From equations to insight: how finite element modelling is powering digital twins for SMEs

Digital twins—virtual models that mirror the behaviour of physical systems—can enable predictive maintenance, smarter design and lower costs. But delivering on that potential depends on one thing: accurate models of how complex structures behave in the real world. For SMEs, building those models is a challenging process.

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Backgound: A thermocouple wire to a robust gas turbine engine.

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Earlier in our series following the CP-Sens project through the lens of Vestas Aircoil, we explored the barriers to adoption of digital twin technology and how SMEs are beginning to prototype affordable digital twins. In this instalment, we turn to finite element modelling (FEM): the mathematical approach that underpins many twins by turning equations into insight. Within CP-Sens, FEM is helping partners bridge the gap between design and operation, creating models that not only represent equipment but also actively inform decisions on performance and maintenance.

Finite element modelling (FEM) explained

FEM is a way of representing complex structures as many small, connected elements. By analysing each piece and how they interact, engineers can predict the behaviour of the whole system. It's like breaking a structure into a 3D puzzle. Once assembled, that puzzle can be tested virtually to show how the object responds to heat, stress, vibration or other forces acting on it.

Giuseppe Abbiati, Head of Section for the Department of Civil and Architectural Engineering – Structural Engineering at Aarhus University, explains: "Finite element modelling is basically a mathematical method to model physical systems like mechanical systems and thermal systems. For example, marine engine coolers developed by Vestas Aircoil are essentially heat exchangers; devices that transfer thermal energy from one place to another. To design these systems, you need to model the thermomechanical response of a steel block with pipes. FEM is a combination of theory and numerical implementation that enables an engineer to create a virtual model of the system for design purposes. As engineers, FEM is our day-to-day calculator nowadays."

A clear example is the link between thermal and mechanical effects. Giuseppe continues: "The temperature causes the materials to expand. Expansion is restrained to some extent and therefore produces stresses. The thermal loading we apply to these devices also produces a mechanical response, and that has to be assessed and controlled in the design phase."

FEM is also increasingly integrated with geometric design tools: "Traditionally, FEM starts with a geometrical representation of the system. Tools that deal with geometrical modelling are becoming more tightly connected to the FEM pipeline, which introduces physics into the geometry."

Keeping the model alive in operation

In CP-Sens, FEM goes beyond design. The models stay active to help monitor and understand real-world performance. "What we are trying to do in CP-Sens is to link finite element models to the operation of the physical device. We want our FEM to keep being alive after the design has been concluded and provide information on the physical device that we cannot directly observe," explains Giuseppe.

"Based on a few sensors installed on a physical cooler, we can use the FEM to infer boundary conditions—for example, how tight the bolts are that connect it to an engine. The FEM can simulate measurements and produce additional information related to things we typically have a hard time measuring, like stiffnesses of connections, distributed temperature fields and strain fields over the entire geometry."

From Vestas Aircoil's perspective, this interplay between field measurements and virtual models is critical. Bilal Ali Qadri, R&D Vibration Engineer at Vestas Aircoil, explains: "Aarhus University develop the methods and models. We realise the hardware part—we go out and measure the physical system, which is modelled by the University. Giuseppe prepared the numerical model for us, mapping the data we capture from our physical cooler to the model of our cooler. That should provide us with more information on boundary conditions."

Even so, there have been challenges.

"In the first couple of analyses, we could see there was actually a significant deviation between the numerical model and the physical model—higher than the guidelines we normally set as design norms," continued Bilal.

"We try to see if we can take the data we've stored and prepared to extract information that tells us where to fine-tune the model."

As R&D Heat Exchanger Engineer at Vestas Aircoil, Lasse Uhd Christensen is particularly close to the practical realities of realising digital twin technology through the CP-Sens project. Even with experience, turning models into decision-ready tools has its demands. Lasse explains: "Before you understand what the software can do and then be able to model something that makes sense, it takes a lot of resources."

Barriers for SMEs: software costs and smart choices

For SMEs, software is one of the steepest hurdles to adopting digital twin technology. Commercial FEM packages are powerful but expensive, while open-source alternatives demand significant in-house research and expertise.

Giuseppe clarified the cost implications: "One of the main issues is the licensing cost of simulation software. As you develop a physical asset and associate it with a digital twin, the simulation models must run independently, hosted by another user who is not necessarily the vendor. The licensing costs can become prohibitive."

The project team is therefore assessing open-source alternatives and the communities behind them.

"There is a lot of simulation and data analysis software developed as open-source projects. These packages are extremely robust, well-documented and used by thousands of researchers and consultants. We're learning to screen the communities behind these projects to understand the risk profile of each choice. It's a lot of work—some projects are fragmented, some are inactive—but it's worth it," says Giuseppe.

For manufacturers, taking on that work alone would be unrealistic. Bilal confirms: "We don't have the capacity to do all of these things by ourselves as a company. It's good to have partners who are so strong in this area."

Lasse echoes: "It takes a lot of time to select and be sure that we have what we need. I don't think it would be realistic to have used anything other than commercial software without the CP-Sens project."

YAFEM: a lightweight sandbox for fast learning

Existing open-source FEM packages can be powerful, but they are often large and complex. So the Aarhus team developed its own minimal toolbox for the project.

