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Strengthening Simulation's Business Impact: New Strategies in Aircraft Engines

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Executive Summary

Aircraft engine manufacturers are among the world's most mature and sophisticated users of digital simulation and analysis – bringing the technology to bear earlier and more pervasively in product development than most any other industry. Nevertheless, these companies still experience program-gating constraints on getting the value they need from these technologies and the work processes that employ them. What are they doing about it? To find out, we interviewed experts at industry leaders around the world. We investigated business drivers for investing in simulation, current state of industry practice, chief constraints on maximizing simulation's value, and new strategies for overcoming these constraints.

This report summarizes our findings:

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This report offers a practical, action-oriented analysis of new directions and emerging best practices for getting more value than ever before from digital simulation and analysis. Program managers, discipline leads and practitioners will find first-hand advice and lessons of experience for planning new and ongoing investments in simulation technology, and for managing these tools to exploit their organizations' simulation competencies to the fullest.

Digital Simulation and Analysis Investments: Business Drivers

Aircraft engine manufacturers are among the industrial world's most advanced and sophisticated users of digital simulation and analysis. Why? What drives investment in these tools and in the methods and work processes around them?

One reason is that products of today's complexity, performance and efficiency simply can't be developed in a timely way without simulation:

> *"What we're striving for is more robust designs. And the only way to achieve that is by using simulation – you cannot examine all the possible variations using physical test alone." – Alexander Karl, Robust Design, Rolls-Royce*

Further, developing a new aircraft propulsion system is a massively complex undertaking that can cost hundreds of millions of dollars, and historically took as long as a decade. By helping reduce development costs and cycle time, simulation and analysis confers competitive advantage out of all proportion to its direct cost.

Commercial aviation business crisis Simulation and analysis technology holds the key to competitive advantage in other ways as well. With the commercial air travel industry under intense cost pressure even as fuel prices soar, every increment of improved engine efficiency translates into significant savings for airlines. Major aircraft manufacturers also face growing competition from regional jet makers now developing larger and more capable planes. As a result, these companies face unprecedented challenges to deliver products that are more efficient, better performing, and with a smaller carbon footprint – all while keeping development and production costs under control:

> *"…through the use of analysis tools, we have improved our products dramatically. How can we get 1% better in fuel burn? The advanced tools are showing us the way…" – Aircraft engine manufacturer A*

Another critical driver of simulation and analysis usage is the nature of aircraft engine sales activity:

> *"...marketing [uses] simulations to decide what they can or can't quote as a product…" – Aircraft engine manufacturer A*

Global project execution In aircraft engine design, project execution has increasingly gone global. This has spurred the search for ways to virtualize the various product development and validation workflows that, for most of the industry's history, were carried out by physically co-located teams:

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"We are working to define how we represent the data interfaces between component simulations, so we can mix and match our component models with our global partners and customers." – Ron Plybon, Manager, Propulsion Simulation Technology, GE Aviation

Flight certification A perennial driver of technology investments in the aircraft engine industry is the requirement to certify products for flightworthiness. While physical test remains the predominant method, analysis results are increasingly provided and accepted as part of the engine certification process – even as practitioners see room for further advancement here:

"…current [CAE data management] processes can meet certification requirements, but improvements could benefit productivity and improve the development and certification process…" – Plybon, GE Aviation

In-service support Finally, both commercial and defense aircraft manufacturers are among the many industrial firms looking to in-service support and sustainment of their products as increasingly vital revenue and profit centers. On average, after-sales services and parts typically yield 25% of revenues and nearly 50% of profits for industrial companies, according to a study by Accenture Ltd. recently cited in *The Wall Street Journal*.[1] In addition to aiding urgent diagnosis of unanticipated performance problems as well as routine MRO (maintenance, repair and overhaul), ownership of simulation and analysis results can also help manufacturers fend off competition from third-party after-market service providers:

"[Simulation's value is] cradle to grave – not only the design and analysis support effort during the design and certification phase; simulation is also critical to doing the best you can in service and long-term support. That will be critical to the engine business in future – providing cradle-to-grave support." – Plybon, GE Aviation

Simulation: Current State of Industry Practice in Aircraft Engines

Against this background, we interviewed experts at industry leaders around the world to find out what best practices they have developed for using simulation and analysis to achieve the business objectives that they and all manufacturers face – to boost product quality, performance, efficiency and innovation, shorten program schedules, improve engineering productivity, and reduce development costs.

