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

Optimizing Extended Warehouse Management for Make-to-Order Plants: Slotting, Wave Picking, and Yard Orchestration at Scale

Ramesh Babu Potla
Digital Transformations Delivery Manager, United States
Corresponding Author: Ramesh Babu Potla, **E-mail**: potlaramesh8386@gmail.com

| ABSTRACT
The make-to-order (MTO) production setting introduces high levels of operational complexity to the warehouse execution because of the high variability of products, variable demand trends, and high levels of synchronization with production and outbound logistics. The conventional management techniques in the warehouse, based on unchangeable slotting policies, fixed wave formations, and separated yard activities, cannot normally be scaleable to these circumstances. The given paper offers a combined optimization model of Extended Warehouse Management (EWM) in large-scale MTO plants, and the central issues to be considered are correlated ameliorations of slotting approach, wave picking, and yard coordination. The offered solution is a hybrid of demand-based SKU profiling, dynamically-based slotting heuristics, workload-based wave generation, and event-based yard and dock coordination, which allows real-time flexibility in warehouse and yard activities. The concept of an integrated architectural framework is presented to bring EWM and upstream production planning and downstream transportation system at par with one another so that there is consistency in the end-to-end execution. The validation of the framework is made by the industrial scale case study that proves the quantifiable reduction of order cycle time, picking productivity, dock turnaround time, and the overall warehouse throughput compared to the baseline settings. Findings suggest that co-optimisation of storage, picking and yard operations is fundamental to attain scalability, resilience and performance efficiency of MTO manufacturing settings, where advanced EWM has the potential to be deployed as a strategic enabler to responsive and high-performance execution of supply chain operations.

| KEYWORDS

Extended Warehouse Management (EWM), Make-to-Order Manufacturing, Slotting Optimization, Wave Picking, Yard Management, Warehouse Automation, ERP Systems, Make-To-Order (MTO).

| ARTICLE INFORMATION

ACCEPTED: 01 August 2024 **PUBLISHED:** 25 August 2024 **DOI:** 10.32996/jcsts.2024.6.3.15

1. Introduction
In highly customized products, short life cycle, and unstable demand, make-to-order (MTO) manufacturing is now a prevailing production paradigm in industries. [1-3] In contrast to the make-to-stock setting, MTO plants have to dynamically cope with customer-specific setups, fluctuating order quantities and rigid delivery vows. These features subject the functions of warehouse execution to heavy loads, they are expected to serve fragmented order profiles, frequent material movements as well as constant alignment with the functions of production and outbound logistics. Execution-level visibility and control are available with Extended Warehouse Management (EWM) systems, but again, in the MTO environment, the effectiveness of system-based slotting, picking, and yard operations are critical to success. Traditional techniques including fixed slotting, fixed picking waves, dynamic loosely connected yard processes are becoming inefficient to the magnitude and uncertainty of the current MTO operations.

This is because although automation and ERP integration have improved, major inefficiencies are still evident in the MTO warehouse execution. The decisions that they use to slot are typically based on historic averages or manual heuristics which cannot reflect short-term demand variability and bill-of-material (BOM) constraints. Fixed time-based waves are often used that ignore real-time disproportions in workload, avenues to labor and limitations on the sequencing of manufacturing, to pick. Simultaneously, yard and dock processes are often considered different functional layers, which leads to an unsatisfactory synchronization of inbound receipts, internal staging, and shipments. Such shortcomings are further expanded in large, multi-plant manufacturing networks where high levels of transactions and shared resources cause even greater risk of congestion and bottlenecks and execution delays and require a system of scalable and integrated optimization.

In order to overcome these difficulties, the given paper suggests a systematised optimization model of Extended Warehouse Management that is adapted to the conditions of large-scale production by MTO. The framework is a combination of demand-based SKU velocity-driven slotting, order give-ups, and dependence to production; wave picking amenityfulness to workload and real-time order urgency and resource constraints; and an occasion-based yard and dock synchronisation to orchestrate warehouse action with transportation endeavours. These elements are combined into a complex architectural model that incorporates EWM with both up-stream production infrastructure and down-stream transportation infrastructure. A case study on an industrial scale shows that the suggested solution provides objective increases in throughput, resource usage and operational resiliency in comparison to conventional WMS designs.

2. Background and Related Work

2.1 Make-to-Order Manufacturing Logistics

Make-to-order (MTO) manufacturing is a form whereby the manufacturing processes would only start after the customer has placed a confirmed order. [4-6] In high product customization and variability in configuration, this paradigm is used most often in the industrial equipment sector, automotive parts, aerospace sector and manufacturing under its high-technology, including automotive, aviation, and manufacturing. The plants of MTO are characterized by low forecast accuracy, low planning horizons, frequent changes in order priorities, which requires the high responsiveness of the logistics systems and high responsiveness toward execution. Logistically, MTO environments produce discontinuous order profiles with small quantity of batches, mix of various SKUs and high interdependence between warehouse sequencing and production sequencing. Access to materials staged has to be under strict schedule based on manufacturing schedules usually with strict lead times. Consequently, the warehouse activities as well as yard are no longer auxiliary support activities but rather parts of production continuity. The direct impact of ineffective execution of the warehouse quality is the disruption of the manufacturing process and the growth of the work in process inventory and the delay of the delivery to customers, which is associated with the urgency of involving all processes of storage and picking as well as yard operations.

2.2 Extended Warehouse Management Systems

Warehouse Management Systems (WfMS) have changed a lot as compared to the primitive inventory oriented systems that emphasized on simple receiving, put-away, and shipping capabilities. Classical implementations of WMSs were based on fixed process flows, de jure master data, and a manual decision-making process and therefore were not flexible enough to serve as a solution to the complex manufacturing context. As the size and integration intensity of enterprise systems grew, Extended Warehouse Management (EWM) systems developed that fulfilled sophisticated execution needs by becoming more closely coupled with Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES), and Transportation Management Systems (TMS). Nowadays EWM solutions offer a commanding granularity of the granules by enabling modular capabilities of advanced slotting, labor management, interleaving of tasks, as well as wave management and yard and docking control, and real-time analytics. These are systems that provide event based execution and optimization of resources, thereby making the operations of the warehouse more responsive. Nevertheless, as much as EWM platforms possess powerful functionalities, they may be useful in MTO situations depending on the success or failure with which the modules are synchronized. Practically, throughout implementations EWM modules are frequently deployed in isolation where they tend not to offer the advantages of solution to cross-functional execution issues that are characteristic of the MTO manufacturing.

