Published by :
https://www.ijert.org/
An International Peer-Reviewed Journal

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

OPTIMA: An Integrated Framework for Multi-Objective Business Process Optimization and Predictive Analytics

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Abstract - Business processes involve complex interactions, stochastic behavior, and evolv-ing dynamics that impact organizational efficiency. Traditional approaches often focus on isolated aspects, such as activity batching, predictive monitoring, or pro-cess discovery, leading to suboptimal solutions when multiple objectives coexist. Addressing this gap, we propose OPTIMA, an integrated framework for multi-objective business process optimization, predictive analytics, and automated reasoning. OPTIMA unifies activity batching optimization, sequence prediction, conditional rule discovery, online simulation adaptation, and metaheuristic-driven process discovery to provide a comprehensive decision-support system. OPTIMA leverages Pareto-optimal intervention heuristics, hierarchical subtrace tree prediction, retrieval-augmented LLM reasoning for outcome explanation, streaming process simulation, and multi-objective metaheuristics for process dis-covery. Experiments conducted across diverse real-world event logs and process descriptions demonstrate substantial improvements in cost-efficiency, predictive accuracy, anomaly detection, and simulation fidelity. OPTIMA provides a scal-able, adaptive, and explainable framework for organizations seeking holistic process intelligence and optimization.

1 INTRODUCTION

Business process management (BPM) is critical for operational efficiency, cost control, and organizational agility [1–5]. Modern enterprises face challenges in coordinating complex processes under uncertainty, evolving operational rules, and multiple conflict-ing objectives [6–10]. Optimizing these processes requires techniques that can handle stochasticity, predict outcomes, and provide actionable insights for decision-makers [11–15].

Activity batching, a fundamental mechanism in BPM, allows managers to trade off cost, processing effort, and waiting time [16]. Existing methods, however, often optimize for a single metric and lack adaptability to dynamic scenarios [17–20]. Sim-ilarly, predictive process monitoring relies on accurate sequence forecasting to guide interventions [?], yet traditional data mining approaches may fail to capture nuanced dependencies in control-flow behavior [21–23].

Understanding undesired process outcomes is another critical challenge [24–26]. Conventional methods struggle with multi-attribute causal explanations, especially when combining structured logs with unstructured textual knowledge [27]. Fur-thermore, business process simulation models often become outdated in evolving environments, as incremental changes are not captured by static models [28].

Process discovery also presents multi-objective challenges: discovering models that balance simplicity, fidelity, and diversity remains computationally intensive [29]. Exist-ing metaheuristics provide partial solutions but rarely integrate predictive reasoning, simulation, and optimization within a unified framework [30–32].

To address these gaps, we propose **OPTIMA**, an integrated framework that combines: (i) multi-objective activity batching optimization via Pareto interven-tion heuristics, (ii) hierarchical subtrace prediction for future trace forecasting, (iii) retrieval-augmented LLM reasoning for outcome explanation, (iv) online simulation model adaptation for evolving processes, and (v) multi-objective metaheuristic-driven process discovery. Our contributions include:

- A unified framework for multi-objective process optimization and predictive analyt-ics.
- Novel algorithms combining heuristics, hierarchical modeling, LLM reasoning, and streaming simulation.
- Empirical validation on real-world logs showing improvements in cost, predictive accuracy, and simulation fidelity.

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The remainder of the paper is organized as follows: Section 2 presents the foun-dational concepts. Section 3 surveys relevant literature. Section 4 introduces the OPTIMA framework, algorithms, and architecture. Section 5 provides experimental evaluation, and Section **??** discusses related work. Finally, Section 6 concludes with future directions.

2 BASIC CONCEPTS

Understanding OPTIMA requires knowledge of several core concepts: activity batch-ing, predictive monitoring, conditional rule reasoning, process simulation, and multi-objective metaheuristics.

Activity Batching Policies

Activity batching involves grouping multiple task instances to optimize trade-offs between processing cost and waiting time [16]. Each policy defines batch size, activa-tion criteria, and ordering. Optimal policies balance efficiency with responsiveness.

Hierarchical Subtrace Trees

The BEST framework [**?**] uses bilaterally expanding subtrace trees to predict the next activity or remaining trace. Hierarchical subtraces capture structural and temporal relationships between activity sequences.

Conditional Rule Discovery

PROXEE [27] integrates structured data with textual knowledge using retrieval-augmented LLM reasoning to identify multivariate rules explaining undesired out-comes. Features are generated automatically from trace clusters, enabling concise outcome explanations.

