

SYSTEMATIC EVALUATION OF MULTI-OBJECTIVE EVOLUTIONARY ALGORITHMS FOR COMBINATORIAL ELECTRIC DRIVETRAIN DESIGN

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Abstract

Designing electric drivetrains requires navigating a high-dimensional space of categorical and combinatorial design decisions, such as winding patterns or semiconductor module types. In such discrete search spaces, the structural properties of the optimization landscape differ fundamentally from continuous domains. As a result, widely used multi-objective evolutionary algorithms (MOEAs) exhibit characteristic failure modes. These include premature convergence toward dominant categories, a systematic loss of diversity across categorical variables, strong sensitivity to initialization, and inconsistent statistical behavior across independent but equivalent runs. Although these effects are well documented for synthetic benchmark problems, their manifestation in real industrial optimization tasks, such as drivetrain configuration, remains insufficiently understood.

This study conducts a systematic analysis of NSGA-II on a real combinatorial drive train design problem, where a typical single model evaluation requires approximately 42 seconds of computational time. The objective is to determine how initialization strategies and evolutionary operator settings influence the algorithm's convergence behavior. A further goal is to examine whether the algorithm exhibits systematic limitations when operating in high-dimensional categorical decision spaces. To this end, several initialization mechanisms are compared, including Latin Hypercube Sampling, Balanced Marginal Selection, and Fractional Sampling. In addition, mutation and crossover hyperparameters are examined in detail. Multiple independent local optimization runs enable a quantitative assessment of statistical stability and support the identification of structural drivers of premature convergence in discrete multi-objective design spaces.

Beyond NSGA-II, the study includes a benchmark comparison with state-of-the-art optimizers.

These comprise evolutionary algorithms such as MOEA/D and DECMO2, surrogate-based methods such as ParEGO, and deterministic direct-search approaches such as DMultiMADS. All methods are evaluated on identical drivetrain design tasks to ensure comparability.

The results provide a comprehensive quantitative evaluation of algorithm performance using Hypervolume, Spacing, and IGD+ measures. Additionally, entropy-based diversity metrics are applied to analyze structural patterns in the decision space, with a particular emphasis on indicators of premature convergence. A statistical evaluation across independent runs is conducted to investigate whether notable variance in NSGA-II's convergence behavior emerges, particularly in the presence of categorical variables with imbalanced decision structures. Although the analysis is based on a single powertrain scenario, the problem structure reflects characteristics common to many high-dimensional categorical engineering domains. Consequently, it functions as a high-fidelity stress test that complements synthetic benchmarks by allowing a systematic investigation of the algorithm's behavior in realistic discrete design spaces.

Based on these empirical findings, the study identifies the influencing factors that most strongly affect Pareto-front quality in combinatorial industrial design problems. The results offer a data-driven basis for understanding algorithmic behavior in high-dimensional discrete design spaces and support the selection and configuration of MOEAs within industrial drive train design workflows.