2.3 Slotting and Storage Optimization Techniques

The problem of slotting optimization has been known as a significant factor of warehouse efficiency with direct impact on the distance of traveling, time spent in picking, as well as the space taken. The conventional slotting methods are mainly rule-driven based on fixed criteria like SKU velocity, storage type or ABC classification. Although these approaches are computationally easy and are used much more commonly, they presuppose constant demand dynamics and small SKU variability, which are not very common in MTO settings. Developments in recent studies have involved analytics-based and optimization-based slotting models that utilize historical demand, order associations and stochastic models. State of the art methods use the clustering algorithm, heuristics and machine learning models to dynamically allocate storage locations using varying demand profiles. Regardless of these developments, the majority of available techniques are too narrow to take into account upstream production requirements, downstream transport restrictions, and dynamism of real-time execution. As a result, the slotting decision is usually not linked to picking strategy and yard operations, which minimizes their performance in highly uncertain MTO warehouses.

2.4 Wave Picking and Order Release Strategies

Wave picking is one of the popular methods to use order fulfillment whereby several orders are lumped together and released based on pre-defined factors like time windows, shipping schedules or resource availability. When the order flows are predictable and the environment is in a constant and highly voluminous form, then the technique of picking static waves, which assumes constant release periods and fixed wave sizes, works. But in MTO environments where order priorities are non-predictable and that experience last-minute adjustments, the wave structure will happen to create imbalances in workloads and cause congestion, and slow order filling. In order to overcome these constraints, dynamic wave picking techniques are suggested that positively alter the composition of the waves in reaction to instantaneous order arrivals, labour, and equipment constraints. Such strategies enhance responsiveness and add more complexity to implementation and system setup. Additional wave forming constraints in high-mix MTO include production sequencing, kit completeness and requirement to stage materials. The current literature typically solves the problem of wave picking optimization considering it in isolation, not in cooperation with slotting strategies or the yard capacity, which leads to suboptimal end-to-end performance.

2.5 Yard Management and Dock Orchestration

Yard management involves management and control of vehicles, trailers and containers in the warehouse yard including gate processing, yard movements and dock assignments. A proper yard organization is critical in the facilitation of timely material flow in and out of the warehouse between the incoming transportation, staging in warehouses and dispatching. In a sizeable manufacturing facility, the availability of little visibility of the yardage and manual coordination leads to being significantly greater in the amount of trailer dwell and docking and ineffective utilization of handling assets. Extensive yard management systems will offer real-time tracking of yard assets, automatic assignment of dock doors as well as prioritization of inbound and outbound transactions according to rules. Nevertheless, regardless of such capabilities, yard operations are typically operated as an independent execution layer, without being tightly connected with warehouse picking and production schedules. This synchronization issue is critical especially in MTO systems, as waiting time in the receipt of material or loading of outbound shipments may propagate to cause stoppages or missed delivery deadline in the production process.

3. System Architecture and Operational Model

3.1 End-to-End EWM Architecture for MTO Plants

The designed system architecture establishes Extended Warehouse Management (EWM) as a coordinator execution-layer in an ecosystem of manufacturing and logistics that is highly integrated. Make-to-order (MTO) plants imply that warehouse operating needs are embedded in the production plans and delivery schedules, and that the data sharing and synchronization of events between various systems of the enterprise need to go on without interruption. EWM also provides real-time execution status and inventory visibility as illustrated in the architectural model and bidirectional communication with Enterprise Resource Planning (ERP) systems to receive sales orders, production orders and master data. Combination to Manufacturing Execution Systems (MES) makes it possible to perfectly coordinate the staging of materials and the production processes. Given production demand signals, component requirements, and sequencing constraints via MES, EWM coordinates the implementation of warehouse activity, like picking, kitting, and line-side staging activities, dynamically with those of the shop-floor activity. In its turn, EWM execution feedback containing material availability, picking completion, and shortages, supports adaptive production rescheduling. Simultaneously, it can be integrated with Transportation Management Systems (TMS) to enable the coordination of outbound and inbound logistics. WM provides transformation of shipment plans, carrier assignments and delivery windows information supplied by TMS to wave picking and dock planning but real-time yard and loading status updates allow proactive change in transportation. The end-to-end integration will help them make sure that decisions in warehouse execution are made within the frame of production and transportation constraints since, in this way, the coordination and scalability of operations at MTO plants will be possible.

