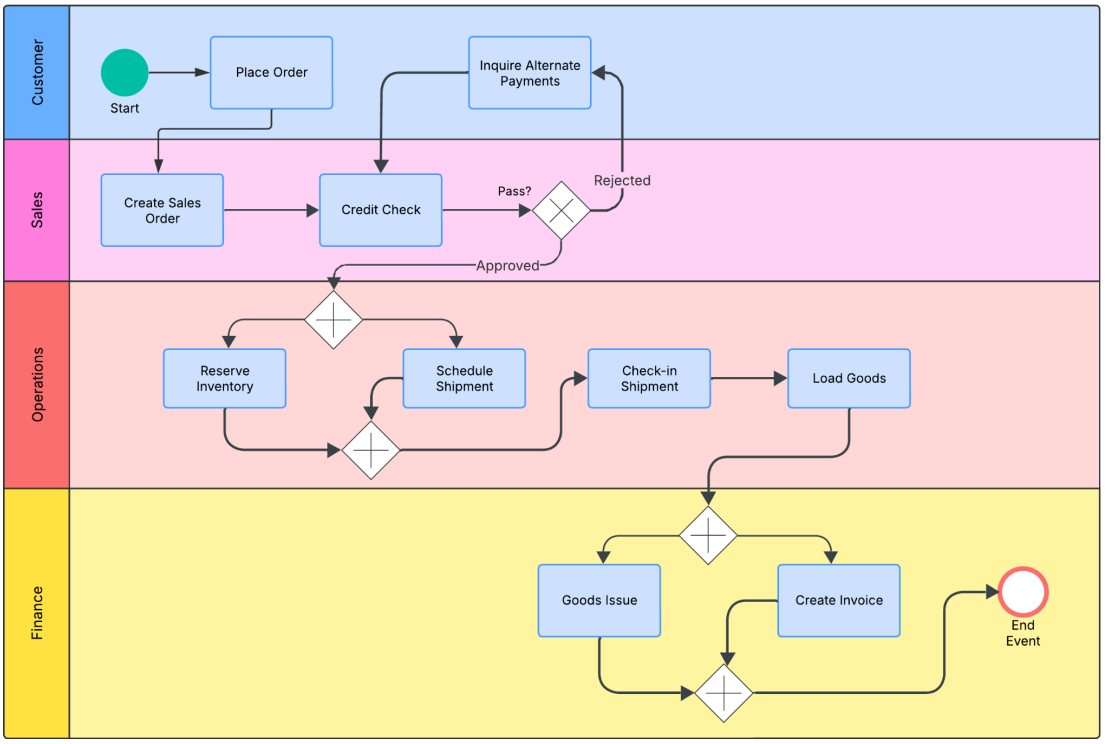
Digital Twin Development Approach for Supply Chain Business Processes



Introduction

Digital twins (DTs) represent a virtual replica of physical objects or systems that evolve alongside their real-world counterparts. The paper by Perez et al. (2022) introduces a framework for building digital twins specifically for supply chain business processes, focusing on the order-to-cash (OTC) process. This report evaluates the most suitable DT development approach for this use case and explains why alternative methods may be less effective.

Overview of Digital Twin Development Approaches

There are three main approaches to developing digital twins:

1. **Physics-based approach**: Uses first-principles and theoretical models to simulate system behavior based on physical laws, mathematical equations, and engineering principles.

2. **Data-driven approach**: Relies primarily on historical and real-time data to build models using statistical methods, machine learning, and artificial intelligence techniques.

3. **Hybrid approach**: Combines elements of both physics-based and data-driven methods to leverage their respective strengths while mitigating their limitations.

Analysis of the Supply Chain Business Process Use Case

The order-to-cash business process described in the paper has several characteristics that influence the selection of an appropriate DT development approach:

- **Complex system dynamics**: The system involves multiple agents performing tasks on orders flowing through a network with stochastic behavior.
- **Mixture of structured processes and unpredictable elements**: While the business processes follow defined structures, they incorporate stochastic elements like variable task durations and unpredictable order arrivals.
- **Availability of both historical and real-time data**: The framework integrates data from enterprise resource planning (ERP) systems and historical databases.
- **Need for simulation and optimization capabilities**: The digital twin must support Monte Carlo simulations and mathematical programming for scheduling optimization.

