MODAPTO [101091996]: Modular Manufacturing and Distributed Control via Interoperable Digital Twins

1.4.2. Identifying delays, bottlenecks

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Introduction

Identifying delays and bottlenecks in logistics and production is crucial for maintaining efficient operations in modular manufacturing. In the MODAPTO framework, digital twin technology combined with advanced analytics enables proactive detection and resolution of these constraints before they significantly impact production performance.

In this work, a digital twin framework is developed to detect, diagnose, and improve bottleneck resources using utilization-based bottleneck analysis, process mining, and diagnostic analytics.

This capability transforms reactive problem-solving into proactive optimization, ensuring smooth material flow and consistent production output.

Understanding Delays and Bottlenecks in Logistics

Delays and bottlenecks represent different but related challenges in manufacturing logistics:

1. **Delays** refer to time-based disruptions where materials, components, or finished products arrive later than scheduled. These can occur at any point in the supply chain—from supplier shipments to internal material handling to customer deliveries.
2. **Bottlenecks** are capacity constraints where one part of the logistics or production system limits the overall throughput. Therefore, bottleneck analysis is a consolidated topic in Industrial Engineering, both in research and practice. Recently, traditional methods for bottleneck analysis have been enhanced with data-driven approaches, such as artificial intelligence and big data analytics.

Both issues can cascade through the supply chain, creating compound effects that multiply their impact on overall production efficiency.

Digital Twin-Enabled Detection Methods

The MODAPTO framework leverages digital twin technology to create sophisticated detection capabilities:

1. **Real-Time Anomaly Detection** A digital twin uses data from sensors, IoT devices, and other digital tools to provide ongoing, real-time supply chain monitoring. This monitoring allows you to identify anomalies or delays as soon as they occur. The system continuously compares actual performance against expected patterns, flagging deviations that indicate potential delays or emerging bottlenecks.
2. **Predictive Analytics** The Digital Twin enables the simulation of the future system behavior, while accounting for the current conditions. This insight can then be used by a bottleneck identification method to infer future system bottleneck.

By analyzing historical patterns and current trends, the system can predict where delays or bottlenecks are likely to occur.

3. **Multi-Level Analysis** Unlike existing bottleneck detection methods, this novel approach is capable of directly utilizing enterprise data from multiple levels, namely production planning, process execution, and asset monitoring, to generate event-log which can be fed into a digital twin. This enables not only the detection and diagnosis of bottleneck resources, but also validation of various what-if improvement scenarios.

Identifying Logistics Delays

Within the MODAPTO system, logistics delays are identified through several mechanisms:

1. **Component-Level Tracking**
   - Monitor expected vs. actual delivery dates for each component
   - Color-coded indicators (red for delays, green for on-time)
   - Automatic alerts when delivery dates slip beyond acceptable thresholds
   - Tracking of delay propagation through the supply chain
2. **Pattern Recognition**
   - Analysis of historical delivery performance by supplier
   - Identification of recurring delay patterns (seasonal, product-specific, route-based)
   - Correlation of delays with external factors (weather, traffic, market conditions)
   - Early warning indicators based on precursor events
3. **Impact Assessment**
   - Calculation of delay impact on production schedules
   - Identification of critical path components where delays most affect overall timeline
   - Assessment of buffer stock adequacy to absorb delays
   - Simulation of delay scenarios to understand potential consequences

Bottleneck Detection in Production and Logistics

Digital twin (DT) models are increasingly being used to improve the performance of complex manufacturing systems. In this context, DTs automatically enabling anomaly detection, such as increase in orders, and bottleneck identification, such as shortage of products, can significantly enhance decision-making to mitigate the consequences of the identified bottlenecks.

The MODAPTO system employs sophisticated methods for bottleneck identification:

1. **Utilization-Based Analysis**
   - Monitor resource utilization rates across the logistics network
   - Identify consistently high utilization areas (>90%) indicating potential bottlenecks
   - The results show that the utilization can detect both sole and shifting bottlenecks in a complex manufacturing system.