3.2 Integrated SAP S/4HANA ERP–EWM–TM Execution Architecture

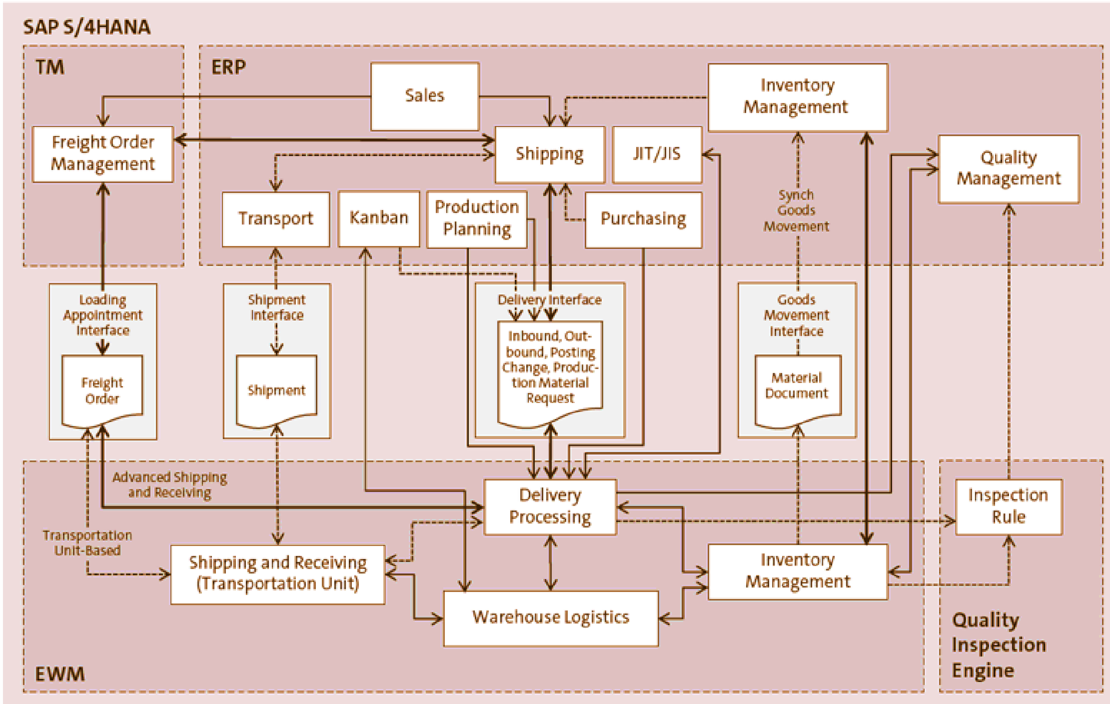


Fig.1. Integrated SAP S/4HANA ERP–EWM–TM Execution Architecture

The figure shows a detailed end-to-end integration framework of the SAP S/4HANA ecosystem that ensures a close relationship between Enterprise Resource Planning (ERP), Extended Warehouse Management (EWM), and Transportation Management (TM) functionalities. [7,8] Core business processes, which include Sales, Production Planning, Purchasing, Inventory Management, and Quality Management at ERP layer are those that make use of documents, which are relevant in execution like deliveries, production material requests and goods movements. These documents are interchanged using standardized delivery and goods movement interface, which provides synchronized inbound, outbound and inbound logistics flows. The EWM layer manages the detailed warehouse execution, such as the delivery processing, warehouse logistics and shipping and receiving, according to the transportation units, and the advanced shipping and receiving facilities make sure they are correctly handled at docks. TM components operate freight seed orders, transportation organization, and loading arrangements in coordination up and down the street with carriers. Moreover, the Quality Inspection Engine executes inspection rules and quality checks as a part of the warehouse operations and goods movement. In general, the architecture illustrates how real-time information exchange and event driven interfaces between ERP, EWM and TM provide the basis of synchronized production, warehouse, transportation and quality operations that create the basis of scalability and robust execution in a complex manufacturing and logistics environment.

3.3 Data Model and Master Data Dependencies

The success of the mentioned optimization model depends on the cogent and stable data model that rightly explains actual physical structures of warehouses, material properties, and operational facilities. Materials, storage bins, handling units, and warehouse resources are considered to be core master data elements whose essential role is in the planning and optimization of the execution. SKU attributes included in material master data include dimensions, weight, hazard classification, and handling requirements, which are directly applied in the slotting determination and eligibility of storage. Storage bin master data defines the physical arrangement of the warehouse, the type of storage, the bin capacity, restrictions on access, and achieving production or shipping. Handling units are the logistic means of grouping materials in the form of grains that allow effective movement and tracking of goods through the processes in the warehouse. Resource master data includes labor, material handling equipment and automation material and are capacity restricted on availability and skill. Proper resource modeling is a prerequisite in the MTO environments where resource utilization varies substantially interfering with the workload balancing and the planning of waves. These master data objects have dependencies on each other that comprise the basis of dynamic slotting, picking that is aware of the workload, and coordinated yard activity. Any discrepancies or stagnant patterns in this data model will severely impact the performance of the system, which is why the governance and active data alignment need to be considered the necessary actions.

3.4 Event-Driven Warehouse Execution Flow

The model of operations of the proposed architecture is based on an event-driven execution paradigm that allows being responsive to the changing demand and operational conditions in real-time. Instead of using only predefined schedules or batch operations, warehouse operations are caused more by discrete business events, like order creation, production order release, inbound arrival notifications, or resource status changes. When a customer order or a production order is received, EWM starts the dynamic slotting assessment and order prioritization according to the current stocks locations and execution restriction. Picking tasks are created and assembled into adaptive waves, which react to the workload situation, availability of resources, and downstream shipping or production information. As the execution advances the completion events and the exception signals, including shortages, delays, and unavailability of equipment, are communicated throughout the system where they can be used to re-optimize tasks and priorities in real time. Operation in yards is also promoted by the occurrence of events related to checking in of vehicles, the availability of dock, or confirmation of readiness to ship. Automated dock assignment, optimization of yard moves and synchronized loading operations are possible through these events. Through the utilization of an event-based approach, the suggested system will reduce the time lag between decisions and actions, increase operation visibility, and facilitate constant optimization in slotting, picking, and yard organization in MTO warehouse settings.

4. Slotting Optimization Framework

4.1 Slotting Objectives and Constraints

The slotting optimization is a key element in the performance of warehouse execution, which directs picking efficiency, replenishment workload, and space use in general. [9,10] Some of the competing but often conflicting performance objectives must be considered in make-to-order (MTO) settings in the design of slotting goals. The main goal is to reduce the picker travel distance by placing high frequency and high priority SKUs nearer picker and staging. Secondary goals will involve minimizing the number of replenishment using slot capacity to consumption rates, maximizing the use of space by heterogeneous types of storage, and keeping ergonomic and safety limits. These goals have a variety of operational constraints. Physical restrictions entail size of bins, weight, compatibility with storage and accessibility conditions. The constraints around the processes are in the forms of material handling techniques, the automation interfaces and the replenishment policies. Also, constraints due to production, like kitting, proximity on line side staging and bill-of-material (BOM) synchronization, also limit viable slot assignments. In MTO plants wherein demand trends change swiftly, slotting choice ought to consider both short run performance of execution and long run stability of layout and thus the stagnation optimization frameworks prove to be inadequate.