Pervasive and early… What we found is that use of simulation and analysis is pervasive throughout the product development process. In contrast to many industries, aircraft engine manufacturers bring this technology to bear at the earliest stages of product development for whole-product performance characterization, then continue using it throughout product development and refinement into detail design.

"We are doing more detailed, higher-fidelity simulations earlier in the design process than ever before. Things that were done through pure empiricism can now be done with more physics-based simulations. Simulations are becoming more and more critical because we have to do the job right the first time and understand the limitations of the simulations over the design space." – Plybon, GE Aviation

Maximizing the technology's business impact involves far more than simply buying today's best point functionality and handing it off to the analyst or discipline lead. Instead,

[1] "GE's Focus on Services Faces Test," *The Wall Street Journal*, March 3, 2009.

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contemporary best practices focus on making more efficient use of existing resources – both software and engineering staff. No one we interviewed named software budgets as a constraint on product development's ability to contribute to corporate business objectives – all identified time and human resources as limiting factors. New demands on product performance, mission complexity, product efficiency, total cost of ownership (TCO), new product cycle time and product development costs are driving companies to wring more value and output from their engineering resources.

> *"Robustness and accuracy are the key drivers of simulation usage, and the key limitations. Simulations must cover the full range of scenarios we want to look at in the design process. In many cases we only have test data at a few operating conditions. We need the simulation to assess the current design and the implications of design changes at all the potential operating conditions over the flight envelope." – Plybon, GE Aviation*

…but working to achieve still more: integrated variable-fidelity system simulation, robust design Notwithstanding the aircraft engine industry's leadership position in early and pervasive use of simulation, current initiatives to increase its business impact focus on more closely tying together the analysis tools for various disciplines and of varying fidelities that are used across the different phases of product development – enabling a unified system simulation environment that fosters freer usage and movement between and among these tools, and at the same time eases the burden of tool upgrading and new-technology insertion:

> *"We have an across-the board need to do simulations on our engine systems. We can capture our legacy proprietary tools and methods in NPSS to make historical comparisons along with new tools and methods. We're trying to bring the best-in-class tools and methods into the system simulation environment." – Plybon, GE Aviation*

A related focus of current initiatives is to leverage the value of simulation point tools by extending simulation into more highly automated exploration of design spaces:

> *"[Why] robust design?… Why the pressure to explore more design variants than before? Because the marketplace has developed in such a way that new design in aircraft engines, automobiles and so much else is driven by the fine points of the different design variations possible. Twenty or thirty years ago, there was margin in the design envelope that you didn't have to do this. But today the push is to get closer and closer to the limits, and this is feasible only if you can do variation analysis [and thus robust design]." – Karl, Rolls-Royce*

Constraints on Maximizing Simulation's Value

What constrains aircraft engine manufacturers from achieving the goals laid out above? We found that constraints fall into two primary categories: (1) technology constraints and (2) organizational and work-process constraints:

> *"There are several big bottlenecks. One is the data: the CAD data is all stored in one set of databases, whereas simulation data management is only just now picking up. Lack of a mature tool for simulation data management is still a big bottleneck on broader use of simulation. If you want to start moving CAE data around under version control, we need more of SDM.*
>
> *"A second bottleneck is that the process integration tools…are only now [starting to be made deployable] on an enterprise-wide basis; at present they're typically used at the workgroup level.*

