Real-Time Optimization for a Multi-Reactor Polymerization Process

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Abstract: This paper describes the development and implementation of a Real-Time Optimization (RTO) system for large-scale industrial polyolefin (polyethylene/polypropylene) production processes. The RTO operates at a level above existing model-predictive controllers (MPCs), computing economically optimal steady-state setpoints for key reactor and recycle variables. The motivation is to maximize profit, while respecting all quality and operability constraints. The RTO architecture and optimization formulation are outlined. A dynamic first-principles model combining reactors and recovery unit operations underpins the RTO, with on-line model estimation to ensure accurate steady-state predictions. The commissioning of RTO on a Borstar polyethylene plant is summarized. In closed-loop operation, it was demonstrated that the RTO could achieve a significant reduction in catalyst consumption at fixed production target. The work underscores how plantwide RTO complements existing MPC layers in modern polymer plants, serving as a supervisory economic optimizer that continuously drives the process towards its optimum. Deployments in 2023 and 2025, with a third planned for 2026, indicate the approach is scalable for continuous economic optimization in polymer plants.

Keywords: Real-time optimization, MPC, NMPC, economic optimization, polymerization plant

1. INTRODUCTION

Large-scale polymerization plants (e.g., for polyethylene and polypropylene) involve multiple interconnected units (slurry or solution reactors, gas-phase reactors, and complex recycle systems), so operating conditions must be carefully chosen for optimal economics. Real-time optimization (RTO) is an approach that integrates process models, economic objectives, and on-line plant data to compute optimal setpoints for continuous processes (Marlin and Hrymak, 1997). Conceptually, RTO sits above the regulatory control layer (e.g. MPC), providing targets that maximize profit or minimize cost at steady-state (Forbes and Marlin, 1996). In practice, RTO has been widely applied in refining and petrochemicals, but in polymer production its adoption has been more recent due to the complex nonlinear kinetics and stringent product quality constraints.

Borealis[1] was among the first to implement advanced nonlinear model predictive control (NMPC) in polyolefin reactors (Hillestad and Andersen, 1994). Since then NMPC has been continuously developed and implemented in more than 20 polyolefin plants within Borealis. Building on that success, the company has pursued higher-level plantwide optimization in its proprietary multi-reactor Borstar process. The present work continues this direction by implementing a RTO in a running industrial polymerization plant, above well-established MPC applications that separately control a slurry loop reactor, a gas-phase reactor and a recovery area. The objectives are to automate economic setpoint optimization – formerly done via manual engineering heuristics – and to sustain optimal operation despite changing feedstock costs, catalyst activity, and production requirements.

2. CONTROL AND OPTIMIZATION ARCHITECTURE

The RTO system is structured as a hierarchical supervisory layer above the existing MPCs. In the Borstar plants, each major reactor has the proprietary in-house developed nonlinear MPC controller maintaining product quality and stable operation. In addition, there is a commercial linear MPC controller stabilizing and optimizing the recovery area.

The RTO runs a coordinated steady-state economic optimization using a combined model of the entire polymerization train and the recovery area. The RTO determines where to operate (optimal steady-state), while the underlying MPCs ensure how to get there dynamically without violating constraints.

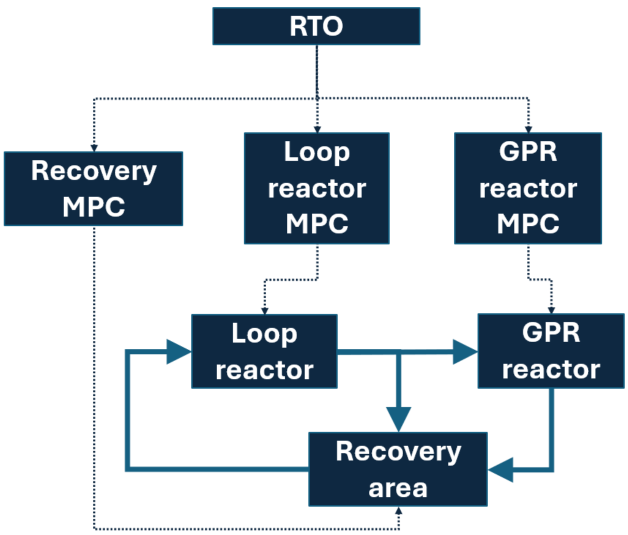

Figure 1: Hierarchy of RTO and MPC for a Borstar plant

[1] Borealis had recently merged with Borouge and Nova Chemicals to form Borouge International

Communication between RTO and the MPCs uses the existing plant data server infrastructure. The RTO application is deployed on the same control server as the MPCs, and may execute at a slower cycle (e.g., 1–5 minutes) as the purpose of RTO is to guide the process to the economic optimal point at steady state. Crucially, the RTO includes a steady-state detection logic: it monitors process stability indicators (temperature, rates, product composition) and only closes the loop (applying its optimized setpoints) when the plant is at or near steady-state. If disturbances or grade changes occur, RTO switches to open-loop mode (calculating but not applying new setpoints) until stable conditions return. Operators can also manually set RTO to open-loop or closed-loop at any time.

During commissioning, the RTO is typically run in open-loop (advisory mode) to allow engineers to validate the optimized targets before activating closed-loop control. This conservative approach builds operator confidence in the RTO recommendations.

3. OPTIMIZATION PROBLEM FORMULATION

The RTO problem is formulated to maximize the economic performance of the polymerization process at steady state.

Depending on business needs, the profit is maximized in two different modes:

(i) Throughput-constrained (meeting a fixed production target with minimum cost) or

(ii) Throughput-maximizing (producing as much as possible within equipment limits and quality specifications).