4.2 Demand and Order Profile Analysis

To optimize slotting in the MTO warehouses, demand signals and order make-up demand should be analyzed in detail instead of using aggregation of historical averages. The SKU velocity indicators are provided based on the rate of arrival of orders, pick patterns, and consumption patterns by production, which focus on both short term and steady demand. In comparison to make-to-stock environments, MTO demand is usually bursty and strongly correlated across SKUs motivated by customer-specific build-to-order. The analysis of the order profiles goes above and beyond the velocity of SKUs of an order and the order of co-occurrences in BOMs. The co-location of SKUs often ordered together on a particular variant of a product or a production kit can be strategically placed so that travel and staging is made simpler. BOM dependencies also enhance slotting process since important components with availability that directly influences production continuity are found. Combining order-level and BOM-level information in slotting framework of various products constructs a better integration of storage decisions and priorities of execution to achieve more predictive and responsive movement of materials in highly varying MTO environments.

4.3 Optimization Algorithm

The offered slotting framework can be optimized using various strategies, starting with more refined rule-oriented heuristics and analytics-based and AI-assisted solutions. [11,12] Rule-based approaches offer visibility and simplicity to achieve by use of configurable rules like velocity classes, store type preferences and proximity rules. Although they are appropriate in the optimization of baselines, they are not flexible in such situations where the demand conditions are changing very fast. In order to overcome this limitation, the use of heuristic and metaheuristic solutions, like greedy assignment, simulated annealing, or genetic algorithms, might be conducted to search a wider solution space, without violating operational constraints. In the case of an environment that already has enough data maturity, AI-assisted strategies would use machine learning models to forecast upcoming demand trends and use reinforcement learning to continually improve slot allocations according to feedback of executions. The algorithm is dependent on the scale of the warehouse, the complexity of the computation, and the frequency of re-slotting which can be tolerated. In any approach used, the optimization process is meant to produce viable, execution ready slotting plans that are associated with downstream picking and replenishment processes.

4.4 Dynamic Re-Slotting Strategy

As the demand in MTO manufacturing is volatile on its own, the static slotting parameters nearly become suboptimal very fast. The suggested framework thus adds to the scheme the dynamic re-slotting planning, within the framework of which the slotting performance is constantly measured and changes are initiated once predetermined thresholds are broken. Reminder indicators like the growth of the travel distance, of the replenishment activity or a continuous congestion in definite areas are the performance indexes indicating the re-slotting consideration. Dynamic re-slotting is performed in a manner that is controlled and gradual to reduce the operational disruption. The candidate SKUs are given priority as per impact potentiality and move feasibility and the re-slotting activity is planned during the low activity time or linked with the scheduled replenishments. The framework will be used to effect preemptive slotting based on adaptive real-time execution information, and predictive demand responses to dynamic pattern orders. The methodology guarantees a long-run warehouse efficiency and maintains a layout stability, thus it suits well when dealing with large scale MTO settings where the variation in demand is high.

5. Wave Picking Optimization

5.1 Order Classification in MTO Environments

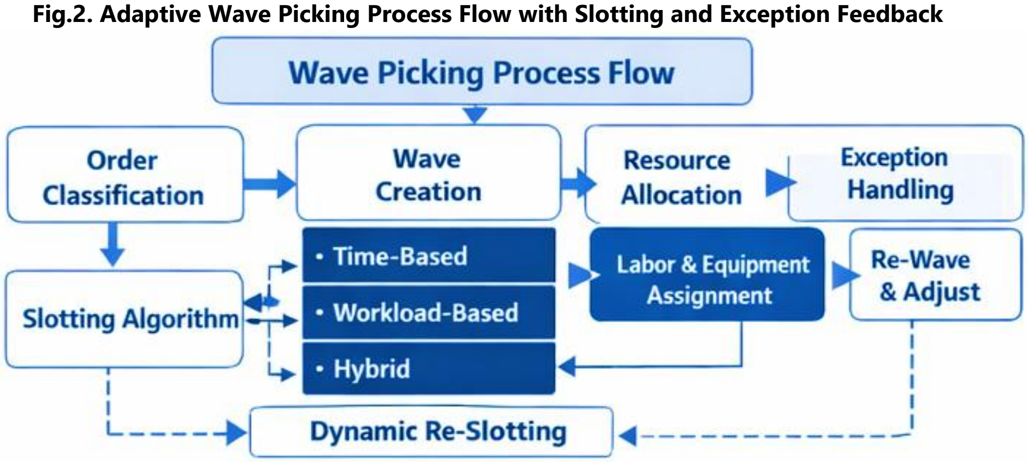
Make-to-order (MTO) systems have wave picking optimisation which is initiated by the use of excellent order classification to capture both customer commitments and production constraints. [13,14] As opposed to make-to-stock operations, where the order at times becomes autonomous, MTO orders are closely associated with production schedules, completion of kit requirement and the availability of material along the line of production. Consequently, the criteria of classification go beyond simple priority flags to those of due dates, production start times and dependency relationships based on the production of a BOM. Orders are divided into classes like production-critical, shipment-driven, and replenishment-triggered like production-critical which have high urgency to execute, and delay tolerance, and another which have low urgency to execute and long delay tolerance. Other orders such as production-critical orders which include production-critical orders are directly correlated to manufacturing processes and have to be discharged according to sequencing in production to avoid line-stoppages. Orders based on shipment drive focus on customer delivery schedules whereas replenishment based orders propagate ongoing picking and inventory control. This multi-dimensional categorization makes it possible to have differentiated wave release strategies to be as realistic as the reality of MTO manufacturing is.

5.2 Wave Creation Logic

The logic suggested to create waves supports several strategies of waves formation, such as time-based, workload-based, and hybrid ones. Time-based waves cluster release orders to be discharged at specific times and they work well in keeping rhythm in predictable environment. Nevertheless, when faced with uneven arrivals of the order and changing. priorities in MTO, time-based waves are usually subject to resource underutilization or congestion. The workload based waves overcome this limitation by dynamically creating waves in response to real time picking capacity, availability of labor and equipment constraints. Orders are dispatched when adequate amount of work has been amassed to efficiently make use of available resources and enhance equilibrium within the picking areas. Hybrid wave strategies combine both temporal releases and workload limits, and through this one can be able to release the waves in control, but remain flexible. The wave creation logic also supports the fact that in the face of end-to-end operation needs, the area where the picking process takes place will be in line with the order classification, zone capacity, and downstream production or shipping constraints.