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> *"And a third bottleneck is that you need to organize your workgroup and your department and your organization to help all this happen. We can always find enough people to do a job – even if we don't always have them readily available, we can train the people to get a job done – but establishing the workflows is the first thing you have to do." – Karl, Rolls-Royce*

Technology constraints

CAD-CAE gaps A perennial constraint has been the technological gaps that exist between product definition geometry on one hand, and simulation models on the other – and the resulting penalties in time and, sometimes, accuracy exacted by the need to prepare geometric and functional models for input to analysis. Indeed, some believe the advent of CAE and CAD tools came at the same time as a breakdown in the traditional informal but close collaboration between designers and analysts:

> *"CAD and CAE technologies…are two different cultures that don't communicate well with each other – they basically communicate by encyclicals that are thrown over the wall to each other. All the steps are optimal within each of the two domains, but it adds up to a very suboptimal overall process." – Dr. Thomas J.R. Hughes, Computational and Applied Mathematics Chair III, Professor of Aerospace Engineering and Engineering Mechanics, and Director of the Institute for Computational Engineering and Sciences, The University of Texas at Austin*

Cross-discipline analysis gaps Similar barriers impede sharing of results between analysis tools in different disciplines:

> *"An old bottleneck is consistent modeling. Assumptions and methods have varied across disciplines and engine families over five, ten or twenty years – making meaningful comparisons of legacy simulations difficult. One goal in the development of NPSS[2] was to drive toward more modeling consistency while maintaining flexibility to capture alternate methods and assumptions. There is a tension between maintaining a consistent simulation approach, using the best-in-class tool at each phase of a project and being able to do realistic historical comparisons. If I don't use the same methods and assumptions I used ten years ago – never mind the same tools – meaningful comparisons to legacy simulations will be difficult. Overlaying these different assumptions on current tools and methods may suggest or even require that you take a different approach to a problem." – Plybon, GE Aviation*

Need for better simulation data/process management Another chief constraint is the need, seen by many as yet unmet, for robust, capable simulation-specific data management and process management tools:

> *"We've done a very good job of automating geometry data management, as well as change and configuration management. My focus now is simulation data management. The challenge is to ensure that design studies, and the models and simulations used in them, are kept coordinated. We've developed processes and methods to do that, but it's*

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[2] The Numerical Propulsion System Simulation (NPSS) is a full propulsion system simulation tool developed to help aerospace engineers predict and analyze aerothermodynamic behavior in commercial jet aircraft, military applications and space systems. NPSS is developed under a NASA/Industry Cooperative Effort agreement between NASA Glenn and industry and government partners. The NPSS team has included propulsion experts and software engineers from GE Aviation, Pratt & Whitney, Boeing, Honeywell, Rolls-Royce, Williams International, Teledyne Continental Motors, Arnold Engineering Development Center, Wright Patterson Air Force Base and the NASA Glenn Research Center.

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less efficient than we would like because today it's all done essentially manually. The consequences are lost productivity, missed opportunities for innovation, reduced quality, greater difficulty obtaining certification, and inefficient knowledge management." – Mark Miller, Senior Technologist, GE Aviation

Is the need really any greater now than in the past? If so, why?

"The challenge of simulation data management – are we doing enough to keep track of our models, simulations and studies? – is compounded by the fact that, if you look over the last 10 years, the cost of doing computing, doing the actual simulations, is coming way down. Consequently the number of simulations getting done is increasing, because engineers say it is not so expensive anymore. And the models are getting bigger. So the curves are going in different directions, and the space in between is the data management gap." – Miller, GE Aviation

A concrete driver is simulation data management's power to make simulation data more credible to certification authorities, which could ultimately help reduce the high cost of certification-mandated physical test:

"There is definitely a need for better long-term management of CAE data. The current processes can meet certification requirements, but improvements could benefit productivity and improve the development and certification process – supporting data-mining and the overall development process on current programs and providing more effective leverage and re-use on future programs." – Plybon, GE Aviation

What do practitioners see as the key challenges?

