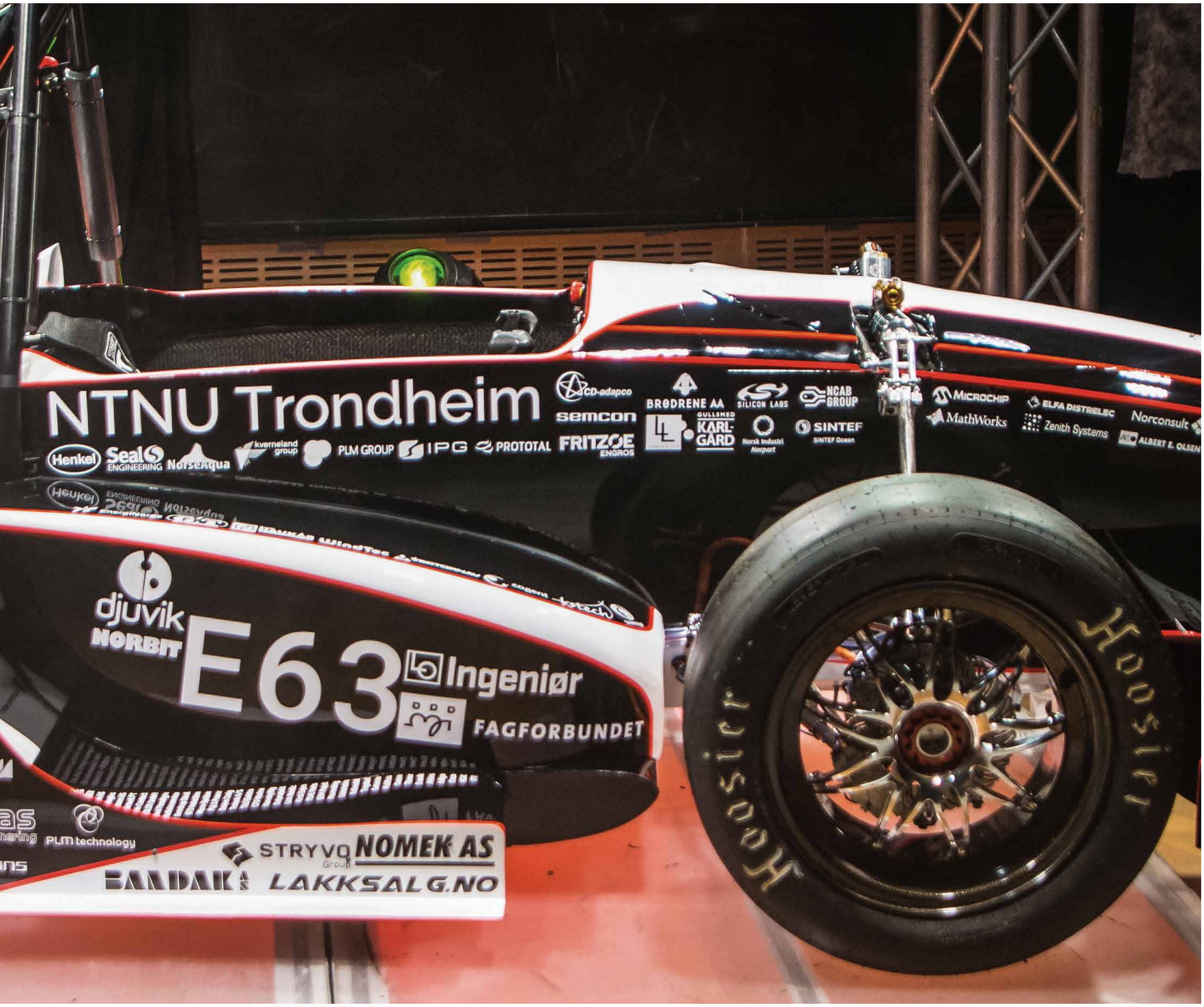
# NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

ACADEMICS



**Challenge:**
University students participating the NTNU Revolve team, a contestant in the international Formula Student racing competition, needed a way to design strong, lightweight, and cost-effective vehicle components.

