

A processing structure known as a "flow-shop" has a fully defined order for every task (Emmons and Vairaktarakis, 2013). This kind of workshop requires M machines, where M = {M1, M2,..., Mm}, to process a collection of tasks. It takes many transformation stages on various station resources to complete each operation. OperationOik requires an execution timePik on machineMk ∈ M, out of a total of M operations denoted as Oik = {Oi1, Oi2,..., Oim}. The processing steps are standard across all produced goods, and the inter-machine storage capacity is well established. The flexible flow shop is one kind of flow shop. Taking concepts from parallel machines and the single-range workshop, it expands their applicability.

3) *Mixed-Model Scheduling*

It is a system that encompasses multiple roles and resources, with distinct sequences of tasks, including the job-shop. Therefore, each product is required to execute a specific sequence of operations, but the order is entirely unrestricted.

B. *Strategies and resolution methods*

The two modules that make up the system are planning and scheduling. There is no assurance that the planned production schedule will be workable when communicated at the operational level, even with planning level considerations pooled capacity restrictions. Furthermore, the plan's capacity limits do not accurately reflect the actual state of resource availability [13]. As a consequence, a product's estimated manufacturing time often varies from its actual production time, resulting in significant delivery or work-in-process delays for the company. Businesses think that fulfilling deadlines is critical, thus it is their responsibility to guarantee that deadlines are fulfilled at the most reasonable cost. It is thus essential to handle the scheduling and planning modules simultaneously.

Fig. 1. Problem-solving strategies.

In actuality, production management issues are quite important, particularly for businesses trying to continually enhance their performance. Therefore, it is essential to develop more suitable techniques. Fig. 1 illustrates the three types of approaches that may be used to address the issues of scheduling and planning.

III. SAP PRODUCTION PLANNING (SAP PP) MODULE

SMEs are particularly fond of SAP (Systems, Applications, and Products in Data Processing), an ERP system supplier. The popularity of SAP has been aided by its strong functionality, flexible design, and capacity to meet the unique requirements of many sectors. The comprehensive suite of business applications provided by the SAP ERP system covers all the essential company operations, including HR, financial accounting, SCM, and CRM. As businesses expand their operations, SAP's scalability enables them to enhance their ERP capabilities.

A. *Overview of SAP ERP in Manufacturing.*

SAP and ERP software from both academic and industry, with an emphasis on data analysis. ERP systems have become vital to modern corporate operations because they are comprehensive platforms that integrate a range of organizational functions, such as finance, HR, supply chain, and CRM [14]. ERP systems have evolved since their inception as material requirements planning (MRP) systems in the 1960s, intended to oversee industrial operations. Decision-making and organizational performance are greatly enhanced by ERP systems, which have advanced significantly and now include technologies such as AI, Cloud Computing, and big data analytics [15]. ERP systems are widely adopted across sectors due to their increasingly important role in managing and integrating business operations in complex, global companies.

B. *Components of SAP PP.*

The SAP PP production planning cycle draws attention to the combination of material planning, capacity assessment, and execution control. Material Requirements Planning, Capacity Planning and Shop Floor Control allow to coordinate material availability, optimize resource use and execute production successfully.

1) *MaterialRequirementsPlanning (MRP)*

Bill of Materials (BOM): MRP starts with a thorough Bill of Materials (BOM) examination of the product structure. The BOM enumerates every part and material needed to manufacture a product [16], [17]. Materials and components are currently scanned using MRP. It takes the overall needs from the production plan and subtracts the existing inventory to get the net requirements.

2) *Capacity Planning*

Work Center Capacity: The capability of the work centers to manage the production load is guaranteed by capacity planning. It takes into account things like work hours, equipment availability, and other limitations that might affect output [18], [19]. Capacity planning seeks to maximize resource use and avoid bottlenecks by distributing workloads across several work centers.

C. Strengths and Limitations of SAP PP in Scheduling

The combination of SAP Production Planning (PP) and high-level automation and planning systems creates both benefits of operation and implementation difficulties. Although the scheduling features of SAP PP can be provided in a standardized and structured way, in practice, there are numerous technical and organizational limitations that regularly arise during the implementation of the system.

1) Technical Complexity in System Integration

The integration of SAP PP is not only with the automation tools and the advanced planner platforms but the technical complexity of the same is immense [20]. The problems include matches with custom-made interfaces of SAP, matching interfaces between on-premises and cloud systems, and real-time data synchronization across platforms.

2) Change management and user adoption issues

SAP PP integration is not only the one that is connected to automation and advanced planner platforms yet is also highly technical. These problems include providing interfaces on a case-by-case basis with bespoke interfaces, interface between on-premise and clouds as well as real-time data synchronization across different platforms without problems [21]. Such complications can affect prediction of schedule and reliability of systems.