"In working to implement simulation data management, I see five significant risks to consider.

"First, can the engineers adopt simulation data management? They've built all these processes and their own tools to deal with the situation over the years, and [in implementing simulation data management], I would be asking them to work within a management system. So there is an adoption risk.

"Second, security. Within all the industries that we support, we have to deal with two aspects of security. One is export control – we're very much a global company, and stakeholders either do or don't have rights to see certain data depending on where they live, what country they're citizens of. And the second is intellectual property reasons: we want to control the IP that we have. So any system I come up with has to manage both of those security aspects.

"Third is legacy data migration. If your data is spread to the wind on engineering desktops all over the world, you have to figure out how to bring it back together in one place. A bigger problem than physically moving it to one place is that the sequence information – the handoffs – is lost. That's not coded anywhere. Folder structures have some metadata, but not enough. We have a lot to learn in this space from the social-media explosion going on now. Tweeting, blogging, putting up wikis – those are capturing all that metadata.

"Fourth is the data model. If you have very point-source-oriented solutions, the names of the folders you choose for your folder structures are likely to be very esoteric. If you want to roll out a solution across the enterprise, you have to find a way to standardize that – and one that doesn't upset everybody. Deciding on that data model is difficult.

"The fifth risk, and the biggest, is infrastructure capacity – networking, storage and computing. At this point in time, I'm not yet convinced we can [implement simulation data management], because the infrastructure may not be able to handle it. I think the

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weakest link today is the network: the network capacity is not there to carry the actual model files. We are able to manage moving CAD files around the globe just fine – an assembly of CAD files can be up to 500Gb, and it moves. But often that's the size of just one file in the CAE space. So we are faced with a one- to two-order-of-magnitude increase in the data volume that needs to be moved around the world. And I'm not sure even gigabit pipes to the desktop will solve that one.

"My challenge is to determine whether we can mitigate those risks and, if so, how. I've asked the vendors to come in and help with that." – Miller, GE Aviation

A final challenge arising from CAD-CAE and cross-discipline analysis gaps, and exacerbated by immature simulation data/process management capabilities, is the lack of fast, efficient simulation model creation and problem setup:

"There is a lot of interest in [aircraft engines and aerospace in general] in MDO – multidisciplinary design optimization. It's a step in the right direction – acknowledging the overall process, rather than one discipline trumping another – but it still seems to me that it's hard to carry out unless you have fairly integrated technologies. The idea that you will gather up all the results from all the point technologies and put them into one optimization bowl is well and good, but very hard. We really do need to rethink the technologies that will support such a vision. The vision is correct, but is the technological underpinning there yet to support that vision?" – Hughes, University of Texas, Austin

Organizational and work-process constraints

Methods development, work-process integration, culture change issues One constraint is the requirement to integrate the tools, intelligently and with forethought, into an organization's work processes – and effect the changes in culture, mindset, and institutionalized working habits necessary for the tools to have greatest impact:

"Some of the biggest constraints are the established engineering processes. Senior management has caught on to simulation-driven design, but the doers in the design department (as opposed to the simulation department) still have to be convinced." – Karl, Rolls-Royce

Certification requirements Another constraint is flight certification authorities' ambivalence toward simulation relative to physical test:

"One of the big problems is that the certification authorities are still skeptical – they still want physical test results. That is one of the things impeding uptake of simulation, most especially in the aerospace industry, because it forces you to still spend the money to do testing." – Karl, Rolls-Royce

Overcoming Constraints: New Directions, Emerging Best Practices

Fortunately, our research identified significant progress now being made on all these fronts.