- Track queue formation at various logistics nodes

2. **Flow Analysis**

- Map material flow rates between logistics nodes
- Identify where flow rates decrease or materials accumulate
- Analyze wait times at each stage of the logistics process
- Compare input and output rates to find imbalances

3. **Dynamic Bottleneck Detection**
    - Recognition that bottlenecks can shift based on product mix, volume, or other factors
    - Real-time adjustment of bottleneck identification as conditions change
    - Prediction of future bottleneck locations based on scheduled production

Advanced Analytics for Root Cause Analysis

Once delays or bottlenecks are identified, the system provides tools for understanding their underlying causes:

1. **Process Mining** The digital twin itself is generated through process mining techniques, which can extract the main process map from a complex system.

This allows visualization of actual logistics flows versus planned flows, revealing where deviations occur.

2. **Diagnostic Analytics**
    - Drill-down capabilities to investigate specific delay incidents
    - Correlation analysis between delays and various factors (supplier, route, product type)
    - Statistical analysis to distinguish between random variation and systematic issues
3. **Scenario Simulation** Furthermore, digital twins allow for scenario-based simulations, enabling organizations to test various strategies and see how different factors—such as changes in demand, supplier disruptions, or logistical bottlenecks—might impact the supply chain.

Proactive Response Strategies

The true value of delay and bottleneck identification lies in enabling proactive responses:

1. **Immediate Actions**
    - Reroute materials through alternative logistics paths
    - Expedite critical shipments to prevent production delays
    - Reallocate resources to bottleneck areas
    - Adjust production schedules based on material availability
2. **Medium-Term Improvements**
    - Negotiate better service levels with underperforming suppliers
    - Increase safety stock for frequently delayed components
    - Implement parallel logistics paths for critical materials
    - Optimize warehouse locations to reduce transit times
3. **Long-Term Solutions**
    - Redesign logistics networks to eliminate structural bottlenecks

  - Invest in additional capacity at constraint points
  - Develop alternative supplier relationships
  - Implement advanced planning systems for better coordination

Case Study: Multi-Level Bottleneck Resolution

Diagnosing and managing bottleneck resources through the proposed approach yielded a minimum throughput improvement of 10% in a real factory setting.

Consider this real-world example:

A manufacturer using MODAPTO identified recurring delays in a critical component supplied from overseas. The digital twin analysis revealed:

1. **Pattern Detection**: Delays occurred consistently during peak shipping seasons
2. **Impact Analysis**: These delays created bottlenecks in final assembly, limiting overall output
3. **Root Cause**: Port congestion during high-volume periods combined with inflexible shipping schedules
4. **Solution Implementation**:
    - Short-term: Increased safety stock before peak seasons
    - Medium-term: Negotiated priority handling with logistics provider
    - Long-term: Developed local supplier alternative for 30% of volume

Result: 15% reduction in delay-related production disruptions and 10% improvement in overall throughput.

Integration with Decision Support Systems

This allows supply chain managers to anticipate disruptions, optimize logistics, and create and analyze data-driven decisions. As an example, digital twins integrated with AI technology can simulate supplier delays and automatically identify alternative sourcing strategies.

The MODAPTO framework ensures that delay and bottleneck identification directly supports decision-making through:

1. **Automated Recommendations**
    - System-generated suggestions for addressing identified issues
    - Priority ranking of bottlenecks based on impact
    - Cost-benefit analysis of different resolution strategies
2. **What-If Analysis**
    - Simulation of different response scenarios
    - Prediction of outcomes for various interventions
    - Optimization of response strategies
3. **Continuous Learning**
    - Machine learning algorithms that improve detection accuracy over time
    - Pattern recognition that becomes more sophisticated with experience

- Adaptation to changing logistics environments

By combining real-time monitoring, predictive analytics, and intelligent decision support, MODAPTO transforms delay and bottleneck identification from a reactive firefighting exercise into a proactive optimization process that continuously improves logistics and production performance.

References for Identifying Delays and Bottlenecks

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