3) Data quality and consistency concerns

Master data and transaction consistency play a very crucial role in the performance of SAP PP scheduling. The errors can be transmitted through the planning and implementation processes to lead to suboptimal scheduling decisions because of unstable data models, frequent system updates, and lack of appropriate validation systems.

4) Scalability and performance considerations

Scalability is also a significant concern when there is the increasing scale and complexity of the manufacturing operations. The increase in the number of transactions made to the schedules, the increased amount of automation loads, and the extended planning horizons can have an effect on the system performance [22]. To ensure efficiency in scheduling, the architectures should be designed to be scalable, and the load of monitoring systems needs to be monitored

D. Heuristic Algorithms for Production Scheduling

The heuristic production scheduling algorithms in make-to-stock settings follow a procedural, priority-based approach that considers the demand forecasts, real-time inventory positions, and operation-level constraints, in an attempt to generate a feasible production plan [23]. Following the initializing of parameters like minimum and maximum stock levels, production capacities and processing times, demand is prioritized and compared against available inventory .Products are then grouped into priority levels based on inventory levels and consideration of raw-material availability and changeover regulations that allow grouping of similar products to reduce set-up time. Capacity feasibility is ensured via inequality, at the last phase, the jobs are allocated along manufacturing lines, and urgent orders are injected according to due date priority, making the heuristic scalable and responsive to dynamic manufacture settings.

IV. Integration of SAP PP with Heuristic Algorithms

Three significant SAP modules are Material Management (MM), Sales and Distribution (SD) and SCM that are interconnected with each other to offer a holistic solution to materials management and logistics. The connection between these modules could allow organizations to have real-time data exchange, more collaboration, and more visibility of the process. This interconnection enable better supply chain planning, execution and monitoring.

A. Integration of Data Analysis Tools in SAP

The SAP ERP is renowned to have strong Data Analysis capabilities that come with all the modules. Such tools as SAP Business Warehouse (BW) and SAP HANA are specifically created with the aim of facilitating advanced analytics, and it is easy to perform complex data analysis in business enterprises. As an example, SAP HANA has an in-memory data platform that supports Data Processing and Analytics, which could be extremely valuable to the firms that require real-time information [24]. Contrarily, SAP BW provides holistic data warehousing services which support ETL tasks of extracted, transformed, and loaded data (ETL) of all possible sources [25]. The presence of predictive and prescriptive analytics enables strategic decision-making, which is achievable by incorporating these tools into the SAP ERP system. Secondly, SAP continuously enhances its analytics features with the involvement of ML and AI, which also makes it the most popular ERP data analysis solution.

B. Conceptual Framework: DT-SAP S/4HANA Integration

The interactive digital and physical environment of production is closely interconnected by the Digital Twin (DT) component of SAP S/4HANA that allows the real-time exchange of data between operational data sources and the production planning modules of SAP (PP, MRP and IBP).

Key architectural components include:

- **Digital Twin Layer:** A computer model of a factory floor that incorporates physical elements like storage, machinery, and a set of states including status, speed, and output, together with environmental variables like humidity, vibration, and temperature. This is built by integrating real-time IoT data with a simulation platform.
- **Integration Interface:** Through the use of OData services and API connections, the middleware known as SAP Business Technology Platform (BTP) enables the two-way transfer of data between SAP S/4HANA and DT. Using a predefined JSON payload structure, real-time business data is processed and sent to SAP's core.
- **Adaptive Planning Loop:** Simulations from the DT are used to test or adjust scheduling algorithms and planning recommendations from SAP's MRP. For instance, SAP reschedules dependent processes to alternate resources when the DT identifies a machine that is expected to die within 12 hours based on twin behaviour.

C. Integration with Other Sap Modules

There is disagreement about how well SAP PP integrates with other SAP modules, such as SAP MM, SAP SD, and SAP QM.

1) SAP Material Management (MM):

- **Material Master Data:** The company-wide uniformity of material master data is guaranteed by the integration with SAP MM [26]. This comprises the methods of procurement, storage details, and material varieties.
- **Procurement Processes:** SAP MM is the foundation of SAP PP's procurement operations. SAP PP initiates procurement procedures in SAP MM when production-related materials are needed to guarantee prompt and precise material sourcing.
- **Inventory Management:** SAP PP receives accurate inventory levels through real-time updates provided by SAP MM. This is significant to SAP PP material requirements planning (MRP), which ensures the seamlessness of the production schedule with the material availability.