Overcoming technology constraints

Toolset integration: CAD-CAE We found substantial progress in efforts to narrow the gaps between design and simulation models:

"Traditional software has exacerbated the [gaps between designers, analysts and their respective work processes], because the two started speaking different languages. To solve software problems, you need software solutions. The answer is to build CAD software such that a designer can do what a designer wants to do, and does the things

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he needs to do his job – but also to build the software so that what comes out is suitable for other processes beyond those of the designer. The software has to be written with the right intent. That should not put a burden on the designer; the software should automatically put his work into a file format that is usable by other [disciplines and their software tools]… A software environment that facilitates the overall process [will make] both parties – designer and analyst – happier. It's a win/win, but it has to be embedded in the software." – Hughes, University of Texas, Austin

New technological approaches offer promise of greatly narrowing if not eliminating these gaps. For example, this researcher is leading development of an approach to make NURBS-based geometry, used by CAD systems, a viable replacement for finite element models as input to currently used analysis codes. He terms this approach "isogeometric analysis."

Meanwhile, development and promulgation of common data standards is an important element of solutions being implemented today:

"Part of our job in the NPSS initiative is to push toward common data standards. We are working through the NPSS consortium to define how we represent the data interfaces between component simulations so we can mix and match our component models with customers and partners." – Plybon, GE Aviation

Toolset integration: cross-discipline analysis Similarly, we found substantial progress in integrating the tools used in the various analysis disciplines:

"Every discipline wants to use its best-in-class tool. You would prefer not to compromise the best-in-class capability, especially for something that is a critical technology for the application. However, there also has to be consideration of interoperability and interaction between tools from other disciplines. A tool that can be used across disciplines and in phases of the engine development process eliminates the need to reconcile differences and uncertainties. Do I use one tool for different areas as the engine program progresses, or do I use different tools that are not quite compatible and put effort into explaining the differences? What we've tried to do in NPSS is make it easier to incorporate the best-in-class tool and minimize the pain of system simulations with different levels of component modeling fidelity. If you make it easier to try alternate approaches you can then take advantage of the extra fidelity in the regions where it pays to do so." – Plybon, GE Aviation

Twin benefits of closer toolset integration are easier new-technology insertion – an especially challenging activity in digital simulation – and a greatly enhanced ability to move between simulation tools of varying fidelity:

"With NPSS we can use simpler methods to run over the flight envelope or for parametric analysis. At the same time, we can insert a higher-fidelity analysis for a selected component into the system simulation, leaving the rest of the simulation intact. This is an advance over the past, where detailed simulations might only be done on an individual component." – Plybon, GE Aviation

Simulation data/process management: mapping the way forward Practitioners we interviewed repeatedly described new initiatives to break through the two most frequently cited constraints on getting more value from simulation and analysis: (1) availability of trained, knowledgeable professionals and (2) time in the program schedule to do all the analysis they would like. Best-practice initiatives aimed at overcoming these constraints focus on tying existing design tools, preprocessors and solvers more closely together, and on using data/process management and knowledge capture technologies and methods to increase work throughput:

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"In our simulation activities, we have to interact with our data management environment, which manages all types of data – part data, manufacturing data, test data, etc. – our simulation data has to interact with that. Each of our customers has a unique data management system; we have our unique environment for managing data here. Our simulations are getting more capable and more flexible; and we have to fit simulation into our data management environment as it exists now. So we are taking a look at its capabilities, figuring out how to read and write data into that environment; everyone is in that mode now. Then, when the overall data management approach has opportunities to expand and change, we are part of that requirement-setting to ensure we have a say in the decision process." – Plybon, GE Aviation

How are industry leaders structuring and attacking the problem?

"[Our work to automate our simulation data and process management focuses on] three areas. The near-term focus is data management. If we manage our data well, it opens up so many opportunities for increased productivity. The key benefits are version verification – in handoffs, it's critical that you use the correct data – and data reuse: if you don't know what something is or you can't find it, you can't reuse it.

"Our mid-term focus is automated studies. Once you automate management of the handoffs between simulations and models, then you can more easily run sequences of models – an engineer can select a black-box model, and say: do that again.

