WHITE PAPER

Three Levers for Accelerating Lightweighting in Aerospace:

ADVANCED MATERIALS / ADDITIVE MANUFACTURING / MATERIAL INTELLIGENCE

Reducing the weight of an aircraft is a key aviation industry strategy to control fuel expenditures and limit emissions. In emerging hybrid and increasingly electric aircraft systems, it is also key to maintaining performance while accommodating the additional weight introduced by batteries and other components. A 1% reduction in weight can save billions of dollars each year.

Accelerating the delivery of lighter weight aircraft is possible by focusing on three key levers: more extensive use of advanced materials, such as composites; broader adoption of new manufacturing techniques, especially additive manufacturing; and extraction of more value from materials data that already exist across the enterprise. Using these levers to drive change is a significant challenge in a safety-critical environment with traditionally siloed functions. The keys to overcoming these challenges include achieving predictability and materials data management. The industry's ongoing digital transformation will play a critical role by creating a digital thread from concept to manufacturing and enabling materials, engineering and manufacturing teams to collaborate and innovate in a risk-free, virtual environment.

For lightweighting, this digitalization process places specific requirements on the digital tools that will be used: physics-based solvers must be sufficiently capable to capture complex material behaviors; multiscale and multiphysics phenomena must be accounted for; and a materials data management solution must have the capability to be deployed across the enterprise to support innovation from materials through engineering to manufacturing.

/ A Heavyweight Challenge

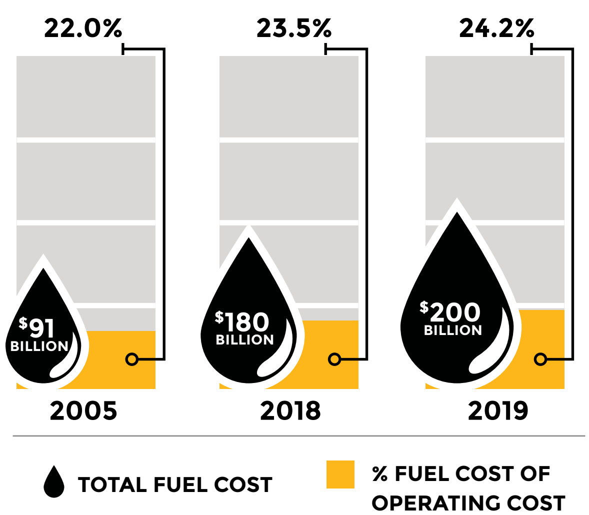
The global airline industry fuel bill is expected to reach $200 billion in 2019, rising to almost one-quarter of operating expenses.1 This is more than double the $91 billion cost in 2005. With such a high proportion of operating costs being associated with fuel, the trend of rising and volatile prices can break airlines. Commercial airline operators already run on low profit margins, and some have even entered bankruptcy. While there are many factors that contribute to this situation, the rising cost of fuel bears the most blame.

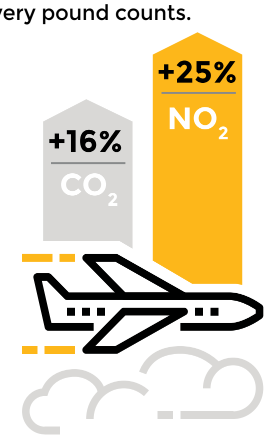
In parallel, the entire industry is committed to reducing its impact on the environment, particularly through emissions. New standards mean that those in-production aircraft that do not conform by 2028 will no longer be produced unless their designs are sufficiently modified.2

As a consequence, the airline industry is challenging the entire aircraft supply chain to deliver more fuel-efficient aircraft to reduce the impact of fuel costs on operations and the amount of emissions produced.

The weight of the aircraft is one of the key contributors to fuel consumption and emissions. Even small percentage savings in the mass of an aircraft contribute billions of dollars in fuel cost savings over the lifetime of its operation.

In addition, as the industry pivots to hybrid and more electric systems, lightweighting is the only way to achieve performance criteria while accommodating the additional weight penalty of components, such as batteries. Lightweighting is critical and every pound counts.





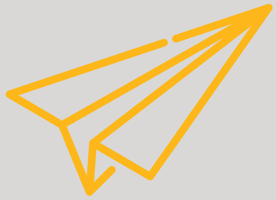
Between 2005 and 2017, CO_2 emissions from aviation increased by 16% and NO_x by 25% due to more flights

[1]https://www.iata.org/pressroom/facts_figures/fact_sheets/documents/fact-sheet-fuel.pdf

[2]https://www.icao.int/newsroom/pages/icao-council-adopts-new-co2-emissions-standard-for-aircraft.aspx

Shedding the Pounds Is Hard

Current configurations of aircraft have been around for decades and, despite the emergence of new designs, these same basic configurations are likely to persist for decades to come. During this time, these safety-centric designs and their derivatives have become highly optimized against performance requirements. The "easy" improvements have long been identified and made. Impactful improvements are therefore challenging and often very difficult to identify using traditional design approaches. To aid the aircraft supply chain in its efforts to reduce the weight of components, subsystems, systems and the entire airframe, this white paper has identified three key levers that determine the extent and the pace with which substantial progress can be made. Each lever offers significant opportunity, but is not without associated challenges.