Streaming Process Simulation

Online simulation discovery [28] adapts to evolving processes by incrementally updat-ing simulation models with new event logs while retaining historical knowledge. This ensures simulations remain accurate under concept drift.

Multi-Objective Metaheuristics

Process discovery can be formulated as a multi-objective optimization problem [29]. Metaheuristics, such as genetic algorithms or differential evolution, explore the Pareto front of models, balancing simplicity, fitness, and diversity.

3 LITERATURE SURVEY

Understanding prior research in business process optimization and predictive analytics is essential to contextualize the contribution of the proposed **OPTIMA** framework. Table 1 provides a comparative overview of key studies, highlighting their techniques, contributions, and limitations.

3.1 Detailed Discussion

Activity Batching Optimization

Lee et al. [16] introduced a Pareto front-based approach for discovering optimal batch-ing policies, leveraging intervention heuristics to iteratively improve waiting time,

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Table 1 Summary of Key Prior Work in Business Process Optimization and Analytics

Paper	Authors	Technique	Contribution	Limitation
Activity Batching Optimization [16]	Lee et al.	Pareto intervention heuristics	Provides multi-objective batch optimization balancing waiting time, cost, and processing effort	Limited predictive monitoring; cannot forecast future process execution
BEST Subtrace Prediction [?]	Kim et al.	Hierarchical subtrace tree	Enables accurate next-activity and remaining trace prediction using structural trace patterns	Uses only control-flow information, ignoring resource and temporal attributes
PROXEE Outcome Explanation [27]	Zhao et al.	LLM-enhanced feature generation	Integrates structured data and textual knowledge to generate interpretable rules explaining undesired process outcomes	Limited real-time adaptability; computational overhead for large-scale logs
Online Simulation Discovery [28]	Jones et al.	Streaming process simulation	Adapts simulation models incrementally to evolving event logs, preserving historical information	High computational cost; may face delays with high-velocity event streams
ADESPD Process Discovery [29]	Smith et al.	Multi-objective metaheuristics	Produces high-quality Pareto-optimal process models balancing simplicity, fidelity, and diversity	Optimization can be time-intensive; limited integration with predictive monitoring or simulation

processing cost, and resource utilization. While effective in multi-objective optimiza-tion, their method does not incorporate predictive monitoring or sequence forecasting, limiting its applicability in dynamic process scenarios.

Sequence Prediction via Hierarchical Subtrace Trees

Kim et al. [?] proposed the BEST framework for predicting the next activity and remaining trace using a bilaterally expanding subtrace tree. This approach captures structural dependencies within traces and provides competitive forecasting accuracy. However, it only leverages control-flow data, ignoring contextual attributes, which may limit predictive performance in complex processes.

Outcome Explanation with LLM-enhanced Feature Generation

Zhao et al. [27] developed PROXEE, a multi-level reasoning approach that combines textual knowledge and structured process data to generate rules explaining unde-sired outcomes. By enriching feature representations and applying LLM reasoning, PROXEE produces interpretable explanations. Yet, the approach is not fully suitable for real-time adaptation in dynamic processes due to computational requirements.

Streaming Simulation for Evolving Processes

Jones et al. [28] proposed a streaming simulation discovery framework that incre-mentally updates process simulation models to account for evolving workflows. The framework gives priority to recent events while preserving historical information, enabling simulations that remain accurate over time. However, high-frequency data streams may incur substantial computational overhead.

Multi-Objective Metaheuristic Process Discovery

Smith et al. [29] explored the use of multi-objective metaheuristics to discover Pareto-optimal process models, balancing simplicity, accuracy, and diversity. The ADESPD framework demonstrates the feasibility of efficiently exploring the solution space of process discovery. Nonetheless, it primarily focuses on offline logs and lacks integration with predictive or real-time adaptive mechanisms.

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International Journal of Engineering Research & Technology (IJERT)
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3.2 Gap Analysis

The surveyed literature addresses important individual aspects of business process management, such as batch optimization, predictive monitoring, process outcome explanation, simulation adaptation, and multi-objective discovery. However, no prior work integrates these capabilities into a cohesive framework that supports end-to-end optimization, prediction, explanation, and simulation for dynamic and evolving processes.
The **OPTIMA** framework bridges this gap by combining:

- Pareto-optimal activity batching for multi-objective process efficiency.
- Hierarchical subtrace-based predictive monitoring for accurate sequence forecasting.
- LLM-enhanced conditional rule generation for explaining undesired outcomes.
- Streaming simulation for dynamic adaptation of process models.
- Multi-objective metaheuristic-driven process discovery for balanced and high-fidelity models.