"Finally, our long-term focus is helping engineers with innovation – which requires that we first accomplish our data management and automated-studies goals. Look at how an engineer does his work with the models that make up a simulation – he has to run the models repeatedly until he gets the right answers. [With better data management and automated studies], engineers can much more readily carry out directed studies – exploring the design space much like a search-and-rescue operation. And they can do optimized studies – using algorithms in effect that tell you to look here and not there. Then the final opportunity, which from an engineering design standpoint is a kind of holy grail, is probabilistic studies – recognizing that reality is not deterministic, that all of the X values going in have some kind of variation with a distribution, and thus that all the results will have some kind of mathematical distribution. The result is that you can determine what confidence you're able to have in your deign results, and you can explore the whole space.

"Each one of those goals depends on being able to manage the data, and to do it efficiently, in order to automate the design studies." – Miller, GE Aviation

Flight certification is one critical area where data management is crucial to having simulation results accepted as a trustworthy adjunct to physical test data:

"There is a clear requirement for long-term data management. Without proper control – versioning, archiving, etc. – the certification authorities will not accept any CAE [results] for certification. And we need this to be integrated with the rest of the toolset." – Karl, Rolls-Royce

After-market service and sustainment, increasingly crucial to the business success of both commercial and defense aircraft manufacturers, is another area where capability and competitiveness increasingly require simulation data and knowledge management:

"There is knowledge from the engine design and certification process that can be used in simulations that support the engines in the field. The simulations can be improved in ways that aren't possible using only the data stream from the engine and aircraft over its operational history. You can use this design information and understanding of the

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> *hardware to add value for the customer and be smarter about how you do the support process." – Plybon, GE Aviation*

Design space exploration, multidisciplinary optimization One notable area of innovation contributing to improved process automation and integration, we found, is the accelerating implementation of tools and techniques for automating and speeding up the execution of simulation and analysis codes in order to more efficiently explore design spaces:

> *"The technical layer of integration is do-able now. We have tools for product integration, the DOE tools, and also all kinds of other integration tools coming from the PLM vendors – the process automation and process integration and data management tools. All these providers are coming up with systems to manage the simulation data. The next step is to better link it with the design processes. The need to coordinate simulation with the designers – there are still big gaps there. In concept, it would help this integration if you took away the complexity of building these simulations. That's why all these simulation data and process management tools are starting to take off – because you can build your processes, then do your analysis much more easily time and again in a design iteration." – Karl, Rolls-Royce*

These new methods – multidisciplinary optimization (MDO), design of experiments (DOE), robust design, Design for Six Sigma (DFSS) – require improved approaches to better managing problem setup and problem execution, as well as data interchange between different simulation and analysis tools, and between analysis codes and CAD systems.

Overall, we found that practitioner priorities are focused on capabilities to:

- Automate data exchange between analysis disciplines, and between geometry modelers and mesh generators
- Ensure that CAD-CAE data exchange capabilities are multi-CAD – partner/supplier collaboration requires this
- Readily re-run or update analyses months or years later
- Ensure that design changes trigger re-analysis; ensure analysts receive correct inputs from modified design; ensure re-analysis results feed back to design
- Manage intellectual property exchange and ITAR compliance issues when sharing data with subcontractors and partners

Knowledge capture and management Another goal of simulation data/process management initiatives is a greatly enhanced capability to capture, archive and retrieve simulation models, input conditions and results, together with related assumptions and conclusions. Indeed, knowledge capture and management is a capability sought by many. Beyond simply securing information, it also involves the collateral activities of classifying data and putting it in meaningful context, so that subsequent consumers will find the information both meaningful and trustworthy – transforming an organization's "implicit knowledge" into "explicit knowledge".

