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OPTIMIZED MOTOR DESIGN INTEGRATING ELECTROMAGNETIC AND STRESS SIMULATION

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Abstract

In this paper, performance driven design of electric vehicle motors is presented using integrated multi-disciplinary optimization for electromagnetic and stress performance requirements. The objective is to maximize the electric motor power and torque while reducing the motor mass and electromagnetic losses. For an efficient development process with reduced time, the design must receive synchronized feedback from all simulation domains. A typical workflow of such a design process, followed by an approach to democratize these complex simulations with ease is presented to show the benefits of this technology.

Keywords: electric vehicle, electric motor, electromagnetics, strength, stress, optimization, process templates, democratization, automation, configured simulations

1. Introduction

The electric motor was invented more than two centuries ago but is only recently gaining attention in the automotive industry to power passenger cars. Environmental awareness, depleting natural resources and the development of new technologies are driving the global electric vehicle market. [1] [2] Government incentives such as subsidies and tax exemptions are expected to increase consumer adoption but the cost of the electric vehicles today prohibits them from becoming mainstream. The time to recharge electric vehicles, limited availability of charging infrastructure, and also limited driving range and speed prevent adoption. [2]

Toyota is a major player in the electric vehicle market who has invested heavily in research and development of electric motors. [1] Honda is also focussed on fuel cell hydrogen and battery powered vehicles as an alternative fuel, both of which power electric motors. They have announced a joint venture with Hitachi to produce electric vehicle motors. [3] The fact that major players are working on development of electric motors in house rather than depending on suppliers means there is much room for improvement in the existing technology. Manufacturers are working on reducing the cost of electric vehicle motors in order to make electric vehicles affordable. Lighter materials, smaller components, alternatives for rare-earth magnets and holistically optimized performance characteristics are areas for motor design improvement. [4] Additionally, a high power-to-weight ratio is desirable in EVs to compete with gas powered engines. This constraint complicates the design further and accommodations are necessary to ensure high torque along with high power as smaller machines produce less torque.

An Electric motor is fairly simple in geometry complexity and has fewer components as compared to internal combustion engines. It contains an iron stator, which may act as a housing for the motor as it is stationary. The rotor, situated within the stator, interacts magnetically with the stator to convert electrical energy into mechanical energy. Current state of the art electric cars use alternating current motors, where the current is supplied by an inverter to coils running along the length of the stator. A dynamic, rotating magnetic field is created within the stator. The cyclically reversing current causes the magnets in the rotor to repel the stator periodically that causes the rotor to spin. [5] Despite the geometry simplicity, the physics involved can be highly complex involving multi-domain requirements of thermal, mechanical, electromagnetic, vibration, durability and lubrication analyses. Improving the design for one requirement can easily affect/worsen the others. For example, reducing the size of the motor to improve the power-to-weight ratio reduces the torque produced for a given speed. Increasing the size improves the torque but also increase the torque ripple, which is undesirable. Therefore, for the same power the rotational speed of the rotor must be higher. Higher speeds require gearboxes of greater complexity, which incur relatively high energy losses. Alternatively, increased magnetic field can increase the torque. This can be achieved by higher current through the coils but this leads to resistive losses creating heat, which could damage the motor. Thermal management of the coils is then required to cool the coils in this method. [5] These and many other steps improve the performance of motors. However, finding the best design necessitates multi-disciplinary optimization. Trade-off and sensitivity studies of the different characteristics including weight, volume and cost helps arrive at the optimum design in a systematic manner.

Democratizing this scenario to design engineers would help to guide product design and boost innovation early in the design cycle. This helps to detect potential design flaws early on in the design process when the cost to make impactful changes is still low. However, deploying sophisticated workflows of this kind is a challenge. The optimization has multiple physics domains and several physical quantities. Traditional automation of the workflow can be cost inefficient because it usually requires programming and additional software licenses.

In this paper, first, a typical design process for multi-disciplinary electric vehicle motor design is presented along with an example problem. An end-to-end integrated optimization approach to maximize power and torque outputs for the example problem to arrive at the optimal design quickly is presented. Configured templates within web-based dashboards to democratize to non-experts and improve collaboration, KPI oriented fast and effective decision-making approach, and focused identification of the design problem are described to overcome the challenges of the electric vehicle motor design optimization workflow.