5.3 Adaptive Wave Picking Process Flow with Slotting and Exception Feedback

Fig.2. Adaptive Wave Picking Process Flow with Slotting and Exception Feedback



The diagram illustrates an adaptive wave picking implementation strategy to suit the high variation make-to-order systems. [15,16] It starts with the classification of orders whereby orders are classified according to priority, due date, and producibility relationships. These categories combine with the slotting algorithm in order to make sure that storage location choices are not inconsistent with the picking needs. This is followed by wave creation to support time-based, workload-based, and hybrid strategies to strike a balance between a throughput and responsiveness. Real time availability and workload are taken into account, after which resources are allocated through allocating labor and material-handling equipment once the waves are formed. Exception handling systems constantly watch execution interference like lack of resources, delays or capacity, and have re-waving and adjustment actions in response when needed. The loop is complete with a dynamic re-slotting feedback loop that updates storage allocations off of execution results to allow further optimization and operational resiliency.

5.4 Resource-Aware Picking Execution

Resource-conscious picking is an important facilitator of wave picking efficiency in large-scale MTO warehouses. The suggested framework clearly includes picking task distribution and ordering, with skill of labor, equipment availability and automation capabilities). The labor resources are modeled and possess the following attributes: qualification, productivity rates and shift schedules, which allows to cover the assignment of the tasks to the most appropriate operators intelligently. All assets such as material handling equipment and automation- e.g., conveyors, automated storage and retrieval systems, and autonomous mobile robots are also part of an execution planning. Composition of waves and sequencing of the tasks is dynamically adjusted to prevent bottlenecks and even distribution of the utilisation in the manual and automated zones. Picking and replenishment (or put-away) where possible: Task interleaving methods are used to ensure that the picking and replenishing activities are combined and less time is wasted and unproductive transportation occurred. The resource conscious strategy also optimizes throughput, increases workforce productivity, and promotes scalable operations under comprehensive MTO operational conditions.

5.5 Exception Handling and Re-Waving

In spite of the developed planning and optimization, exception of the execution is an inevitable aspect of MTO warehouse operations. Disruptions that are common are material shortages, late inbound receipts, equipment failure, and late a last minute change in the order, which is necessitated by production or customer demands. The suggested wave picking model shall have real-time exceptions detection and adaptive re-waving controls to ensure continuity of each execution. In the case of exception, tasks and orders that are impacted are automatically detected and alternative execution paths are considered with regard to newer constraints and priorities. Re-waving can either include redistribution of the orders in the given waves, forming micro-waves to urgent work, or delaying non-critical orders to maintain the flow. The adjustments are made with little human participation and aided by real-time availability of resource status and order progress. The framework incorporates exception handling into the basic execution logic and re-waving, therefore, it becomes more resistant in operation and brings guaranteed reliability of performance in volatile conditions of MTO.

6. Yard Orchestration and Dock Optimization

6.1 Yard Visibility and Vehicle Tracking

Make-to-order (MTO) manufacturing settings need to have an efficient yard management to maintain constant information about the position and condition of inbound and outbound automobiles. The low level of yard visibility usually leads to postponed dock allocations, [17,18] high dwell time of trailers, and poor transportation- warehouse execution coordination. The suggested framework meets these obstacles by way of real-time tracking of vehicles and event-based status reporting capturing the arrival, check-in, yard movement, and dock preparedness events. The synchronization is inbound/outbound where the arrival of the vehicles is synchronized with the warehouse and production demand. Priorities are given to inbound vehicles with a production type of important material to be in the yard and docked, whereas the outbound vehicles are arranged according to the shipment-readiness and delivery-commitments. The system allows to make proactive decisions and minimize the delay between the delivery of vehicles to the yard and the execution of the material flows by keeping real-time information about both the assets in the yard and shipment status.

6.2 Dock Door Assignment Strategy

Dock door assignment is important in reducing the congestion and material handling efforts in the large warehouse yard. The dock optimization strategy as proposed considers the nature of the loads, priority of the order and equipment restrictions in assigning the vehicle to the right dock door dynamically. The load type issues entail inbound and outbound traffic, palletized and loose materials and hazardous and special-handling needs. Priority-based assignment in assigning tasks makes sure that production critical loads or movements that are time sensitive are handled before others of lower priority. Further limitations on feasible assignments include equipment limits, e.g. availability of special handling equipment or automation interfaces at a particular dock. The framework promotes dynamic re-allocation in response to delays or alternations in execution through constant re-estimation of dock availability and workload conditions and enhances the utilization of docks and shorter turnaround time.

6.3 Yard–Warehouse–Production Coordination

In MTO, operations of the yard have to be highly synchronized with warehouse execution and production to eliminate bottlenecks and all wastes. The new model will commit a two-way communication between the yard management, warehouse picking, and staging, and the systems of the production schedule. Such coordination is necessary to ensure that the materials received are presented in the form of stages that need to be produced by the manufacturing process and the fact that the goods shipped are loaded only after all picking and packing processes have been done successfully. Real-time adjustments that are achieved through event-driven coordination mechanisms are possible to take place in cases where disruptions are experienced e.g. delayed inbound arrivals, or a change in the sequence of production. As an illustration, the rescheduling of a production order leads to inbound or involved movement of products being reprioritized automatically to prevent unwarranted handling or congestion at the yard. The framework ensures there are no delays in the flow of operations by coordinating decisions between the yard, warehouse, and production scopes to minimize waiting times, congestion at docks, and overall flow directly in the operations.

6.4 Scalability Considerations

In large MTO manufacturing networks with many plants, the yard orchestration has a severe need to be scalable. With the growth of transaction volumes, the complexity of the yard centralized and manual forms of coordination is no longer sustainable. The suggested structure can deal with scalability by incorporating decentralized decision logic, prioritization rules that can be programmed, and event-based processing facilitating high throughput in transactions. Standard data models and interface patterns enable application to be adapted and deployed across numerous sites and also to customize operations locally. Also the framework accommodates incremental growth to fit more yard capacity, extra dock doors or new transportation partners without interrupting the established operations. Those scalability properties make sure that yard orchestration and dock optimization are not compromised with the increase in size and complexity of MTO plants.