"It's called YAFEM," says Giuseppe. "Short for 'Yet Another Finite Element Modelling Toolbox'. It's designed to be simple, neutral and easy to modify, even for people without strong programming skills."

Humorous name aside, the ambition behind YAFEM is serious: to keep the complexity low while providing a transparent 'sandbox' where preliminary models and real signals can be combined.

Giuseppe continues: "When you combine a finite element model with data, you really need to understand what's going on under the hood. If you start from a closed commercial solution, it might be difficult to understand the interaction between data and models. We try to have a small sandbox where we have access to the full inner workings. Then, when the digital twin is prototyped, you can swap a simple model developed with YAFEM with a more advanced model based on some other software."

In this way, YAFEM future-proofs the work of the SMEs in the project: offering a simple entry point for experimentation while leaving the door open to scale into more advanced packages. Just as importantly, it provides the CP-Sens partners with a common language and platform on which to test ideas before committing to more comprehensive tools.

Learning so far: stacks, languages and scale

Alongside physics, CP-Sens has surfaced lessons in software strategy.

Giuseppe reflects: "What I've learned from a technical point of view is that picking the correct programming language to develop the digital twin is a critical choice. We explored a few and ended up with Python. The selection of the technology stack (programming languages, services, databases) and how they communicate is crucial. This is knowledge I completely neglected four years ago. Now I see the point. It was a great opportunity to work on CP-Sens, as we learned a lot.

"A key aspect of this project is that we incorporate diverse approaches from various institutions and companies. We have a combination of tools and perspectives, and that is something very valuable."

Bilal seconded the sentiment: "At Vestas Aircoil, we don't use the same technology stack as Aarhus University, so bringing those together has been part of our learning."

Culture change: model-based thinking

As FEM becomes embedded in CP-Sens digital twins, it is prompting a cultural shift in how design and engineering are approached.

"Turning your product into a digital twin is also a change of culture. We have to transition from fragmented documentation and models to a more structured way of dealing with models. When models are supposed to run on a physical system, they have to be validated and verified," explains Giuseppe.

That shift points towards model-based systems engineering, an approach where design and documentation evolve together.

"If you change a parameter somewhere, your entire constellation of models and reports gets updated. Embracing this paradigm is necessary to sustain products with digital twins."

It is also a matter of trust and mindset, as Bilal explains: "To really benefit from digital twins, you have to accept that design becomes model based. That requires trust in the models and a shift in mindset."

Closing thoughts: skills, partnerships and legacy

The shift in mindset also extends to the education of future engineers.

As an educator as well as a researcher, Giuseppe was keen to emphasise: "It's not only about developing the models but also about training engineers who understand how to work with them. They need to know how to combine physics, data and software to make the models usable."

It's an observation that resonates with the industry partners, as Bilal explains: "We're looking for graduates who can work across disciplines, who are comfortable with both the modelling and the data side. That's the kind of skill set that projects like CP-Sens are helping to develop."

And for SMEs, the lesson is clear.

"It's not realistic to do this without a project like CP-Sens," concludes Lasse.

As CP-Sens moves forward, the project is not only advancing the modelling of complex equipment but also shaping the skills, tools and trust that SMEs need to make digital twins part of everyday engineering.

New to this series?

We've been following the CP-Sens project through the lens of Vestas Aircoil, one of the project partners representing the needs of SMEs. This aligns with the project's broader mission to equip SMEs with powerful tools that don't come with prohibitive costs.

In earlier articles, we introduced the project's aims, met the key partners, and looked at some of the technical and organisational challenges they were working to overcome. Catch up here:

- *Breaking barriers to digital twin adoption: CP-Sens paves the way for SMEs* doi: 10.54050/PRJ2021840.
- *From concept to reality: Vestas Aircoil's approach to realising a digital twin* doi: 10.54050/PRJ22436.
- *Securing digital twins: how CP-Sens is providing cybersecurity solutions for SMEs* doi: 10.54050/PRJ2222770.
- *Scaling smart: how CP-Sens is helping SMEs prototype affordable digital twins* doi: 10.54050/PRJ23225.
- *Raw data into real insights: algorithm development for digital twins* doi: 10.54050/PRJ2423793.

CP·SENS

CP-Sens – Cyber-Physical Sensing for Machinery and Structures

PROJECT SUMMARY

CP-Sens is working to make digital twin technology accessible to small and medium-sized enterprises (SMEs) in the mechanical and structural engineering sectors. The project is creating a user-friendly platform that combines sensors, simulation models and real-time data to create virtual replicas of physical systems. This technology allows SMEs to monitor, analyse and optimise their products and processes, leading to cost savings, faster innovation and improved efficiency.

PROJECT PARTNERS

Aarhus University
Hottinger Brüel & Kjær (HBK)
Vestas Aircoil
Vienna Consulting Engineers (VCE)
FORCE Technology

PROJECT LEAD PROFILE

CP-Sens is led by HBK and supported by researchers at Aarhus University, specifically in the: Department of Electrical and Computer Engineering; Department of Civil and Architectural Engineering; and Department of Mechanical and Production Engineering.

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