2. Electric Vehicle Motor Design Validation

Figure 2.1 shows a typical workflow for the development cycle of an electric motor using multiple standalone tools for CAD and simulation. The conceptual design of the motor is developed based on product requirements using a CAD tool. The design then needs validation by simulation experts for multi-physics performance requirements in order to verify the outcomes, only this is a multi-step process. The analyst identifies issues for a particular domain, in this case electromagnetics first, before committing to the design, and if need be, re-prioritizes it for further work. The design is then verified for the next physics domain, such as structural strength, and again the geometry requires updates to meet the requirements. The updates to the geometry from the structural simulation could directly affect the outcomes of the electromagnetic simulation. Hence, the updated design must be validated against the electromagnetic performance requirements again. With the addition of more simulation validation for other domains such as thermal management, noise and vibration, etc. the development time is greatly increased. Additionally, this is only one iteration of the design validation for a given design proposal. This cycle repeats until the final design passes review successfully.

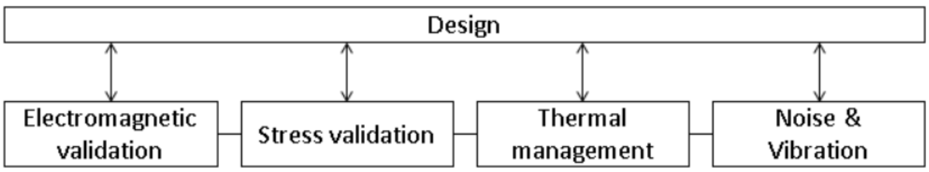


Figure 2.1: A typical product development cycle using multiple standalone tools

This development approach is a serial and manual process. Figure 2.2 shows a serial design Process. This approach has value as eventually all the characteristics meet design and performance requirements. However, the main challenge is the cumulative computing time from the different domains. It usually means employing multiple software tools for the different physics domains, data transfer between each of the tools, which can cause delays, and higher cost to maintain and integrate the tools and manage data loss. Furthermore, it is difficult to quantitatively grasp the trade-off relationship of the different characteristics in this manner and the design might not be first time right. Any major changes late in the design cycle can be cost prohibitive. There is also limited traceability of the decision process owing to unsynchronized feedback from multiple simulation departments. In large OEMs, such a process can take up to twelve months for design validation alone.

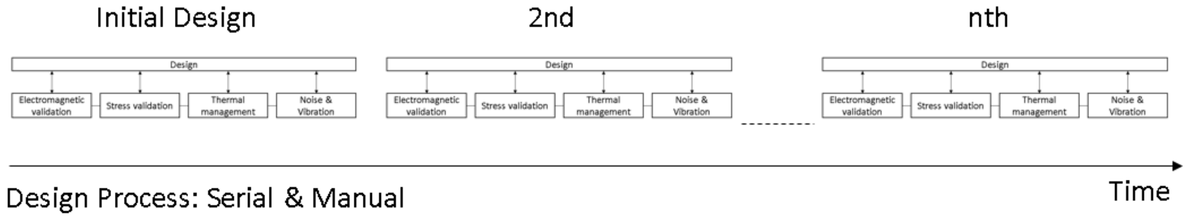


Figure 2.2: Serial and Manual Design Process over multiple design cycles

For an efficient development process to reduce the overall time, the design must be developed with integrated multi-physics analysis to receive synchronized feedback from all the simulations. Figure 2.3 shows an integrated design process that effectively connects all the stakeholders of the design process. This means upfront investment in time to integrate the tools to perform multi-disciplinary analyses, but once set up, optimization performed through design exploration early on in the design cycle on such integrated simulations can further shorten development time and allow for easy and low cost updates.

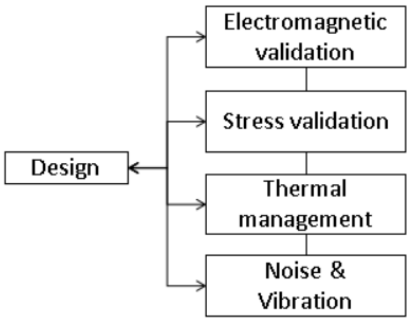


Figure 2.3: A typical product development cycle integrating multiple tools

Figure 2.4 shows an integrated product development cycle. This approach promises a design that is first time right. Furthermore, the data generated from design exploration facilitates trade off relationship and sensitivity studies, and creates a database of prototypes for future designs.