LIGHTWEIGHTING

1% of mass reduction on a medium range, narrow-body aircraft could save more than **$1 BILLION** per year on fuel

Lever 1: More extensive use of advanced, lighter weight materials

The latest generation of aircraft consists of 50% (or more) advanced composite materials, which contribute to some 20% weight savings when compared with more conventional aluminum designs.3 These aircraft represent a step change in the use of lightweight materials versus previous generations. At the same time, this rapid transition has caused significant challenges in the development of the aircraft and may have contributed to program delays.4

In one published example, engineering teams encountered difficulty in accurately simulating the performance of the parts of the composite structure in advance of manufacturing.5 This was due to the more complex nature of the material to be represented, and resulted in an unexpected failure.

The ability to accurately predict the design behavior and manufactured state of these complex composite materials is critical to building design confidence, supporting a first-time-right approach, increasing the use of composites and accelerating their deployment.

The explosion in the quantity and complexity of data and information around advanced materials options is another challenge. It is difficult enough to simply identify and select viable materials and process options from a rapidly growing set of possibilities. This requires good data on the full range of these possibilities and tools to mine that data. Next, whether an entirely new composite system will be developed or an existing system will be applied to a new application, it is necessary to understand the detailed performance of the system in context and, in many cases, to qualify and certify the resulting component. This process can generate very significant testing and analysis requirements – and associated costs. The numbers are staggering. As a rough order of magnitude, a basic tensile test may cost in the region of $1,000 per curve, rising to $100,000 per fatigue curve. One component may require tens or even hundreds of tests. This is a multimillion dollar challenge. Enterprises need the right systems to ensure maximum return from their investment and to leverage the information generated to optimize and qualify new materials and processes.

The same need to capture project information and exploit it to optimize properties applies in the emerging field of additive manufacturing (AM). Good materials information management is a prerequisite for AM success, along with effective use of simulation and topology optimization, as discussed below.

In summary, lever one requires the more extensive and accelerated use of advanced, lighter weight materials. However, to do so requires that engineers have confidence in the accuracy of the design tools they are using to capture the behavior of these more complex materials and the right materials data management systems in place to maximize the return on investment on required testing.

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[3] https://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_2.html

[4] https://www.flightglobal.com/news/articles/787-centre-wing-box-redesign-buckles-schedule-223455/

[5] https://www.technologyreview.com/s/409929/boeings-composite-problem/

Lever 2: Adopting emerging manufacturing techniques and leveraging topology optimization

Topology optimization uses a physics-driven simulation approach to determine where to remove material from a "block" – to get the most efficient shape that meets structural performance requirements while, at the same time, reducing the weight or volume of the part. The results tend to be "organic": designs that aren't necessarily intuitive or easily produced given the constraints of subtractive manufacturing. With the advent of AM, production of components designed using topology optimization techniques is now possible.

According to Roland Berger, aerospace and defense companies employ AM more than any other industry.[6] Excitement around the technology is growing and the supporting tailwinds – reducing cost, increasing design confidence and increasing regulatory acceptance – are gathering strength.

Deloitte quantifies the benefits of AM as: a 50% reduction in part cost, 10% decrease in scrap, 64% decrease in time to market and 64% reduction in part weight.[7]

Despite these stated benefits, most companies in the aerospace industry are not yet making major investments in AM.[8] Rather, they are observing the development of the technology and focusing their efforts on research and development. In addition to workflow process changes and supply chain and certification issues, technology barriers to wide-scale deployment of AM include:

- Cost of equipment, part certification, training and failed print runs
- Understanding of materials properties and quality control of the final parts

These factors are practical inhibitors to the broad-based adoption of AM that must be overcome. Much of this concern centers on predictability – whether predicting the performance of the final part, quantifying uncertainties or predicting the likely success of a print run to avoid waste. Given the highly complex manufacturing process and nonintuitive nature of topologically optimized designs, establishing a design and manufacturing process with a seamless predictive digital workflow – from design through manufacture – is one of the critical factors for reaping the rewards of AM in the aerospace industry.