Hybrid Approach as the Optimal Solution

For the supply chain business process use case, the **hybrid approach** is the most suitable development method for the following reasons:

1. System Complexity Requires Multiple Modeling Techniques

The OTC process combines deterministic process structures with stochastic elements. A hybrid approach effectively models this complexity by:

- Using process modeling techniques (like the metagraph representation described in the paper) to capture the deterministic business process structure
- Incorporating statistical distributions to model stochastic elements like task durations and order arrivals
- Combining discrete event simulation with mathematical programming optimization

As Perez et al. (2022) state, "The modeling approach captures the routing dynamics and stochasticity in both the task durations and order arrivals that are observed in practice" (p. 1). This combination of deterministic structure with probabilistic behavior is best addressed through a hybrid approach.

2. Integration of Knowledge-Based and Data-Driven Components

The digital twin integrates domain knowledge about business processes with data-driven models:

- The process metagraph is based on structured knowledge about the business workflow
- Task duration distributions and routing probabilities are derived from historical data
- Real-time data updates these distributions and probabilities continuously

This integration of domain expertise with data analytics exemplifies the hybrid approach's strengths.

3. Balance Between Accuracy and Computational Efficiency

The hybrid approach provides an optimal balance between model accuracy and computational efficiency:

- The structured process model provides the foundation (efficiency)
- Statistical models capture complex behavior without excessive mathematical formulation (accuracy)
- Optimization models can be deployed as needed when system states change (adaptability)

As demonstrated in the paper's examples, this balance allows the digital twin to outperform heuristic-only approaches while remaining computationally manageable.

Why Alternative Approaches Are Suboptimal

Limitations of a Pure Physics-Based Approach

A strictly physics-based approach would be inadequate for this use case because:

1. **Business processes lack clear physical laws**: Unlike mechanical or chemical systems, business processes cannot be fully described by fundamental physical equations.

2. **Difficulty in modeling human behavior**: The agents in the OTC process include human actors whose behavior cannot be accurately captured through purely mathematical formulations.

3. **Excessive complexity**: Attempting to create deterministic models for all aspects of the system would result in an overly complex digital twin that is difficult to maintain and update.

4. **Inability to adapt to changing conditions**: Without data-driven components, the model would struggle to adapt to evolving business conditions and behaviors.

Limitations of a Pure Data-Driven Approach

Conversely, a purely data-driven approach would be insufficient because:

1. **Lack of structural understanding**: Without incorporating domain knowledge about the process structure, a data-driven model might fail to respect essential business rules and constraints.

2. **Dependence on large datasets**: Building accurate predictive models would require extensive historical data for all possible system states and transitions, which may not be available.

3. **Limited explainability**: Complex data-driven models often lack transparency, making it difficult for business users to understand and trust the digital twin's recommendations.

4. **Challenge in modeling rare events**: Data scarcity for exceptional cases and disturbances would limit the model's ability to respond to unusual situations.

Conclusion

The hybrid approach represents the optimal solution for developing a digital twin for supply chain business processes as described in the paper by Perez et al. (2022). By combining structured process models with data-driven statistical distributions, this approach effectively captures both the deterministic workflow and stochastic elements of the system. The hybrid model supports the various use cases described in the paper, including enhanced order priorities, accurate delivery date estimation, disturbance impact forecasting, and bottleneck identification.

While pure physics-based or data-driven approaches might address certain aspects of the system, they would fall short in providing a comprehensive, accurate, and adaptable digital twin. The hybrid approach leverages the strengths of both methodologies while mitigating their limitations, making it the clear choice for modeling and optimizing supply chain business processes.

References

Perez, H. D., Wassick, J. M., & Grossmann, I. E. (2022). A digital twin framework for online optimization of supply chain business processes. Computers and Chemical Engineering, 166, 107972. https://doi.org/10.1016/j.compchemeng.2022.107972