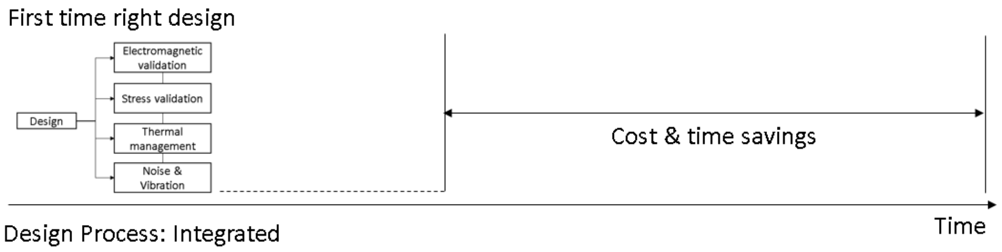


Figure 2.4: An Integrated product development cycle integrating multiple tools

3. Electric Vehicle Motor Design for Electromagnetics and Stress

Figure 3.1 shows an example of electric motor design validated for stress analysis simulations set up in the **3D**EXPERIENCE platform. The objective of the structural simulation is to maximize the strength of the magnets in the rotor when subject to high rotational speeds and optimize the weight and size of the rotor components to avoid excessive reinforcement while providing a structurally safe design. It includes a static analysis and all components are modelled as solid deformable bodies. The rotor and the shaft are modelled with interference fit to simulate the press fit between the two. The rotor core and resin, and resin and magnets are connected via tie connectors. Cyclic symmetry is applied to the section to represent the full rotor. The fixed displacement on the axial centre of the motor is distributed to the shaft via a mechanical coupling. . The pertinent built-in knowledge and parameters are captured for re-use in updated designs. All of the tools needed for the entire set up from design to simulation are integrated with associativity and traceability. Therefore, data loss is prevented during data transfer between design and simulation. Additional native simulation models set up over the same geometric data.

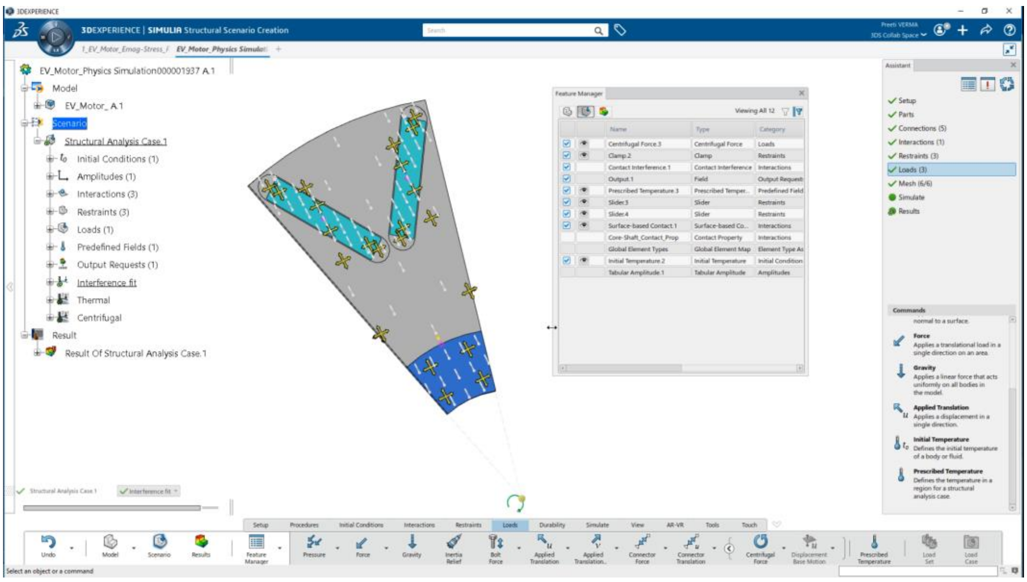


Figure 3.1: Stress Analysis of electric motor section for interference, thermal and centrifugal loading

Electromagnetic simulation of the electric drive shares the model geometry with the stress analysis. A sinusoidal current is applied to the windings of the stator, producing a rotating magnetic field. The amplitude of this current is an input parameter of the model. Permanent magnets with a temperature dependent remanence flux density are placed into the rotor. The time-domain magnetoquasistatic simulation is run in the 2D domain in order to decrease the solution time.