**Solution:**
Using Dassault Systèmes' SIMULIA portfolio, including Abaqus FEA, Tosca topology optimization and Isight automation tools, students were able to develop highly competitive but safe component designs.

**Benefit:**
Aside from the tremendous learning experience that came with the project and the use of Dassault Systèmes products, the team is confident they've put their best racing foot forward, and eagerly anticipate this year's event.

What better way to learn the principles of mechanical engineering than to actually design and build something useful? It might be the next-generation prosthetic hand, a revolutionary solar panel, or...a race car? How about a Formula One-style, four-wheel-drive electric race car, made of carbon fiber and 3D-printed parts and able to accelerate from 0-60 miles per hour (100 km/h) in 2.1 seconds?

And while watching students zoom around a track in a homemade vehicle might not be what their parents had in mind for academic achievement, for those in the Norwegian University of Science and Technology's "Revolve NTNU" project, it's a once in a lifetime opportunity, made possible in part by software from Dassault Systèmes SIMULIA.

## A VISION OF SPEED

Sometime during the 2010 spring semester at NTNU, a group of four engineering students met to discuss ways in which they could gain practical, hands-on knowledge. They soon discovered Formula Student, an annual international racing competition hosted by the United Kingdom's Institution of Mechanical Engineers (IMechE). The program is intended to foster learning and collaboration among university students from around the world who meet for the three-day opening event at the Silverstone Circuit in Northampton, followed by races in Germany and Spain later in the summer.

Formula Student isn't just about speed. Entrants are judged on six categories, ranging from endurance and fuel economy to vehicle presentation and cost effectiveness. For this they need components that are strong and light, readily manufacturable, and that don't cost an arm and a leg—just like in the real world. The four students knew the program would be the perfect tool for them and other students to learn the valuable skills required to advance their careers after graduation.

After working with staff members on a project management structure, securing support and some facilities from the University, and garnering sponsorships from various businesses, the team of students applied for and received permission to participate in Formula Student. Revolve NTNU was born. Their first car came two years later, a petrol engine, steel frame, carbon-fiber body vehicle named the KA Borealis. It placed 17th out of more than 100 contestants, a very respectable first effort. The team has since continued to improve its race car designs, culminating in last year's 190-horsepower all-electric Gnist, which took 6th in acceleration and 5th in handling during the 2016 competition. The race car also received recognition from Jaguar Land Rover for most innovative propulsion system, and best-in-class for high-voltage powertrains from Mercedes-Benz.

## LEND ME A HAND

The Revolve team's sponsor list is extensive, and includes Fortune 150 technology companies, automotive manufacturers, product development and engineering firms, and steel, electronics, and tooling suppliers, many based in Scandinavia. And because the team's primary mission is to build the lightest, strongest, and most cost-effective vehicle possible, Revolve NTNU now takes full advantage of the design and engineering tools provided to them by Dassault Systèmes.

The team is currently hard at work on finishing their latest car. The as-yet-unnamed successor to the Gnist, it's on track to compete in the 2017 Formula Student event. A single-seat, battery powered vehicle with a monocoque composite chassis, it will contain parts made with additive manufacturing. It will utilize torque vectoring technology, and its final performance will be analyzed with Revolve NTNU-developed software. It will use four hub-mounted AMK electric motors to propel it down the track, and four titanium uprights to keep it running true.

In addition to this advanced technology, the Revolve team of 60 students and faculty has a few more tricks up its sleeve for this year's entry.

Team captain Rebecca Sandstø is one of these automotive magicians. She's in her second year of a mechanical engineering (ME) degree path and is enjoying her first year of race car building. Aside from managing various Revolve NTNU board activities, she says one of her main jobs is finding and working with sponsors to secure support with funding, manufacturing services, engineering advice and software tools. It's a lot of work, she finds, but there is a silver lining: "This is our second year that we actually get a quarter of a semester in academic credit for what we're doing," she says. "We spend a lot more time than that, of course, but it's so much fun, it's definitely worth it."