> *"Large data storage and data mining capability, taken in combination with simulation, has great potential. There is a lot of data that is not easy to use directly in our simulations. Being able to filter and understand this data and put it in a form that can help validate and improve analysis will have significant benefits in the future." – Plybon, GE Aviation*

Global project execution support Given the increasingly distributed nature of engine development program execution, the capability to manage simulation/analysis data in ways that support global organizational process requirements is another critical factor being taken into account in planning and evaluating simulation data/process management environments. The challenges, impossible to meet without digital tools and infrastructure, begin with

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supporting and coordinating participation in globally dispersed programs, and extend to managing compliance with International Trafficking in Arms Regulations (ITAR) requirements:

> *"…we have to deal with two aspects of security. One is export control – we're very much a global company, and stakeholders either do or don't have rights to see certain data depending on where they live, what country they're citizens of. And the second is intellectual property reasons: we want to control the IP that we have. So any system I come up with has to manage both of those security aspects." – Miller, GE Aviation*

Simulation/test correlation Improved management of correlations between digital simulation and physical test is another key requirement of simulation data/process management. The goal, practitioners report, is to become better able to use each as a lever to change how both are used in product development:

> *"There will always have to be physical test data to validate that design goals have been met; but more and more, you can use simulations to ensure the testing hits the right points and to limit expensive testing to the most critical points, rather than running lots of tests in areas where simulations could tell you all you need to know. Our priorities are in using simulation to provide more detail early in design, select the right test points and understand the results during certification, and finally understand how the engine is performing in the field to better support the customer. All these areas have improved in recent years – particularly the use of simulations to support the engine in service. We can leverage our detailed knowledge of components with the operational history of the engine to know what's required to best meet the customer needs." – Plybon, GE Aviation*

Overcoming organizational and work-process constraints

Of course, with even the most optimal technology implementations, much of the challenge in optimizing use of simulation and analysis and maximizing its impact has to do with organizational considerations and people factors.

Process capture, methods definition, toolset commonization In concert with the technology initiatives described above, a critical focus at some large enterprises is to document, understand and optimize – *in order to* automate and integrate – mission-critical, value-creating activity chains that utilize simulation and analysis.

> *"Balancing between standardizing on one tool set vs. having all the capability you need is a challenge. We expect the technologies that provide the middle layer…are usable as common platforms to help tie all the tools together. Hopefully, all the tools are starting to link to these frameworks, because then you can do your analysis with whatever tool you want." – Karl, Rolls-Royce*

In turn, the activity of capturing simulation processes and defining best-practice methods can be aided by – and at the same time can be used to foster – movement toward common toolsets across the enterprise.

People factors In dealing with people factors, our research found that best practice focuses on two objectives:

- Garner executive sponsorship
- Create incentives for discipline leads, analysts, engineers to take ownership of the new tools and processes

Garner executive sponsorship Why is executive sponsorship important? Because optimizing use of simulation and analysis is an investment. It requires budget. It requires process change. And progress is not always smooth, so when things hit a bump, it requires

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commitment to stay the course. If improvement initiatives cause short-term hits to productivity, C-level understanding and backing can be invaluable. How to get it: tie simulation process improvement to corporate business objectives, and to C-level initiatives and budgets such as Six Sigma, quality and efficiency programs. Indeed, practitioners report that in the aircraft engine industry, it already may be close at hand. Again:

> *"Senior management has caught on to simulation-driven design…" – Karl, Rolls-Royce*

Create incentives for discipline leads, analysts, engineers to take ownership Of course, winning C-level buy-in is no guarantee of success. Alienating the head thermal analyst by forcing him or her to use a tool he/she doesn't like or trust is not the best way to deliver product on schedule. How can managers create incentives for these individuals to take ownership of new processes and enabling technologies?