The simulation delivers key performance indicators such as:

- Average and maximum torque,
- Motor power,
- Induced voltage,
- Flux linkages,
- Eddy current and iron losses

These values are later considered by the external optimization loop changing the model geometry in order to improve the motor performance.

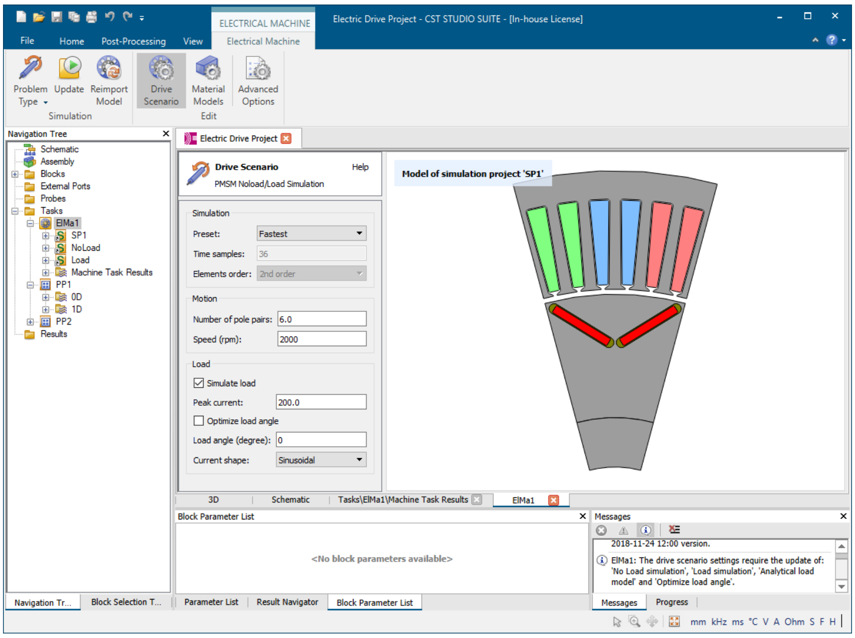


Figure 3.2. Electromagnetic analysis of electric motor in CST Studio Suite

4. Integrated Electric Vehicle Motor Design

Simulation process integration is needed when many software tools are used in a multi-domain system design. Control systems and structural analysis for design optimization are completed in separate tool chains. The end goal of design optimization can be reached by defining cost functions and the associated design parameters, which can be changed to fit the design within the cost function(s). This is Process Integration and Design Optimization (PIDO). Within a PIDO framework, rudimentary simulation workflows can be used to deploy complex workflows to non-expert analysts to validate several design variants with a single model. Simulation processes are used to integrate all of the tools used in a product's development cycle to create reusable and deployable processes. Figure 4.1 shows a simulation process utilizing design of experiments (DOE) over select design parameters in a PIDO manner. A design space is created using DOE or some such optimization algorithm to better understand the product performance with the help of sensitivity studies on the design points. Product engineers are then able to guide their design using approximations created using the DOE design points.