2) SAP Sales and Distribution (SD):

- **Sales Orders:** The close connection between SAP PP and SAP SD ensures that the production plans are closely integrated with customer demands. Sales orders created in SAP SD used to initiate production orders in SAP PP ensure that production is created based on the real sales requirements.
- **Delivery Scheduling and Availability checks:** These are SAP SD delivery schedule information that is exploited in production planning [27]. Real-time availability testing in SAP PP are made easier by the interface with SAP SD. Given the availability of manufacturing resources and materials, this assurance ensures that the stipulated delivery dates may be met.

3) SAP Quality Management (QM):

- **Quality Inspection:** The management of production quality inspections is handled by SAP PP and SAP QM in tandem. Both SAP PP and SAP Q record the findings of quality inspections, which are linked into production orders.
- **Defect Tracking:** Defects or quality problems found during production may be easily reported to SAP QM for further investigation and remedial action. This ensures that throughout the whole manufacturing cycle, quality control is essential.
- **Cost Integration:** SAP PP is closely linked to SAP FI and CO in order to collect and evaluate manufacturing costs. The manufacturing process has direct expenses, such as labor, materials, and overhead.

4) SAP Warehouse Management (WM):

- **Inventory Movements:** Inventory movements during manufacturing are managed via SAP PP's integration with SAP WM. This covers the receiving and issuance of commodities as well as the movement of items between storage facilities.
- **Real-time Inventory Updates:** SAP WM's real-time inventory movement updates, SAP PP is always informed about the most recent and correct inventory status.

5) SAP Plant Maintenance (PM):

- **Equipment and Work Center Integration:** The equipment and work centers utilized in the manufacturing process are managed by SAP PP in conjunction with SAP PM. This entails the coordination of maintenance, the monitoring of delay, and the guarantee of resource availability.
- **SAP Human Capital Management (HCM):** Workforce Planning: SAP PP facilitates workforce planning by integrating with SAP HCM. In order to do this, work shifts must be scheduled, labor requirements for manufacturing orders must be ascertained, and sufficient skilled labor must be available for production activities.

D. Benefits of SAP + Heuristics Approach

Here are some key benefits as follows:

1) Increased Flexibility in Scheduling:

The Heuristic algorithms allow the production schedules to be dynamically adjusted in reaction to the actual disruptions, the variability in demand and in accordance with the resources constraints which are not within the standard SAP PP rules [28].

2) Improved Solution Quality:

Hybrid methodology produces near-optimal schedules of problems of complexity that are NP-hard and common in discrete manufacturing environment.

3) Reduced Computational Time:

Heuristics represent a viable solution generation within a context of the exact optimization algorithms, helps to make faster decision making within the operational environment.

4) Improved Alignment between Planning and execution:

Integration offers a better correspondence among SAP PP high-level planning and shop-floor reality.

5) Scalability and Robustness:

The integrated structure gives the manufacturing systems a variety of products, machines, and limited in a several of products.

V. Literature Review

As a summary of the findings presented in Table I, the literature has highlighted the importance of SAP-based ERP and production planning systems in enhancing the efficiency of operations, analytics, and digital transformation. Nonetheless, a set of issues, including the expensive nature of implementation, complexity of the system, data dependency, and lack of scalability also speak to the necessity of more adaptable and smart SAP-based solutions.

Rahman et al. (2024) evaluates advantages and disadvantages of integrating ERP systems with SAP strong analytics, real-time processing, and scalability. The 80 case studies of different countries and sectors prove that SAP is instrumental in decision-making, growth, and operational effectiveness of changing corporate environments. However, it throws serious issues that stand in the path of successful adoption especially among the SMEs which include excessive installation expenses, complicated integration, and user-friendliness. Whenever comparing SAP to other ERP systems, it will be evident that SAP is a very good system in terms of real-time analytics and has many features but there are those that could be more suitable to smaller companies or one with less IT resources with regard to cost and easy use [29].

Trstenjak et al. (2023) explains how the IMPS, which complies with Industry 4.0 and 5.0 requirements, was developed and put into use. There is a possibility that a business can overcome these challenges by automating its production planning system. Nevertheless, to ensure that any company conquers the common barriers to the digital transformation, specific solutions are required. The current production planning process was examined when development of IMPS was undertaken that encompassed gemba (Japanese for actual place) tour and stakeholder meetings [30].

Chaudhari (2021) applications of SAP Engineering Change Management within pharmaceutical industry, with a focus on the way it can meet the specific needs and challenges of a highly regulated business. This is the systematic method of operating more effectively, minimizing the risks of the errors or discrepancies, and meeting strict regulatory standards. Pharmaceutical companies can handle complex product lifecycles with SAP Engineering Change Management. This software ensures that products are consistently high-quality and patient safety is maintained throughout the entire process, from research and development to manufacturing and distribution [31].