7. Integrated Optimization across Slotting, Picking, and Yard Operations

7.1 Cross-Functional Dependency Analysis

Warehouse execution processes within make-to-order (MTO) settings are already interdependent and decisions in an area have direct implications to other areas. [19,20] Pick path efficiency and frequency at which replenishment is done are determined by the slotting strategies, thereby influencing the wave picking time and labor used. In much the same way, the wave picking decisions affect the staging needs and dock preparedness which directly affect the yard congestion and turnaround time of vehicles. Separate treatment results in local optimal performance of these functions, which reduces the performance of the entire system. The suggested model clearly represents cross-functional dependencies to facilitate the multi-functional decision-making. An example is the slotting assignments that are not considered entirely based on the travel distance, but rather on how the slotting assignment affects the flexibility of the wave-form and dock staging capacity. Wave releases are made with regard to the availability of yards and shipment schedules to avoid picking in advance or congestion of docks. Through the combination of these interdependencies, the framework makes the local execution decisions consistent with the global operational goals minimizing the inefficiencies that were brought about by functional silos.

7.2 Real-Time Decision Orchestration

Adaptive responses are coordinated in real-time by an event-based execution model which is used to continuously monitor operational conditions and cause adaptive responses at slotting, picking and yard. Some of the key events are order releases, production schedule changes, inbound vehicle arrivals, resource status updates as well as exception notices. Every incident acts as a signal of reviewing execution priorities and constraints throughout the system. Decision rules and event driven alerts help to coordinate quickly between functions. As an example, an inbound shipment with late arrival at the production location can provoke a possible temporary re-slotting or reprioritization of a wave to work on the accessible elements. On the same note, the unavailability of docks will suddenly postpone the wave release or can divert the staging activities elsewhere. This orchestrated operation downplays reaction latency, provides a better view of the operations, and also provides the ability to keep the execution decisions in line with the changing demand and resource environments.

7.3 System Performance Trade-Offs

Table1: Progressive Impact of Slotting, Wave Picking, and Integrated EWM Optimization

Metric	Baseline	Slotting Optimized	Slotting + Wave	Full Integrated
Order Cycle Time (h)	14.2	11.5	10.2	9.6
Pick Rate (picks/hr)	410	470	520	540
Dock Turnaround Time (min)	85	70	62	60
Labor Utilization (%)	80	85	88	90

Table projects the progressive improvements in performance with the process of optimizing warehouse execution beginning with isolated slotting improvements to wholesale improvements in slotting, wave picking and yard orchestration. The findings indicate that demand-based slotting can play a significant part in order to decrease the order cycle time, as well as the pick rates are enhanced by reducing the travel path, and distribution of the storage access. Workload-sensitive wave picking is another strategy included that leads to a higher productivity of picking and shorters the delay in execution since the release of orders is synchronized with the availability of the resource. The complete optimization has the best performance in terms of all the metrics, lowest order cycle time, highest pick rate, better dock turnaround, and optimum labor utilization. These results prove that, although individual optimization results in quantifiable benefits, the highest operational advantages can be gained through multilevel, end to end, execution of warehouse and yard operations. VIII. Case Study and Implementation.

8. Implementation and Case Study

8.1 Implementation Environment

This framework of optimization was realized and tested in a massive make-to-order (MTO) production stage with large product variability and strong production-logistics interaction. [21,22] The facility discussed in the case study is a central distribution and supporting-production warehouse that serves a number of manufacturing lines. The warehouse area is more than several tens of thousands of square meters, and has several storage areas, picking areas, staging, and dock doors that serve an inbound and outbound way. It has a number of thousands of active SKUs, but the volumes of daily order attendance vary considerably due to customer-specific arrangements and production cycles. Orders are in small scale kitting requests as well as multi-line shipment orders that have strict delivery obligations. The system landscape consists of an Order and Master Data management ERP, an Extended Warehouse Management (EWM) system to be applied in control of execution, a Manufacturing Execution System (MES) to be utilized in production coordination, and a Transportation Management System (TMS) to be used in carrier and shipment planning. Such systems are interrelated with the standardized interfaces that allow real-time exchange of data and event propagation.

8.2 Configuration and Custom Enhancements

Its implementation was based on the leverage of the standard EWM functionalities, enhanced by specific configuration and individual additions to facilitate integrated optimization. Demonstration of slotting optimization was done on the basis of demand-based criteria based on SKU velocity, order co-occurrence, and production dependency attributes. Selection of rules (Dynamic re-slotting) was created to perform selective adjustments depending upon the performance thresholds and demand volatility indicators. The optimization of the wave picking was deployed by the workload-aware wave templates that are accompanied by the classification of the orders, the capacity of the zone, the availability of the resources. Hybrid wave creation and real-time re-waving on the basis of execution exceptions were possible with custom logic. The improvements of yard orchestration were made consisting of automated dock assignment rules, event-driven yard status updates, and synchronized staging controls in synergy with the completion of waves and a shipment readiness. All of these layouts and additions allowed an integrated implementation of the entire warehouse and yard processes without interfering with the process of regular transactions.

8.3 Performance Metrics

A collection of quantitative indicators that aimed to measure end-to-end execution efficiency and responsiveness were used to measure system performance. Time taken by order from release to order picking and staging completion was taken as order cycle time which indicated the overall speed of the warehouse execution. The pick rate which is in the form of picks per labor hour was used as a major tool to measure picking productivity and resource utilization. Dock turnaround time was used, as the time that passed between checking-in and departing of the vehicle; measures the performance of the yard orchestration and dock assignment strategies. Other measures that were used to support these were labor utility, yard dwell time and replenishment frequency. Overall, the baseline measurements were made in the traditional configurations of EWM before the optimization process to directly compare the results with the offered overall framework.

8.4 Results and Observations

The results of the implementation indicate significant performance gains with all the measures assessed. The time needed in order cycle was also decreased which meant more predictable and faster execution in correlation to the production and the shipping schedules. The pick rate improved because of an efficient slotting, balanced wave formation and resource-aware exercise of tasks. The dock turnaround time also minimized due to increased visibility of the yard and dynamic dock assignment which minimized congestion and idle time. Qualitative observations also point to the enhanced stability of the operations and decreased use of manual interventions. The combined optimization strategy has made it easier to react to changes in demand and execution exceptions in a much faster way that will improve the resilience of the MTO environment. These outcomes support the claim that unified optimization of slotting, wave picking and yard operations are capable of providing quantifiable and sustainable improvement in the performance within large MTO warehouse environments.