We found the answer often comes down to best practices for change management. What will motivate these individuals to change the way they work? One key, we found, lies in individual engineers' professional motivation to excel, and their consequent receptiveness to new processes and technologies – and, in advanced-usage industries such as aircraft engines, in crafting strategies that analysts themselves as drivers of process change and culture change among colleagues in adjacent areas:

> *"The doers in the design department (not the simulation department) still have to be convinced [of simulation's trustworthiness and value]. To win them over, we have to show them what the tools can do, and show them the tools in the context of the process. For example, we have a project in place to use simulation to replace tests; this is part of the winning-over process. And then to show how simulation can be used to help decide how and what to test. That is the way to win the designers over." – Karl, Rolls-Royce*

A related best practice, we heard repeatedly, is to implement simulation and analysis process change in ways that minimize disruption in engineers' day-to-day work habits.

Next Steps

To drive change in an organization, a powerful spur to action can be to benchmark the organization's maturity level against industry best practices. Using this report as a starting point, compare practices in your organization with those of your most successful rivals. Identify areas where more effective use of simulation and analysis would put you in the lead.

One way to begin is to assemble a multidisciplinary team – include representatives from the analysis groups, design, test, and program management – to audit current practices, identify gaps and bottlenecks, and develop recommendations for improvement. First review the constraints identified by practitioners in this paper. Determine which of these is most severely gating progress in your organization today:

Technology constraints

- *CAD-CAE gaps*
- *Cross-discipline analysis gaps*
- *Need for better simulation data/process management*

Organizational and work-process constraints

- *Human resource constraints*
- *Methods development, work-process integration requirements*

Then investigate sources of solutions for both classes of constraints.

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Technology solutions Although in-house development of CAE codes was long widespread, today practitioners tell us they are largely working to get out of this business, choosing commercial solutions wherever feasible. Criteria for qualifying and selecting a solution provider, conditioned on what constraints you need to address first, include:

- *Functionality of solvers*
- *Functionality of meshers, gridders, other tools for problem setup and results execution*
- *Competence as integrator of diverse functionality – multi-CAD, multi-CAE, other product lifecycle functionality from requirements capture through manufacturing into service, support and sustainment*
- *Commitment to providing help with process change, people/cultural issues*
- *Commitment to providing:*
    - *Simulation data management framework*
    - *Process automation tools*
    - *Knowledge capture tools*
- *Reliability as long-term partner*

In your organization's next procurement cycle, revisit your qualification and selection policies for simulation solutions to ensure they address your requirements not just for superior point functionality but also for simulation data management, tool integration and process optimization. Factor in solution-provider stability, longevity and change management experience.

Organizational and work-process solutions Solutions to organizational and work-process constraints may come from commercial software and service providers, as discussed above. In addition, we heard impressive accounts of engine development organizations cooperatively organizing initiatives – with participation not only by analysts, but also by design and data management leads – to collectively advance the goal of simulation-driven design. More efficient, better rationalized toolset procurement is a key enabling element. But even more important are internal change-leadership groups driven by the most experienced and respected discipline and methods leads in each of the key functional areas where change must occur:

> *"[How simulation purchase decisions are made] is starting to change. Up to now it was mainly the respective analysis specialty groups making the decisions. But there is now a drive to centralize and align all these decisions to get to a bigger picture: the aim of the bigger picture is to do the first stages of a project using simulation-driven design, and then to continue doing the whole design with simulation-driven decisions. The technical vision for making that happen is to link all the simulation tools together, from system-level down to detail simulation tools. And you need to have systems engineering in there, to keep track of the complexity; it's not feasible to have everything done in 3D. That's why I am pushing robust design and systems engineering; if you don't do these things together, you can't do robust design.*
>
> *"To drive these changes, our organization has a department which is made up of all the departments responsible for using the tools – the CAD people, and the PDM people, and all the CAE discipline leads. It is more than a committee – it's a functional relationship to those departments. For the people in that group, that role is their dedicated function; they are methods leads who came out of the different organizations.*
>
> *"[At the same time, and reinforcing these changes], the budgets are becoming more corporately organized than before. This is aimed at getting the spending, and the tool decisions under central management." – Karl, Rolls-Royce*

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