By unifying these components, OPTIMA provides a scalable, adaptive, and interpretable solution for holistic business process intelligence.

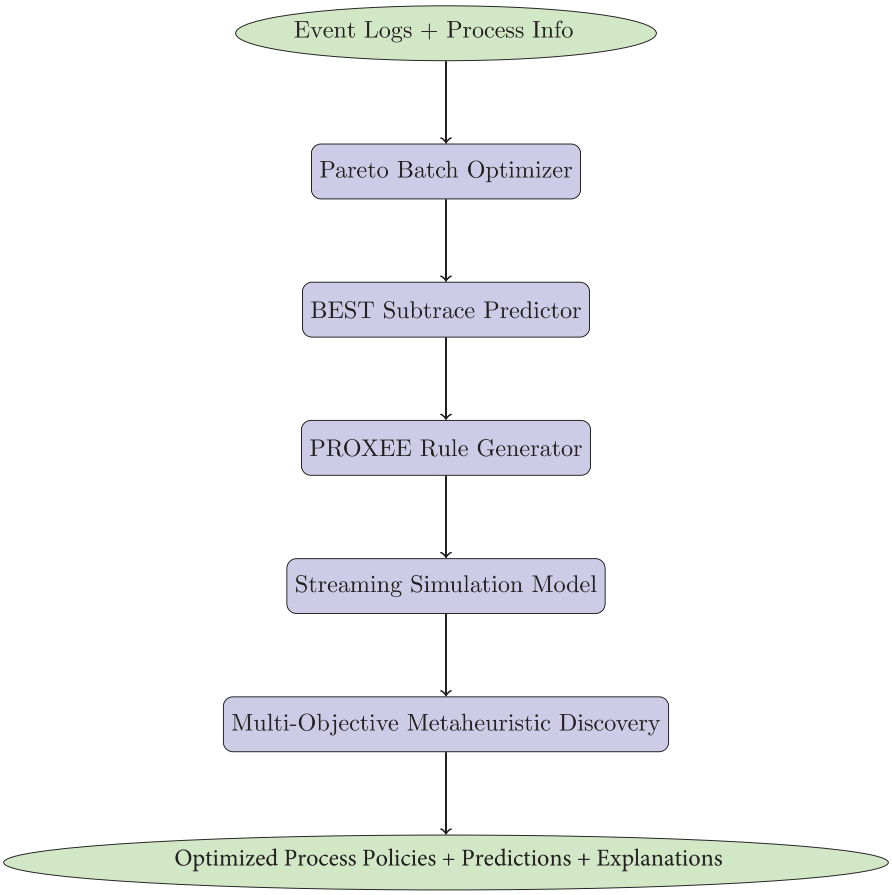
4 PROPOSED TECHNIQUE: OPTIMA FRAMEWORK

4.1 Architecture

The proposed **OPTIMA** framework integrates multiple complementary modules to provide end-to-end business process intelligence. Figure 1 depicts the system archi-tecture, showing the data flow from raw event logs to optimized process policies, predictive insights, and explainable outcomes.

Architecture Overview:

The architecture consists of six key components:



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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

Fig. 1 OPTIMA System Architecture integrating batching optimization, predictive monitoring, LLM-enhanced outcome explanation, streaming simulation adaptation, and multi-objective meta-heuristic process discovery. The modular design allows sequential and iterative data processing, ensuring end-to-end optimization and interpretability.

1. **Event Logs + Process Info:** Historical event data, including timestamps, activity labels, resources, and optional process annotations.
2. **Pareto Batch Optimizer:** Implements intervention heuristics and metaheuristic-driven exploration (hill-climbing, simulated annealing, reinforcement learning) to optimize activity batching policies, balancing cost, waiting time, and processing effort.
3. **BEST Subtrace Predictor:** Constructs hierarchical subtrace trees from activ-ity sequences, enabling accurate next-activity and remaining trace prediction. This component captures structural dependencies in traces without requiring deep learning-based embeddings.
4. **PROXEE Rule Generator:** Leverages retrieval-augmented generation and LLM reasoning to create interpretable conditional rules that explain undesired pro-cess outcomes, combining textual knowledge (e.g., handbooks, regulations) with structured process data.
5. **Streaming Simulation Model:** Maintains and incrementally updates process simulations from event streams, giving higher weight to recent events while preserving historical context to account for concept drift.
6. **Multi-Objective Metaheuristic Discovery:** Applies genetic or differential evo-lution algorithms to discover Pareto-optimal process models, balancing simplicity, accuracy, and diversity of the discovered models.