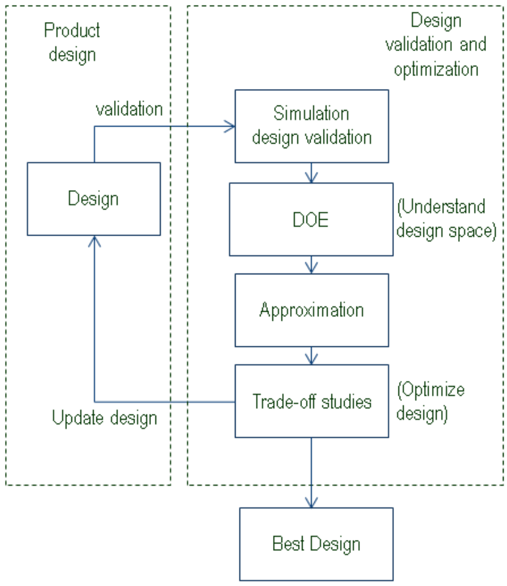


Figure 4.1: Simulation process using a DOE

A PIDO simulation process can be easily set up over the physics models (Figure 4.2). The native structural and electromagnetic simulations can be directly used in the integrated simulation process. In order to optimize the shape, critical geometric parameters are used as inputs for an optimization loop to predict the motor performance KPIs for a number of design points using adaptive DOE algorithm. Adaptive DOE optimization is a space-filling DOE technique. The technique optimizes the position of points in the design space by maximizing the distance from any other point. This strategy ensures that no two points are too close to each other. The objective is to evaluate the Pareto optimality to maximize the rotor torque and power and minimize the rotor mass, magnet stress and electromagnetic losses. The design space generated can also be used to further explore the data and uncover design patterns using integrated data analytics technology. It is found that by employing simulation processes that integrate native simulation models with the geometry data to provide fast turnaround of results reduces the development duration to a quarter of the time as compared performing the same simulations in a serial process as shown in Figure 2.2.

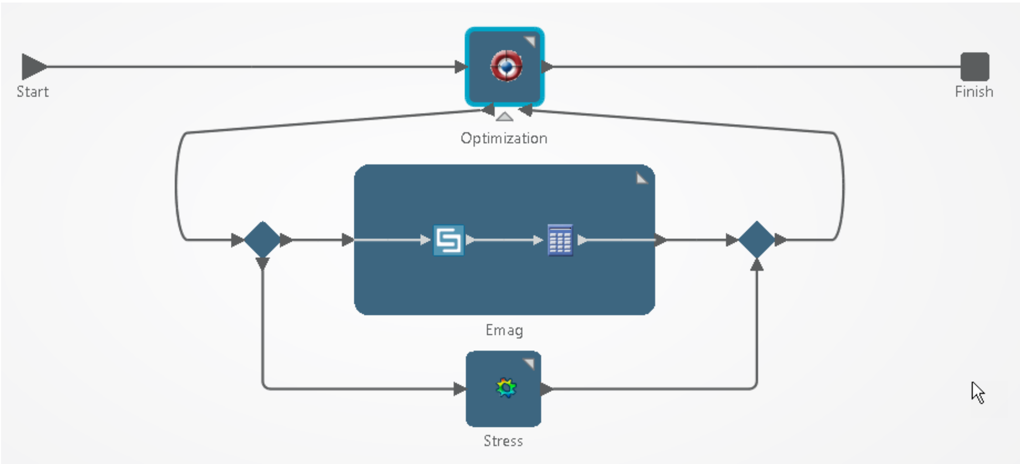


Figure 4.2: Simulation process for multi-disciplinary optimization

Job distribution can greatly speed up the computing time by scaling the problem size and solving large problems, in this case, many jobs at the same time. Each job is one complete run of the optimization loop and consists of many tasks within it such as stress analysis and electromagnetic analysis. A typical production scenario requires 2000-5000 jobs to arrive at the solution. If each job takes 30 minutes to run, the total time to run the optimization problem can be 27-69.4 day or, 1-2 months. Distributing 10 jobs in parallel scales the problem by 10 times, thus reducing the computation time to 4-10 days for 2000-5000 jobs. Job distribution is achieved with the Compute Orchestration Technology in **3D**EXPERIENCE. With effective utilization of compute resources and load balancing, the development cycle benefits in terms of the overall duration to complete the cycle.

This complex simulation process, once captured, can be deployed to design engineers as a template. A web-based app or widget has been developed that allows product engineers to change the input design/geometry parameters to assess critical simulation outcomes. The interface exposes exactly what the users need to see, i.e., simulation model and input parameters. The application allows creating the template using predefined drag and dropping fields with integrated knowledge and parameters extracted from a simulation process like one in Figure 4.2. The template allows incorporating straightforward pass/fail criteria to provide high valued feedback to design engineers. Figure 4.3 shows a snapshot of the user interface for the process created in figure 4.2. As the application is web-based, all users can test their product's behaviour without recreating, editing, or even opening the simulation model. All the users involved in the design process are able to leverage their organizations' library of deployed simulations processes through the web based app. A scenario like this can take a few weeks to set up with traditional configuration methods like VB scripting and CAA. Whereas it only takes 20 minutes to create these configured parametric templates for the entire process with associativity and traceability.

