Surrogate Modeling for Efficient Energy Optimization in Robotic Manufacturing Cells

Alejandro González Casal[1], Diego Crespo Pereira[2], Richard José Duro Fernández[1], and Abraham Prieto García[2]

[1] Grupo Integrado de Ingeniería (GII), Centro de Investigación TIC (CITIC), Universidade da Coruña, Spain
alejandro.gonzalez.casal@udc.es, richard.duro@udc.es

[2] Grupo Integrado de Ingeniería (GII), Centro de Investigación en Tecnologías Navales e Industriales (CITENI), Universidade da Coruña, Spain
diego.crespo@udc.es, abraham.prieto@udc.es

Abstract

Optimizing energy in robotic cells requires meeting production deadlines while using resources efficiently. Time scaling reduces energy by stretching operation times, but its interaction with scheduling and allocation makes optimization computationally expensive when relying only on detailed simulation. This study evaluates surrogate models as an alternative for energy-aware optimization. Neural surrogates are trained on simulation data and integrated into optimization loops, accounting for sampling and training costs. Results identify ranges of computational cost, execution time, and scenario complexity where surrogate-assisted methods outperform direct simulation, supporting their use for energy-efficient operation of robotic cells under industrial constraints.

1 Introduction

Optimization of high-fidelity black-box functions, such as digital twins (DTs), is often computationally prohibitive due to the large number of evaluations required. *Surrogate models* (SMs) provide an efficient alternative by approximating the behaviour of the expensive simulator and enabling fast optimization at negligible cost [1]. In industrial and manufacturing contexts, digital twins deliver detailed and realistic representations of physical systems but remain limited by their computational demand. Integrating surrogate models into DT-based optimization has been shown to accelerate convergence while preserving sufficient accuracy for decision making [2].

In this work, a *Hybrid Robotic System Optimization Methodology* is proposed, combining DT evaluations with surrogate-assisted learning to optimize the energy consumption of a multi-robot manufacturing cell. The study builds on the formulation by Hovgard *et al.* [3], which addresses energy reduction in multi-robot stations operating under time-constrained conditions. The goal is to complete all operations before a global deadline while minimizing total energy consumption. This involves determining the assignment of operations to compatible robots, their execution order, and the time-scaling factors that affect both duration and energy use:

$$\min_{\pi,\, \mathcal{A},\, S} \sum_i E_i(s_i) \quad \text{s.t.} \quad T_f(\pi, \mathcal{A}, S) \leq t_{deadline}, \tag{1}$$

where $E_i(s_i)$ represents the energy consumed by operation i with scaling s_i, and $T_f(\pi, \mathcal{A}, S)$ is the total completion time depending on scheduling π, robot assignment $\mathcal{A}$, and the set of scalings S. This formulation captures the trade-off between energy efficiency and productivity while highlighting the combinatorial and high-dimensional nature of the problem.

2 Methodology and Results

The optimization problem was solved using an evolutionary algorithm evaluated through a digital twin (DT). To reduce computational cost, a hybrid scheme combining DT and surrogate model (SM) evaluations was implemented. The search begins with DT-only evaluations to generate an initial dataset and then alternates between SM-based evaluations and periodic DT retraining. The balance between both evaluators is governed by the DT participation ratio (ρ_T), which defines the share of time devoted to direct simulation—from $\rho_T = 1.0$, where only the DT is used, to $\rho_T = 0.0$, where the DT participates only in initialization and final validation. Different DT evaluation budgets (N_{DT}) were also explored to assess the influence of computational resources. Each configuration was executed ten times to evaluate robustness.

Two scenarios with different baseline difficulty were analyzed (Figs. 1 and 2). For each one, a heatmap reports the average energy ratio and the corresponding p-value of every configuration relative to its DT-only baseline. Ratios below one and $p < 0.05$ indicate statistically significant improvements. Results show that the contribution of the surrogate is more significant in the scenario with higher baseline difficulty, since in that case the DT alone cannot perform an adequate exploration with a limited number of evaluations. Across both cases, the best trade-off appears for ρ_T values around 0.4–0.6, balancing exploration (SM) and accuracy (DT). As the budget increases, direct DT optimization progressively becomes more effective.

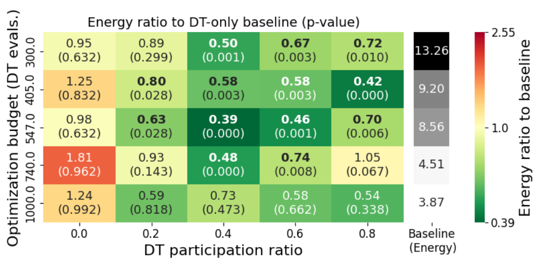

Figure 1: Scenario 1: More complex optimization case with higher combinatorial difficulty.

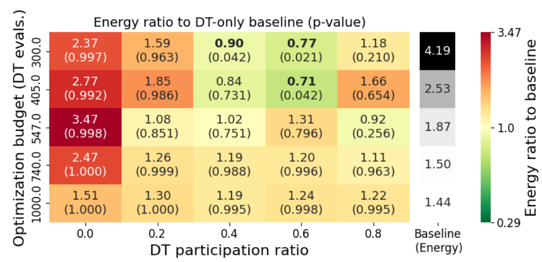

Figure 2: Scenario 2: Simpler configuration with lower combinatorial difficulty.

3 Acknowledgments

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References

[1] Leo Liberti et al. Surrogate-based methods for black-box optimization. *Optimization Letters*, 2016.

[2] R. de Silva and E. Patelli. Modelling for digital twins: Potential role of surrogate models. *Processes*, 10(3):476, 2022.

[3] Mattias Hovgard, Bengt Lennartson, and Kristofer Bengtsson. Energy reduction of stochastic time-constrained robot stations. *Robotics and Computer-Integrated Manufacturing*, 81, 2023.