> "SIMULIA tools...enabled us to think beyond the usual."
>
> —Jørgen Eliassen, NTNU

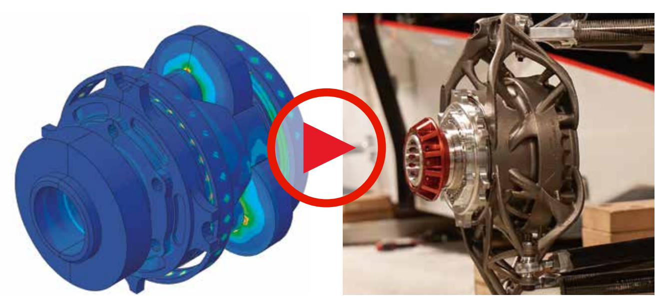
Interestingly enough, the current SIMULIA connection came about through social media, when team member Jørgen Eliassen reached out via LinkedIn for help with improving Revolve's software arsenal. "While the NTNU University Engineering Department has had some licenses for many years, this is the first year we've actually sponsored the team with the complete SIMULIA portfolio," says Clint Davies Taylor, SIMULIA U.K.

Revolve's software suite now includes Abaqus Unified FEA for engineering simulation of dynamic events, such as crash and impact analysis, vehicle loading, and visualization of material behavior, together with structural topology optimization by Tosca and Isight automation tools, along with fe-safe for fatigue and durability assessment. All helped the team address a number of design challenges, among which were developing three components critical to race car performance.

## GEARING UP (PLANETARY GEARBOX)

Team member Jacob Hayes Vigerust is a third year ME student responsible for compound planetary gearbox design. "By equipping each wheel with its own motor, you're able to control the vehicle much more efficiently," he says. "But in order to do that the wheels also require their own gearbox, to transmit power from the individual motors. In our design we decided to mount them inside of the upright (the component that carries the wheel hub and attaches to the vehicle's upper and lower control arms) to increase efficiency, reduce weight and save space, which means the gearbox must be extremely small."

With this small volume comes a big need. Because of the tremendous forces running through the gearbox, the team had to be certain the assembly would not only be strong enough, but that there wouldn't be any misalignment between the many components within it. Also, the risk of gear deformation was of particular concern, considering the application of torque involved during the assembly process, and afterwards when the rubber hit the road. Vigerust turned to Abaqus.



Stresses in gearbox assembly (left) where effect of bearing model, preload and loads are visualized. Gearbox assembled inside the upright (right).

"To achieve the desired results we wanted to make as few assumptions as possible," he says. "That meant we had to assemble the entire gearbox virtually within Abaqus, giving us more than 18 parts and 72 contact pairs (or surface). The simulation was made even more complex by our use of nonlinear bearings. In order to mimic the behavior of the individual ball bearings they were modeled using virtual springs, applying non-linear stiffness values provided by our bearing manufacturer. Once that was done, we pre-tensioned the bolts, bearings and wheel-nut within Abaqus and began to apply several types of multi-dimensional torque and wheel-loading scenarios. Abaqus made it very easy to calculate optimal gear geometry based on deformation and verify there was no misalignment, and that the gearbox assembly could meet our power requirements."

## SPINNING 'ROUND (WHEEL DESIGN)

Fellow team member Christer Oldeide agrees on the importance of simulation and force analysis, but says topology optimization with Tosca was equally vital to his own work on wheel design. A graduate ME student in his third year of Revolve, Oldeide says the wheels used on this year's car are composed of a CFRP (carbon-fiber reinforced plastic) shell inside of which sits an aluminum center. One look at the seemingly fragile, ultra-lightweight wheel assembly might have some of us saying, "No thanks, I'd rather walk." The outer shell itself weighs but 1.5 lbs. (700 grams) and the web-like inner piece little more than that. Yet, when assembled together with the tire the combination is able to withstand intense acceleration, lateral loads, and multi-directional forces.