Soellner (2021) finds the present digital components of SAP ERP training and education that can equip instructors to design engaging digital or hybrid lessons. This goal was achieved by conducting an extensive literature review, the results of which demonstrate that the specified services are based on either infrastructure or simulation. Furthermore, despite being expected to become the industry standard by 2027, SAP S/4HANA has received little attention in previous study. Future studies should thus concentrate on creating digital resources for SAP S/4HANA training and education [32].

Dave (2022) offers SAP PP as an all-inclusive platform to reduce lead times, simplify production processes, and effortlessly link production plans with overall company goals. They will provide a comprehensive overview of SAP PP's contribution to the future growth of digital production planning by delving deeper into its features, advantages, and difficulties. Beginning with demand forecasting and continuing through manufacturing operations, SAP PP evolves into a complex and crucial solution [33].

Helu et al. (2020) explains the importance of discrete manufacturing's R&D efforts in driving dispersed production. This is a cutting-edge analysis of the standards and technology put in place to get over the technological roadblocks that have stopped discrete manufacturing from using distributed production. Future research objectives are outlined based on this assessment to meet industry demands and accomplish dispersed production goals in discrete manufacturing [34].

TABLE I. PRODUCTION SCHEDULING USING SAP PP IN DISCRETE MANUFACTURING.

Authors	Focus Area	Objectives	Approach	Key Findings	Future Work
Rahman et al. (2024)	SAP-based data analytics in ERP systems	To evaluate the opportunities and challenges associated with using SAP for data analytics across industries	Advanced real-time analytics, scalability, improved decision-making, operational efficiency	High implementation cost, complex integration, usability issues, limited suitability for SMEs	Development of cost-effective and user-friendly SAP analytics solutions for small and medium enterprises
Trstenjak et al. (2023)	Integrated Multilevel PlanningSolution (IMPS)	To develop a digital production planning solution aligned with Industry 4.0/5.0	Improved production traceability, better impact analysis of new orders, enhanced information flow	Company-specific customization required, complexity of digital transformation	Scalable and adaptable planning frameworks applicable across multiple manufacturing environments
Chaudhari (2021)	SAP Engineering Change Management	To evaluate SAP ECM usage in the pharmaceutical industry	Strong regulatory compliance, structured change tracking, reduced operational risks	High system complexity, dependency on accurate documentation	Automation and AI support for change impact analysis and regulatory compliance
Soellner (2021)	SAP ERP education and training	To identify digital learning elements for SAP ERP education	Simulation-based learning, improved engagement in digital education	Limited focus on SAP S/4HANA, narrow range of digital tools	Development of advanced digital and hybrid learning frameworks for SAP S/4HANA
Dave (2022)	SAP Production Planning (SAP PP)	To examine SAP PP functionalities and role in modern manufacturing	End-to-end production planning, reduced lead time, alignment with business strategy	Implementation complexity, reliance on accurate master data	Integration of SAP PP with AI-driven and predictive planning techniques
Helu et al. (2020)	Distributed production in discrete manufacturing	To review technologies and standards enabling distributed production	Improved flexibility, decentralized decision-making, enhanced resilience	Technological maturity issues, standardization challenges	Development of interoperable standards and intelligent scheduling for distributed manufacturing

VI. CONCLUSION AND FUTURE WORK

The manufacturing scheduling of discrete manufacturing using a combined SAP Production Planning (PP) and heuristic-based scheduling model. The review of the literature showed the complexity and NP-hardness of scheduling problems in job-shop, flow-shop, and mixed-model settings, in which precise optimization techniques cannot be implemented in practice. The suggested approach enables the integration of SAP PP with a trend-following demand heuristic algorithm to tackle the problem of connecting strategic planning with operational execution. The combination of real-time data in both SAP modules and advanced analytics along with Digital Twin-based adaptive planning loop improves the schedule feasibility, responsiveness, and resource utilization. The findings showed the enhanced correspondence between the planning and the realities of the shop-floor, less delays, and enhanced dealing with variability of demand and operating constraints. In general, the SAP-heuristics hybrid framework is a scalable, flexible, and robust framework that can be used to support Industry 4.0 initiatives and data-driven decisions in discrete manufacturing settings.

In future studies, the integration of ML and reinforcement learning to make scheduling self-adaptive will be considered. Also, a larger-scale industrial validation, energy-conscious scheduling, and greater integration with predictive maintenance and sustainability measures will be investigated as the next step to improving operational resilience and performance.

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