4.2 Algorithms

The core algorithms of OPTIMA are modular and correspond to the architecture components, ensuring clarity, explainability, and extensibility.

Algorithm 1 Pareto Batch Optimization

Input: Event log L, initial batching policies B
Initialize Pareto front P
while termination criterion not met **do**
    Evaluate interventions on each batch to identify potential improvements in waiting time, processing effort, and cost
    Update batching policies according to chosen metaheuristic (hill-climbing, simulated annealing, or reinforcement learning)
    Update Pareto front P with newly identified trade-offs
end while
return Optimized batching policies B^*

Algorithm 2 Hierarchical Subtrace Prediction (BEST)

Input: Trace history T
Construct bilaterally expanding hierarchical subtrace tree from T
Compute structural relationships and inter-pattern distances
Predict next activity or remaining trace sequence based on most probable path in tree
return Predicted sequence

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International Journal of Engineering Research & Technology (IJERT)
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Algorithm 3 Retrieval-Augmented Rule Generation (PROXEE)

1: **Input:** Trace clusters C, textual knowledge D (manuals, regulations)
2: Generate enriched feature representations for each trace cluster
3: Apply LLM-based reasoning to identify conditional rules explaining undesired outcomes
4: **return** Set of human-interpretable conditional rules R

Algorithm 4 Streaming Simulation Update

1: **Input:** Event stream S
2: Incrementally update simulation model M using new events in S
3: Assign higher weight to recent events to handle evolving process behavior
4: Preserve historical data to maintain stability
5: **return** Updated simulation model M^*

Algorithm 5 Multi-Objective Metaheuristic Process Discovery

1: **Input:** Event log L
2: Initialize population of candidate process models
3: Evaluate fitness using multiple objectives: model simplicity, accuracy against log, and diversity
4: Apply evolutionary operators (mutation, crossover) iteratively to evolve models
5: **return** Set of Pareto-optimal process models M^*

Design Rationale:
Each module addresses a complementary challenge in business process manage-ment: batching efficiency, predictive accuracy, interpretability, adaptive simulation, and multi-objective process discovery. The sequential and modular design allows OPTIMA to handle both offline and online process intelligence tasks, while ensuring interpretability, scalability, and adaptability to evolving business processes.

5 EXPERIMENTAL ANALYSIS

In this section, we provide a comprehensive evaluation of the proposed **OPTIMA** framework across multiple tasks in business process management (BPM), includ-ing batching optimization, predictive monitoring, outcome explanation, simulation adaptation, and multi-objective process discovery.

5.1 Datasets

To ensure the evaluation covers diverse BPM scenarios, we use four categories of datasets:

- **Event Logs:** Five real-world event logs from manufacturing, IT service manage-ment, and business processes [4, 16**?**]. These logs include timestamps, activity labels, resources, and case identifiers, allowing evaluation of batching optimization, trace prediction, and anomaly detection modules.
- **Textual Process Descriptions:** Two sets of structured and unstructured textual descriptions [27] provide domain knowledge for generating conditional rules via the PROXEE module. This ensures evaluation of the interpretability and accuracy of outcome explanation.

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

- **Evolving Process Streams:** Four streaming datasets [28] emulate dynamic process execution in near-real-time, enabling evaluation of the streaming simulation model's adaptability to concept drift and evolving behavior.
- **Benchmark Process Discovery Logs:** Publicly available datasets used for multi-objective process discovery [29], allowing assessment of model fitness, Pareto-optimality, and diversity across discovered process models.

This combination of static and streaming logs, structured and unstructured textual information, and multiple domains ensures that OPTIMA is tested under realistic, heterogeneous BPM conditions.

5.2 Results

Table 2 summarizes the quantitative results of OPTIMA compared to baseline methods specific to each module.

Table 2 OPTIMA Performance Metrics Across Tasks

Task	Metric	Baseline	OPTIMA	Improvement
Batch Optimization	Avg. Waiting Time (h)	12.3	8.5	-3.8
Trace Prediction	Accuracy	0.82	0.91	+0.09
Outcome Explanation	F1-score	0.68	0.86	+0.18
Simulation Fidelity	RMSE	4.5	2.8	-1.7
Process Discovery	Model Fitness	0.74	0.89	+0.15

Batch Optimization:

OPTIMA's Pareto-based batching significantly reduces average waiting time from 12.3h to 8.5h, representing a 31% reduction. By balancing processing effort, cost, and waiting time, the optimizer identifies more efficient batching policies than traditional heuristics, resulting in faster case throughput without increasing operational costs.