Optimization of the wheel shell (left) required over 4,000 iterations in Abaqus and two days of compute time, the majority of which was automated via Isight. Complete rim mounted with CRFP shell and aluminum center (right).

"SIMULIA tools were responsible for most of the wheel design," says Oldeide. "They enabled us to think beyond the usual. I started by throwing out what I knew about how the wheel should look. Instead, I entered the required boundary conditions into Abaqus—the wheel dimensions and target weight, along with its material properties from MATLAB—and then used evolution-based optimization to perform the analysis."

In the rim shell alone, Oldeide was faced with more than 1040 possible "layups" (fiber orientations). By using Isight he was able to automate the analysis process, performing 4,000 iterations over the course of a couple days. "After the first several thousand iterations, it was pretty clear which way the math was pointing," he says. "At this point, I can say with confidence we have the optimal design for the given boundary conditions."

Oldeide enjoyed similar results while designing the rim center. By combining Tosca topology optimization with Isight automation, he quickly discovered the ideal shape for this critical component. At first it wasn't very machinable. Yet by entering a few machining constraints into Tosca, Oldeide was able to drive the software to the correct conclusion. "It's an iterative process, but with Tosca, you can be sure that the final design is the right one," he says. "At the end, we had a wheel that was stiff, light, and durable."

## PULLING IT ALL TOGETHER (THE UPRIGHT)

Of course, even the strongest wheel and most efficient gearbox are useless without an equally robust upright to support and contain them. This is the domain of Jørgen Eliassen, who is currently pursuing a master's degree in mechanical engineering and worked four years in the automotive industry before entering the university. "For me, the Revolve project was meant to be," he says.

Eliassen needed an upright that would be stiff enough to handle the complex loads encountered during racing, yet still light enough to win the race, and also able to accommodate the various interfaces to the braking system, the suspension, the wheels, gearboxes and electric motors. With all this in mind, he decided to steer down a relatively new manufacturing road: direct metal laser sintering, aka 3D printing or additive manufacturing (AM).

"After developing the initial upright design, I performed finite element analysis in Abaqus to validate my work," he says. "I had to do a few manual iterations along the way, adjusting the geometry around the upper suspension mounting holes, for example, and at the caliper contact points, as well as some re-tensioning of the bolts. I then re-validated the design in Abaqus. As expected, the overall stiffness of the model was really high. And because I was going to use 3D printing to produce the part, I was able to optimize the topology using Abaqus and Tosca, then take the design back into SolidWorks CAD for 3D printing setup, with very few concerns over production constraints."

Afterwards, Eliassen worked closely with a 3D-printing operator, using Abaqus again to optimize the support structures needed during the additive manufacturing process. The result: a reduction in build time from 44 hours to only 17, and a 30-percent reduction in waste material. Best of all, the Ti-6Al-4V titanium upright weighs just over one pound ( Front = 679grams, Rear = 545grams). Says Eliassen, "I think the capabilities SIMULIA offers in the context of 3D printing will be a huge benefit going forward."

Topology optimization of the front upright in Tosca (left) was performed prior to preparation for 3D printing. The 3D-printed, left-rear upright before support removal and post heat treatment and prior to finishing via machining (right). The final product weighs a little more than a pound (545grams).

## THE NEXT RACE

Each of the team members agrees that being a part of Revolve NTNU has been a wonderful learning experience, and all look forward to using SIMULIA and other Dassault Systèmes products after graduation. Still, it's been a lot of work. "For many of us it was a little hard in the beginning to grasp the size of it all," says team captain Sandstø. "You definitely have to do some reprioritization. But I also think you come to know what you're made of. That, and it's just super cool being a part of Revolve. It becomes your life."

Oldeide sums up the experience best. "This is my third year with Revolve NTNU, and every year I say it's going to be my last. With all the late nights, I think we drank so much coffee that our coffee sponsor couldn't afford to sponsor us anymore," he laughs. "But when you're at the competition and you see what you've done together with your teammates, and recognize that you've accomplished something that's never been done before, it's really a fantastic feeling. That's when you know you'll be doing it again next year."



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