9. Experimental Evaluation and Results

9.1 Baseline vs. Optimized System Comparison

Table 2: Baseline vs. Optimized Warehouse Execution Performance Metrics

KPI	Baseline	Optimized	% Improvement
Order Cycle Time (h)	14.5	9.6	+33.8
Pick Rate (picks/hr)	415	540	+30.1
Dock Turnaround Time (min)	88	60	+31.8
Yard Dwell Time (min)	112	75	+33.0

A performance analysis of the most important indicators during the performance of a relevant warehouse before and after the adoption of the suggested integrated EWM optimization model is provided. The findings indicate significant changes in all the KPIs that were measured. The order cycle time is minimized by 14.5 hours to 9.6 hours, which is showing that the coordination between the slotting, wave picking, and yard processes is improved. The pick rate rises over 30, which means that there are better labor usage and better plans in formulating waves. There are also 31.8% and 33.0% improvements in dock turnaround time, and yard dwell time, respectively, indicating the usefulness of event-based dock allocation and closer yard-warehouse coordination. Altogether, these gains prove the effectiveness of the integrated and data-driven optimization of the throughput, responsiveness, and operational efficiency of the warehouse environment based on large-scale make-to-order.

9.2 Throughput and Scalability Analysis

Throughput and scalability were evaluated by gradually decreasing the order volumes and the level of complexity in execution to replicate peak times of operation and future expansion situations. The optimum system ensured consistent performance even with an increase in the volume of transactions and its degradation was evident only at insignificant levels of cycle times and resource use. Conversely, the baseline system demonstrated vivid performance decline with high load e.g. incidence of greater wave backlogs, staging congestion, and longer dock turnaround times. Scalability was also tested in terms of system responsiveness between several warehouse areas within and yard operations at the same time. The event-based execution model allowed tasks to be processed in parallel, and allowed distributed decision making; this allowed a high transaction throughput with no central bottlenecks. All these evidence suggest that the proposed framework is scalable with increased demand and operational complexity, and therefore can be used with large, multi-plant MTO manufacturing networks.

9.3 Sensitivity Analysis

The sensitivity analysis was done to determine the strength of the proposed framework when operating at different operational conditions. Important parameters such as the demand volatility, availability of labor and inbound arrival variability were manipulated systematically to understand the effect on the performance of the system. The outcomes indicate that the execution efficiency may be impacted when extreme deviations of a single parameter are introduced, and the integrated system of optimization is never inferior to the base system in all the situations. It is important to note that the system was highly resilient to the demand variability based on dynamic slotting and adaptive wave development, whereas the variability inbound and outbound variability were event-driven using a yard orchestration approach. These results prove the advanced strategy is not only good in nominal conditions but also resilient to uncertainty and operational cripples prevalent in MTO conditions.

10. Discussion

10.1 Operational Implications

The findings of this paper draw out some crucial operational implications on make-to-order (MTO) manufacturing settings. To begin with, the results indicate that the execution performance in warehouses is not effective with the help of the individual functions, i.e. slotting, picking or yard management optimization. Genuine, long term beneficial performance improvements are, in fact, the result of system level optimization orchestrated to explicitly take into consideration the interdependencies between these spheres. Second, demand-driven slotting and workload-sensitive wave picking implementation helps warehouses to react to demand variations and production priorities better. Such responsiveness minimizes the execution time, enhances labour productivity and minimizes the risk of production interruptions due to unavailability of materials. Third, additional yard visibility and active dock orchestration solutions greatly enhance the congestion and idle time through better inbound/outbound flow synchronization. All of these functional enhancements can be used to achieve more stability in execution, throughput, and service-level conformity under large-scale MTO warehouse settings.

10.2 Limitations of the Proposed Approach

The given framework has a number of limitations that should be taken into consideration, although it proved to be advantageous. Integrated optimization highly depends on the quality and punctuality of underlying data such as demand signals, master data correctness and the real-time execution events. The performance gains that are possible can be limited in an environment where there is intermittent data governance or where there is poor system integration. Also, both dynamic slotting and adaptive wave picking are added causing system complexity and overhead in configuration. Companies that are not analytically advanced or limited by resources can find it difficult to tune the optimization parameters and change adoption. Lastly, the framework focuses on the possibility of scaling but extreme breakages in the functioning of the system i.e. a deep-seated system outage or extreme laxity cannot be handled by automated optimization and will require manual intervention. All these restrictions emphasize the importance of the deployment planning and the constant operational control.

10.3 Generalizability to Other Manufacturing Models

Although the presented framework is particular to the MTO manufacturing, a lot of its principles can be applied to other manufacturing and fulfillment models. The integrated optimization strategy can also be used in the context of assemble-to-order (ATO) settings where the efficient kitting and component preparation becomes crucial according to the final assembly plans. On the same note, engineer-to-order (ETO) processes can take advantage of dynamic slotting and event-based execution of the highly customized and of low-volume processes. The dynamic properties of the framework can be selectively used in make-to-stock (MTS) systems that are characterized by lower demand variability to peak periods or during promotional demand peaks. Nevertheless, the relative benefits might be lower than in the case of MTO. Altogether, the potential generalizability of the suggested approach implies that integrated EWM optimization is a versatile technique of facilitating warehouse performance in a wide variety of manufacturing and distribution schemes so long as the configuration and prioritization is adjusted to the operational environment.

11. Future Research Directions

The suggested integrated optimization framework can be developed in a number of promising ways in the future, in particular, the use of modern analytics, simulation tools, and self-execution features can be introduced. AI-based adaptive slotting is one of the major prospects to even improve responsiveness of warehouse in make-to-order (MTO) setting. Although the existing structure uses demand-driven heuristics and the ability to use prominent optimization logic, future efforts may focus on the usage of machine learning and reinforcement learning-based approaches to learn the best slotting policies on the basis of execution information continuously. Short term demand changes, changes in the production schedule as well as congestion patterns can be predicted by predictive models hence slotting can be optimally adjusted in advance with very little human involvement. These methods can also use explainable AI methods to ensure transparency and operational trust.