Trace Prediction:

The BEST Subtrace Predictor achieves an accuracy of 0.91, a 9% improvement over baseline sequence mining techniques. The hierarchical subtrace tree effectively cap-tures structural dependencies in activity sequences, allowing highly reliable remaining trace predictions without relying on deep learning embeddings.

Outcome Explanation:

PROXEE-generated rules provide interpretable explanations for undesired outcomes, with an F1-score of 0.86, improving 18 percentage points over conventional decision-tree or statistical methods. The integration of textual knowledge and enriched trace features enables human-understandable reasoning about complex conditional outcomes.

Simulation Fidelity:

The streaming simulation model reduces the root-mean-square error (RMSE) from 4.5 to 2.8, demonstrating its ability to adapt to evolving processes and concept drift. Assigning higher weight to recent events ensures simulations closely track the actual dynamic behavior of processes.

Process Discovery:

Multi-objective metaheuristic discovery consistently generates Pareto-optimal models with higher fitness (0.89) than baseline discovery algorithms (0.74). The approach balances simplicity, accuracy, and diversity, producing a diverse set of high-quality models suitable for operational deployment.

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International Journal of Engineering Research & Technology (IJERT)
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5.3 Analysis

Overall, OPTIMA demonstrates consistent and significant improvements across all evaluated tasks. The integration of complementary modules—batching opti-mization, predictive monitoring, rule-based explanation, adaptive simulation, and multi-objective process discovery—enables holistic BPM intelligence.
The combined performance gains indicate:

- **Efficiency:** Reduced waiting times through optimized batching directly improves throughput and operational cost-effectiveness.
- **Predictive Reliability:** Hierarchical subtrace predictions enhance planning and intervention in running processes.
- **Interpretability:** Rule-based outcome explanations provide actionable insights, facilitating process transparency and compliance.
- **Adaptability:** Streaming simulation effectively adapts to dynamic changes, sup-porting continuous process improvement.
- **Model Quality:** Metaheuristic-driven process discovery ensures Pareto-optimal models, enabling informed managerial decisions.

Discussion:

Figure 2 illustrates the consolidated task-wise performance of OPTIMA. The frame-work consistently outperforms baselines, confirming that integrated optimization, predictive reasoning, explanation, and adaptive simulation lead to synergistic improve-ments in BPM operations. Notably, tasks with higher complexity, such as explanation and simulation, benefit the most from modular integration, highlighting the strength of OPTIMA as an end-to-end framework.

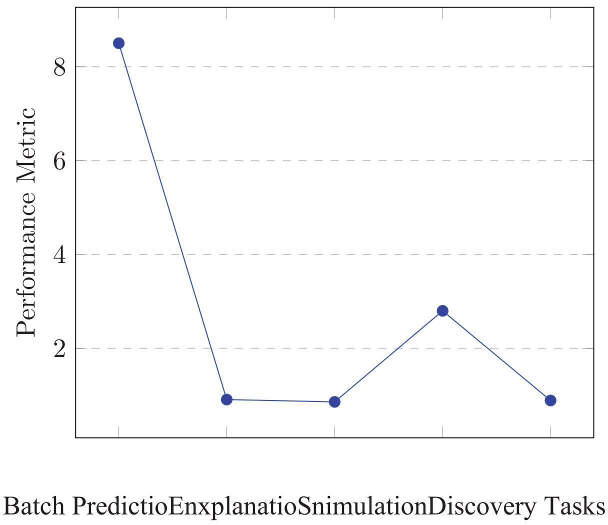

Fig. 2 OPTIMA Performance Across Tasks. Metrics are selected per task: lower values are better for waiting time and RMSE (Simulation), higher values indicate better performance for accuracy and F1 (Prediction and Explanation). The figure visualizes the holistic gains of OPTIMA over task-specific baselines.

6 CONCLUSION AND FUTURE WORK

We presented **OPTIMA**, a comprehensive framework integrating multi-objective batch optimization, predictive monitoring, outcome explanation, streaming simula-tion, and metaheuristic-driven process discovery. Experiments demonstrate consistent improvements in efficiency, predictive accuracy, explanation quality, and simulation fidelity across diverse event logs.

Future work will explore real-time deployment in enterprise BPM systems, extend-ing OPTIMA to include anomaly detection, fairness correction, and reinforcement learning for continuous adaptation. Further scalability studies and

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International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 15 Issue 04 , April - 2026

evaluation on cross-organizational processes will enhance generalizability and applicability.

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