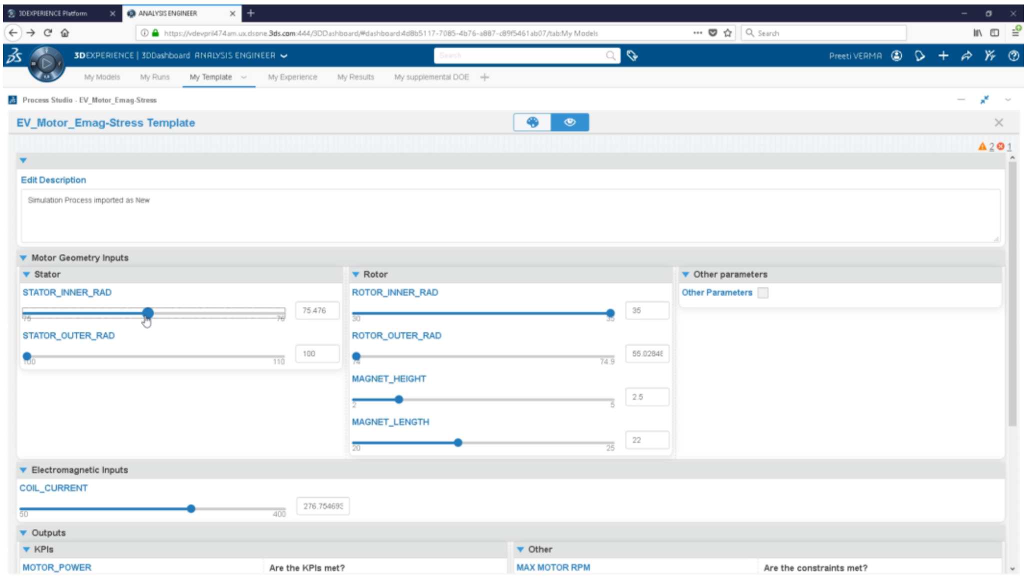


Figure 4.3: A multi-disciplinary optimization process template

5. Large Data Analytics

Analysts comb through a large number of design points generated by DOE or optimization to find the optimal design parameters. Various techniques are implemented to help decision-making and find optimized designs in terms of visualizing, post-processing and analysing large datasets. Complex relations between data can be analysed, including both test and simulation data. The design points are ranked based on objective functions making it easy to investigate the best-to-worst designs. Approximations generated from the large data set generated by the optimization, allow predicting the behaviour of the system. The optimal design variables can be transferred into the geometry using embedded design parameterization and knowledgeware. Figure 5.1 shows a snapshot of sensitivity and trade-off studies for select design points. For example, what is the optimal motor geometry parameter to achieve high motor torque and yet low torque ripple? Although the optimization provides the best design for the given constraints, the integrated data analytics capability allows understanding the patterns in the data generated, and reusing it for future designs.

