Optimal Systems Design of a Permanent Magnet Synchronous Motor for a Formula Student Vehicle

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Formula Student is the world’s largest engineering competition, where teams compete in both static and dynamic events, including Acceleration, Skidpad, Autocross and Endurance. **Formula Electric Belgium** participates with a fully electric, autonomous-capable racecar. Within their vehicle, the powertrain plays a critical role and is equipped with **four in-wheel Permanent Magnet Synchronous Motors (PMSMs)**. These motors must deliver high performance while meeting strict packaging constraints, as they are tightly integrated within 10-inch rims. Commercial motors are currently used but lack the performance density and integration flexibility required for a competitive Formula Student drivetrain. This thesis addresses that challenge by developing a custom PMSM optimized for performance, efficiency and in-wheel integration.

1 Defining requirements & objectives

Formula Student events were simulated using OptimumLap to extract **motor-level torque and power requirements** (Fig. 1). A **sensitivity analysis** evaluated the impact of motor mass and efficiency on competition performance, guiding the optimization objectives.

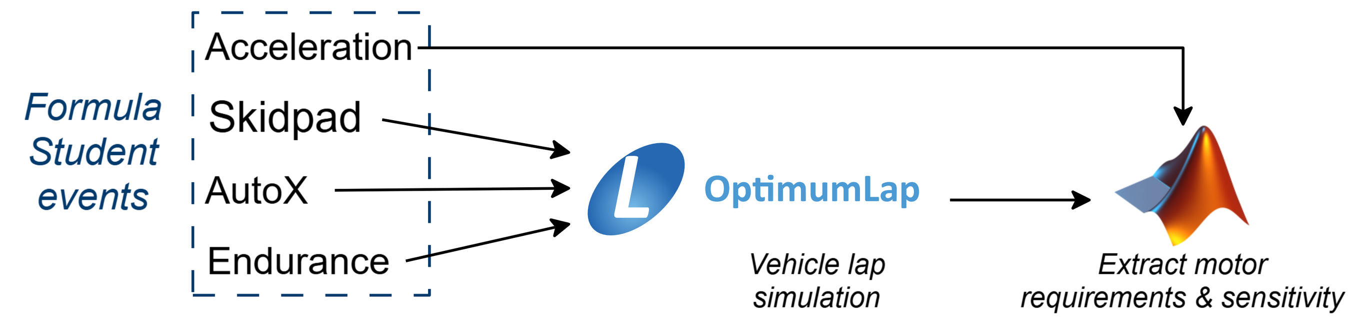

Figure 1: Simulation workflow to extract motor-level requirements

The results define the torque-speed envelopes for **peak and nominal operation** (Fig. 2). Sensitivity analysis (Fig. 3) quantifies how changes in motor **mass** and **efficiency** affect performance in individual events. Based on competition scoring, a **weighted performance index** is defined and **maximized** during optimization:

$$\textbf{Total Performance Increase} = 0,135\ \Delta\eta - 0,344\ \Delta m$$

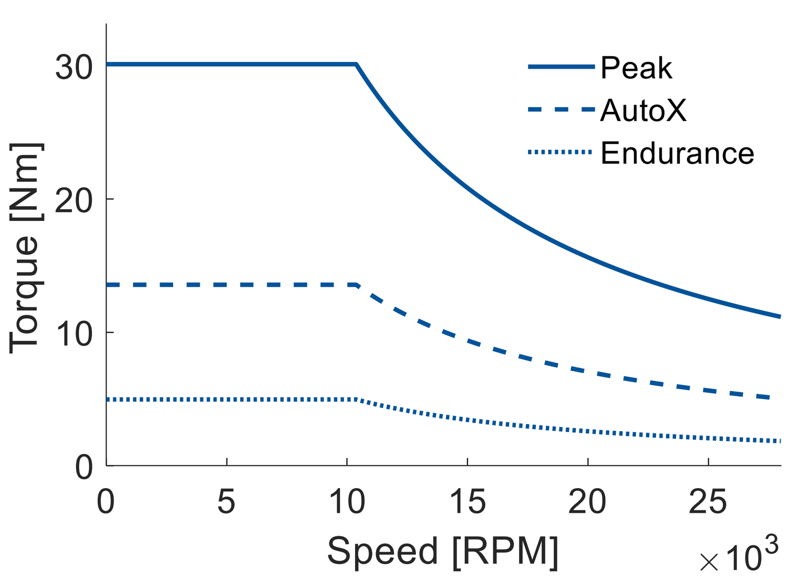

Figure 2: Motor torque-speed curves for peak and nominal AutoX and Endurance conditions (gear ratio 11,36)