Another lucrative research stress point is provided by digital twin-based warehouse orchestration. Through the effective creation of digital simulations of warehouse and yard settings with high fidelity, researchers can design nursing execution situations, optimization policy, and trade-offs with different demand levels and resource availability. Digital twins have the potential to help steady increase in decision-making by making comparisons of predicted and measured system behavior to allow the implementation of constant adjustments in slotting, wave picking, and yard orchestration parameters. This strategy could greatly lower the operational risk in the event of altering systems and peak operating loads.

Lastly, yard management may be autonomous and this will offer the opportunity to further optimize beyond the good town. The communication between autonomous vehicles, smart gates, and yard monitoring using sensors can be explored as a coordination issue in the future through an integrated implementation structure. Autonomous yard systems can also increase throughput by allowing self-controlled movements of trailers, automated dock allocation and predictive traffic congestion of yards to reduce manual intervention. The combination of these capabilities with decision coordination provided by EWM is an open and effective research problem.

12. Conclusion

This paper introduced an unified optimization model of the Extended Warehouse Management (EWM) to the operational peculiarities of make-to-order (MTO) manufacturing settings. The approach suggests that interdependent execution functions such as slotting, wave picking and yard orchestration are addressed to eliminate the traditional, single-ation warehouse optimization strategies. The model integrates a demand driven slotting, workload sensitive wave formation, and event sensitive yard and dock coordination to execute warehouses responsively and at scale, using the same architectural and operational model.

By deploying the framework in a MTO environment at an industrial scale, it was observed that this framework could substantively enhance the key performance indicators such as order cycle time, productivity in picking and dock turn around time. The experimental test also verified the scalability and resiliency to high workload and demand variability of the framework. It can be summarized that the proposed findings emphasize end-to-end optimization and real-time decision orchestration in ensuring efficient execution and resilience in operations.

The research results of this work go beyond theory and practice because they offer a comprehensive methodology of developing advanced EWM capabilities with the production and transportation systems. With support to the overall manufacturing and logistics interests, the proposed framework puts EWM as a strategic facilitator of the high-performance MTO operations. The results highlight the issue on the promise of data-centered formulations of integrated execution models to facilitate the future developments of intelligent aerobic and self-directed warehouse and yard management systems.

Reference

[1]. De Koster, R., Le-Duc, T., & Roodbergen, K. J. (2007). Design and control of warehouse order picking: A literature review. European journal of operational research, 182(2), 481-501.
[2]. Gu, J., Goetschalckx, M., & McGinnis, L. F. (2007). Research on warehouse operation: A comprehensive review. European journal of operational research, 177(1), 1-21.
[3]. Rouwenhorst, B., Reuter, B., Stockrahm, V., van Houtum, G. J., Mantel, R. J., & Zijm, W. H. (2000). Warehouse design and control: Framework and literature review. European journal of operational research, 122(3), 515-533.

[4]. Ledner, A. (2001). Supply chain management: strategy, planning and operation.
[5]. Ganbold, O., Kundu, K., Li, H., & Zhang, W. (2020). A simulation-based optimization method for warehouse worker assignment. Algorithms, 13(12), 326.
[6]. Roodbergen, K. J., & De Koster, R. (2001). Routing order pickers in a warehouse with a middle aisle. European Journal of Operational Research, 133(1), 32-43.
[7]. S/4HANA Embedded Extended Warehouse Management (EWM) Overview, SAP, 2020. Online. https://community.sap.com/t5/supply-chain-management-blog-posts-by-members/s-4hana-embedded-extended-warehouse-management-ewm-overview/ba-p/13426599
[8]. Bortolini, M., Galizia, F. G., & Mora, C. (2018). Reconfigurable manufacturing systems: Literature review and research trend. Journal of manufacturing systems, 49, 93-106.
[9]. Stadtler, H. (2005). Supply chain management and advanced planning—basics, overview and challenges. European journal of operational research, 163(3), 575-588.
[10]. Boysen, N., Briskorn, D., & Emde, S. (2017). Sequencing of picking orders in mobile rack warehouses. European Journal of Operational Research, 259(1), 293-307.
[11]. Gunasekaran, A., Subramanian, N., & Papadopoulos, T. (2017). Information technology for competitive advantage within logistics and supply chains: A review. Transportation Research Part E: Logistics and Transportation Review, 99, 14-33.
[12]. Christopher, M. (2016). Logistics and supply chain management: logistics & supply chain management. Pearson UK.
[13]. Frazelle, E., & Frazelle, E. (2002). World-class warehousing and material handling (Vol. 1). New York: McGraw-Hill.
[14]. Yu, M., & De Koster, R. B. (2009). The impact of order batching and picking area zoning on order picking system performance. European Journal of Operational Research, 198(2), 480-490.
[15]. Waller, M. A., & Fawcett, S. E. (2013). Data science, predictive analytics, and big data: a revolution that will transform supply chain design and management. Journal of Business logistics, 34(2), 77-84.
[16]. Ivanov, D., Dolgui, A., & Sokolov, B. (2019). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. International journal of production research, 57(3), 829-846.
[17]. Mourtzis, D., Vlachou, E., & Milas, N. J. P. C. (2016). Industrial big data as a result of IoT adoption in manufacturing. Procedia cirp, 55, 290-295.
[18]. Zhang, C., Xu, W., Liu, J., Liu, Z., Zhou, Z., & Pham, D. T. (2021). Digital twin-enabled reconfigurable modeling for smart manufacturing systems. International Journal of Computer Integrated Manufacturing, 34(7-8), 709-733.
[19]. Min, S., Zacharia, Z. G., & Smith, C. D. (2019). Defining supply chain management: In the past, present, and future. Journal of business logistics, 40(1), 44-55.
[20]. Saniuk, A., & Waszkowski, R. (2016, August). Make-to-order manufacturing-new approach to management of manufacturing processes. In IOP Conference Series: Materials Science and Engineering (Vol. 145, No. 2, p. 022005). IOP Publishing.
[21]. Hompel, M., & Schmidt, T. (2006). Warehouse management: automation and organisation of warehouse and order picking systems. Springer Science & Business Media.
[22]. HOTZE, T. (2021). Advanced warehouse management systems and innovations. E-Logistics: Managing Digital Supply Chains for Competitive Advantage, 118.