Correspondingly, the objective function is an economic profit indicator, expressed (in relative units) as product revenue minus raw material and utility costs. For confidentiality, only relative improvements or percentage savings are considered in this publication. Key contributions to the profit function include monomer costs, co-monomer costs, catalyst cost, hydrogen cost, energy costs, and a refund price for hydrocarbon in offgas streams to external cracker. By adjusting reactor conditions and recycle flows, the RTO seeks an operating point that maximizes the objective function, while satisfying all quality and constraint requirements.

The decision variables (degrees of freedom) defined in RTO include selected critical setpoints that were previously fixed by operators: including various reactor conditions that are not linked to product quality.

These setpoints affect catalyst productivity, reaction rates, and recycle economics. The RTO manipulates them within allowable ranges to find the best economic trade-offs. Several hard constraints and specification targets are embedded in the optimization model to ensure feasible and safe operation. These needed: polymer quality specifications (to achieve target molecular weight and density), equipment limits, and operability constraints. The optimization thus resembles a classic steady-state RTO problem (Marlin and Hrymak, 1997), solved repetitively on-line:

Maximize Profit = Product value – (Catalyst + Monomers + Utilities + Off gases cost)

Subject to: all process unit constraints, and meeting required production rate & quality.

When the production rate is fixed (scenario i), rate is entered as a constraint and the cost is minimized; when maximizing production (scenario ii), the rate becomes part of the objective until a new constraint activates (bottleneck reached). By design, any available degrees of freedom (after satisfying quality targets) are exploited to reduce cost.

4. MODELLING APPROACH

A high-fidelity first-principles model is at the core of the RTO. The RTO model builds upon the existing nonlinear dynamic models used by the reactor NMPC controllers (Haugwitz et al., 2010), extended to encompass relevant plantwide balances. Specifically, the model includes the main reactor system (pre-polymerization, loop slurry reactor, gas-phase reactor) as well as simplified representations of the recycle and recovery section. This holistic approach allows RTO to evaluate, for instance, how changes in reactor conditions impact recycle flows, catalyst utilization, and overall yields. The model contains dynamic mass states for key components (monomers, hydrogen, inert gases, polymer, catalyst activity), but the focus is on accurate steady-state predictions since the objective is to find the best economical steady state operating point.

To ensure model accuracy in the face of inevitable plant-model mismatch, the RTO employs on-line state and parameter estimation similar to the reactor NMPC controllers: certain measured variables (e.g., product flow, composition analyzers) continuously correct corresponding model states or parameters. For example, the catalyst deactivation rate parameter is adjusted so that the model's predicted production rate aligns with plant measurements. These corrections executed every sample keep the model "calibrated" to the true process, which is crucial for reliable optimization results. The estimation mechanism has proven robust in NMPC for more than 20 years.

Overall, the modelling and estimation approach ensures that the model converges to the plant measurements at steady state, allowing the optimizer to make economically sound decisions based on realistic process conditions.

5. IMPLEMENTATION AND RESULTS

The first RTO system was implemented in 2023 in a Borstar polypropylene plant, which uses a two-reactor cascade (slurry loop + gas-phase). After rigorous off-line simulations and operator training, the RTO was commissioned in stages: initially open-loop (advisory mode) for several weeks, followed by fully closed-loop operation where the RTO writes setpoints directly to the underlying MPC controllers. Operators retain ultimate supervisory control via DCS HMI graphics and can deactivate RTO if needed. The RTO is now continuously used when the plant is in steady state.

The second implementation was in 2025 in a Borstar polyethylene plant which uses a two-reactor cascade (slurry loop + gas-phase). The third implementation on a Borstar polyethylene plant will be commissioned in 2026.

Case Study PE plant implemented 2025:

The loop reactor had been traditionally operated at conservative levels. The RTO suggested loop reactor setpoints, that reduced catalyst usage significantly without increasing other relevant production costs, while keeping total throughput and product properties constant. In effect, the RTO found a sweet spot balancing catalyst productivity against gas-phase reactor capacity and constraints.

Throughout the commissioning, the RTO's decisions were carefully monitored. No violations of quality specs or safety constraints occurred, thanks to the layered control design. It was noted that the plant's operation became more consistent and required fewer manual interventions to adjust setpoints, as RTO handled those adjustments proactively. Over several months of closed-loop use, the average offgas losses were reduced (more reuse of recycle streams) and catalyst consumption moderated without sacrificing production targets, confirming the economic benefits predicted.

Operators have now adapted their baseline control targets as suggested by the RTO, which has resulted in closer operation to the economic optimal point even when RTO is not in closed loop.

To get the maximum economic benefit, the RTO should be in closed loop, since the catalyst activity and other disturbances may influence the economics from day to day, and the RTO is able to predict and respect the limitations of the reactors.

6. CONCLUSIONS

A plantwide Real-Time Optimization (RTO) layer has been implemented for multi-reactor polyolefin processes above existing MPC applications. The RTO computes economically optimal steady-state targets for key reactor and recycle variables and hands these targets to the MPCs for constraint-compliant execution.

The optimization is based on a first-principles plant model with on-line estimation, and was commissioned using steady-state detection and a staged open-loop/closed-loop rollout.

In industrial operation, the RTO has delivered sustained economic improvements, showing significant reduction in catalyst consumption at constant throughput and product properties. Deployments in 2023 and 2025, with a third planned for 2026, indicate the approach is scalable for continuous economic optimization in polymer plants.

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