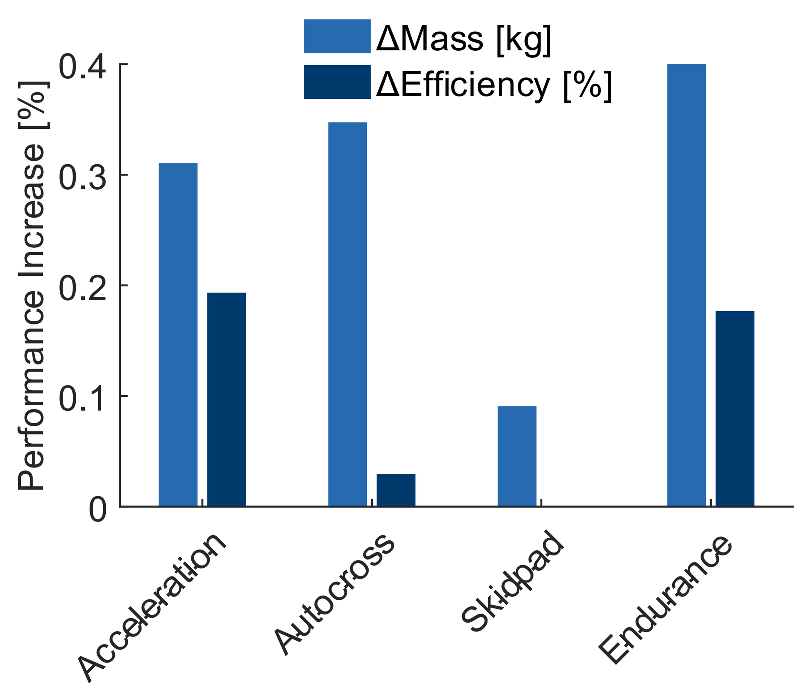

Figure 3: Sensitivity of performance by 1 kg motor mass reduction or 1% efficiency gain

2 Design of experiments

OptiSLang generates motor candidate samples from the design space, which are evaluated in Motor-CAD using a Python interface. Each design is processed through a **fully automated simulation workflow** (Fig. 4).