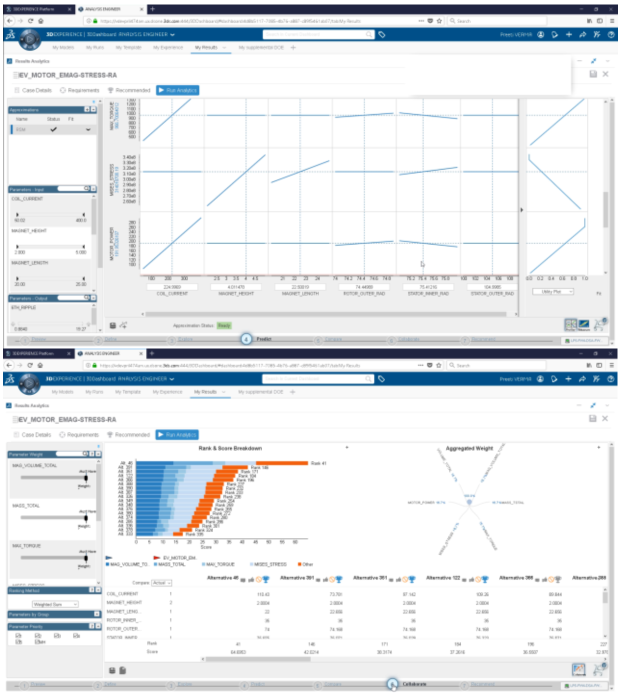
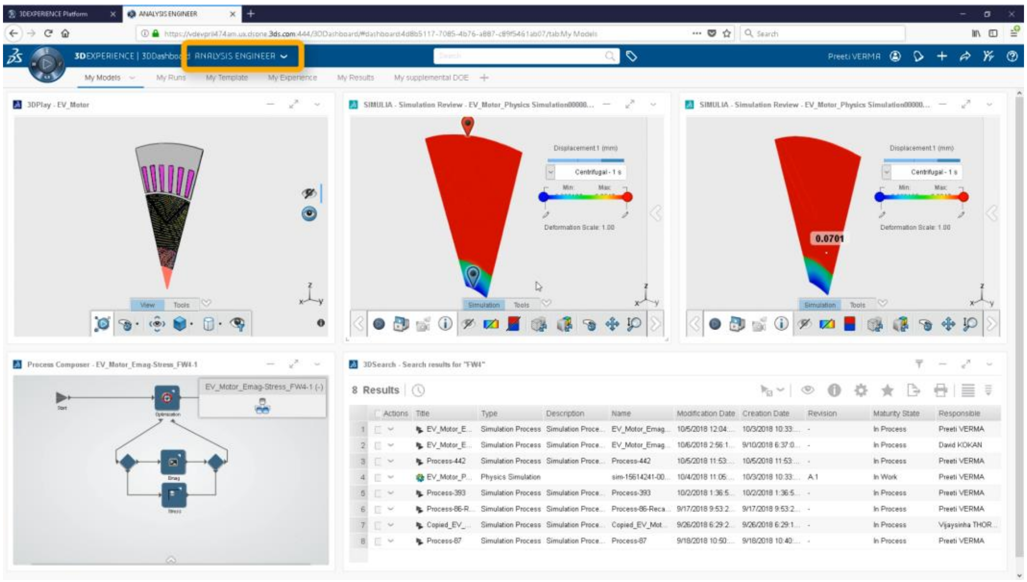


Figure 5.1: Trade-off studies using an optimization design space

6. Dashboarding

Dashboards combine multiple views of data to get richer insights into the key performance indicators relevant to a particular objective or business problem. It is displayed on a webpage, which is linked to a database that contains all the relevant information related to the engineering problem, i.e. the design, simulation and manufacturing data. Even the simulation process and process templates described in Section 4 may be created and used within the interface. Furthermore, essential knowhow such as status of simulation jobs running and status and health of resources used to run the simulations may be monitored in the same interface. Dashboards allow for focussed engineering of the design problem at hand facilitating fast and effective decision-making. Since it linked to a central database, the data is most up to date at any given time with a single source of truth. Dashboards improve collaboration between all the stakeholders involved in a project by allowing sharing information, data and reports easily and quickly with anyone with access to the dashboard. All data may be viewed, operated on and managed using widgets, which are interoperable allowing seamless usability for all stages of the digital thread from upstream thinking, design and manufacturing. Figure 6.1 shows an example dashboard for an electric drive motor design project for an expert analyst working on the project.



7. Summary

The electric vehicle motor design optimization problem to find the best design for electromagnetic and stress requirements provides an example that demonstrates tools that can be used to construct seamless multi-disciplinary integrated workflows for product engineers. The scenario may be scaled to include performance indexes from more physics domains such as thermal management, noise and vibration, multi-body dynamics etc. Simulation processes set up over native simulation models can be deployed to all the stakeholders in the design process reducing the product development time to a fourth of that with a serial development process. Additionally, associative advanced data analytics can be performed on the design space generated using simulation processes empowering product engineers to make better decisions with approximations, trade-off and sensitivity studies. Dashboarding capability increases product engineers' ability to collaborate, take action on most up to date data, and provides a focussed workspace for tackling engineering problems.

8. References

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