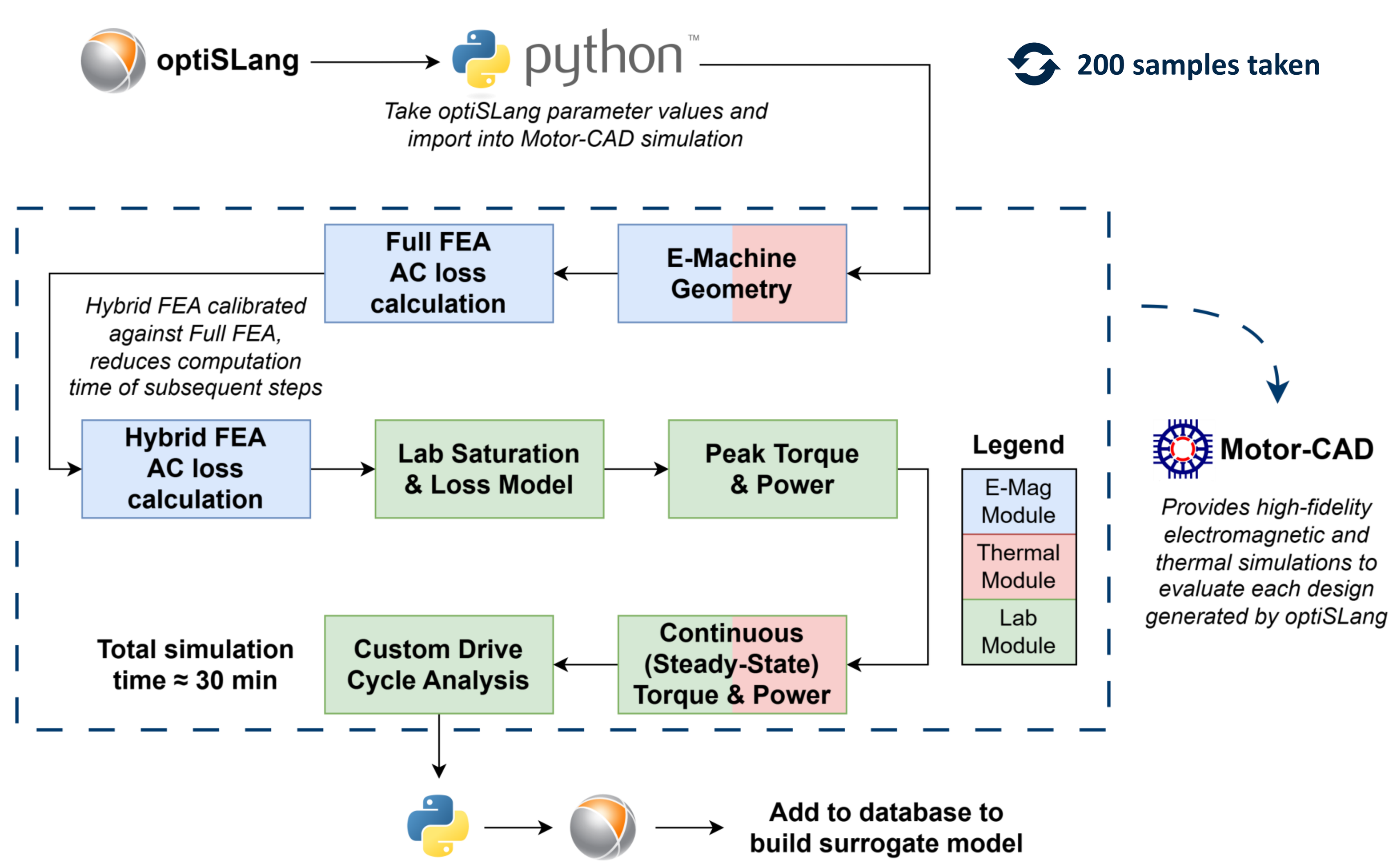

Figure 4: Automated simulation workflow for evaluating design samples and generating data for the surrogate model

3 Multi-objective optimization

The surrogate model, or metamodel, approximates simulation outputs based on 200 samples from the Design of experiments, enabling **efficient exploration of the design space.** This approach allows rapid evaluation of **10.000 motor designs** and reduces computation time by over 100 days. The Coefficient of Prognosis (COP) matrix (Fig. 5) quantifies the influence of each design parameter on performance objectives and is used to guide the optimization process.

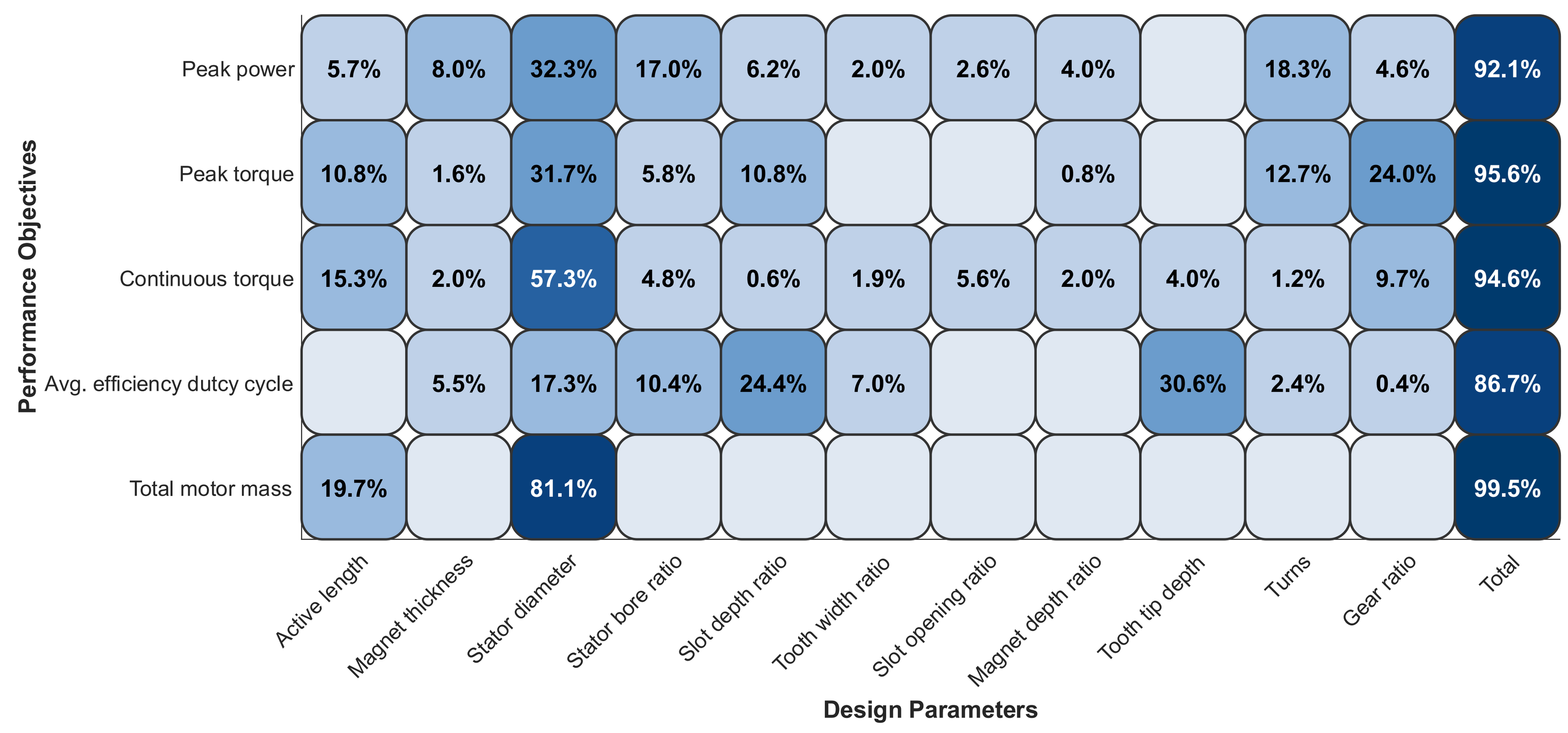

Figure 5: Coefficient of Prognosis matrix quantifying parameter influence on key performance objectives.

An evolutionary algorithm was used to identify optimal designs within the design space through the surrogate model. The resulting **Pareto front** (Fig. 6) highlights the best-performing feasible designs, with the selected concept achieving the desired balance between weight reduction and efficiency gain.

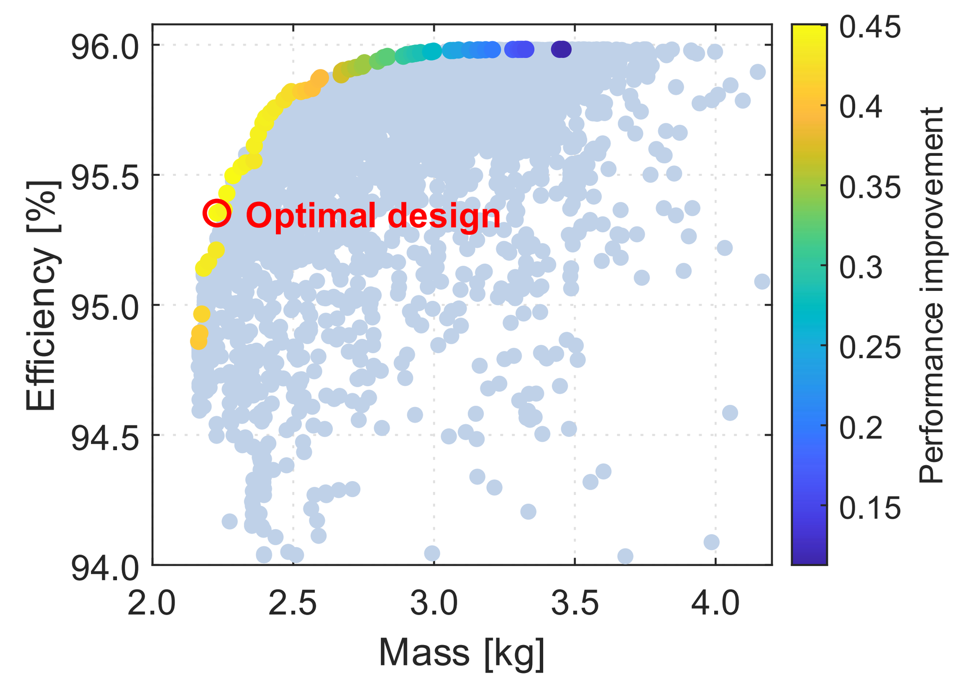

Figure 6: Pareto front showing trade-offs between motor mass and efficiency. The selected design maximizes the weighted performance index based on competition scoring sensitivity.

4 Results

The results of the optimal design are summarized in Table 1.

Table 1: Characteristics of the optimal design compared to the current setup

	New	comparison to old	Unit
Gear ratio	17,94	+ 6,58	/
Total peak torque	402	+ 71	Nm
Peak power	32,8	- 2,2	kW
Total continuous torque	177	+ 51	Nm
Mass (excl. housing)	1,8	- 1,0	kg
Nominal efficiency	96,8	+ 0,6	%
Power density	**17,8**	**+ 5,3**	**kW/kg**
Performance increase	**+ 0,4**		**%**

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