Lever 3: Exploiting materials IP throughout the value chain

Integrating new materials into an aircraft takes a long time. The Defense Advanced Research Projects Agency (DARPA) acknowledged this when launching its Materials Development for Platforms (MDP) program,[9] which seeks to address the problem of material insertion times averaging more than a decade. The World Economic Forum also found that organizations already have access to vast amounts of materials and suggests that "existing materials can serve as building blocks for potential new solutions and not merely individual commodities. This enables companies to reallocate resources from developing new materials to combining existing materials into a holistic solution."[10]

Considering the challenges of long insertion times and untapped organizational material intelligence leads to two key conclusions. First, enterprises need to do whatever they can to speed the deployment of materials innovations downstream in design, development and production. Second, they need to more effectively extract value from the vast amount of materials information and experience that they already possess. The challenge is how to do both across highly diverse, safety-conscious and often siloed organizational functions.

The potential impact of more effectively managing materials information, introduced earlier in the context of developing and qualifying new materials systems, also applies here. This impact was brought home in a 2016 survey.[11] In an average organization, 50% of the expensively acquired materials test data were used once and never reused when, in fact, the data could have supported later analyses or been used to further understand and optimize materials performance. Typically, 20% of materials tests duplicate existing work and the average materials engineer spends 30 minutes per week just looking for data.

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[6] https://www.rolandberger.com/publications/publication_pdf/roland_berger_additive_manufacturing.pdf

[7] https://www2.deloitte.com/insights/us/en/focus/3d-opportunity/additive-manufacturing-3d-opportunity-in-aerospace.html

[8] https://www.rolandberger.com/publications/publication_pdf/roland_berger_additive_manufacturing.pdf

[9] https://www.darpa.mil/program/materials-development-for-platforms

[10] http://www3.weforum.org/docs/WEF_Advanced_Materials_Systems_Chemistry_Advanced_Materials_report_2016.pdf

[11] https://grantadesign.com/industry/publications/white-papers/the-business-case-for-materials-information-management/

This is particularly true when materials data are scattered across the multiple functions of a typical aerospace organization. There is a risk that materials innovations do not get deployed because design and simulation engineers do not have easy access to approved "design allowable" data that capture the performance of these materials. Also, feedback around currently used materials may not filter back to the development team. Fortunately, the positive benefits of effective management of these processes are becoming evident. In a recent case study, a leading aircraft engine manufacturer quoted over $8 million in annual savings through the implementation of more effective materials information management across the enterprise.[12]

Clearly, being able to better organize, manage and interrogate existing materials intellectual property (IP) within an organization is key to eliminating waste and rework and accelerating the development of new material solutions and their deployment in aircraft, as well as serving as a source of additional value creation and cost savings for the company.

/ Predictability and Data Management: The Keys to Unlocking the Levers of Lightweighting

From the three levers discussed above, two technology factors stand out for accelerating aircraft lightweighting initiatives:

- Accurate performance prediction of more complex materials and parts during design and manufacture to eliminate late-stage failures and reduce cost
- Materials information management to enable better use of the collective corporate IP already in possession and deploy resources more efficiently

The aerospace and defense industry remains a leader in the use of high-fidelity, physics-based simulation and associated data management tools, and is entering a new era of digital transformation. This transformation will play a critical role in overcoming the challenges of accurately simulating the performance of parts made from complex materials, manufacturing these materials and managing materials data. Yet to do so requires very specific capabilities and characteristics – some of which are still evolving – because design teams today are hampered by a multitude of tool choices and inefficient, disconnected workflows.

/ Simulation requirements for composite materials

The challenge of accurately simulating a composite material is achieving an accurate depiction of its formulation. Unlike a conventional material (steel, for example), a composite is typically a mix of fibrous materials of different thicknesses that may be layered to create a single material. The fiber orientation in each layer (the direction of the main fiber) differs in terms of angles, thickness and material from the layer above and below it. This complexity in design is rewarded with the flexibility to locally customize the stiffness and strength properties in every part. Most aircraft designs use black metal, meaning they substitute aluminum with quasi-isotropic carbon. A large weight reduction can be achieved when the orthotropic (directed) material properties of carbon fibers are exploited. The engineering challenges of such designs can only be tackled with detailed finite element analysis and highly specialized simulation tools. When performing a composite material simulation, it is necessary to accurately capture and define all of these components. A single model, then, might require dozens, hundreds or even thousands of layers or "plies." For practical use, therefore, a simulation tool must be able to efficiently scale across high-performance computing resources and quickly run through design iterations in an associative, end-to-end workflow.

Investigating failure is also different for composites compared with conventional materials. In a composite, designers analyze local failures to define where, how and under which loading conditions it is failing. Composites can fail in many ways (delamination, matrix, fiber failure under compression or tension). Assessing the complex failure modes is a key challenge in designing composite structures. Engineers need suitable pre- and post-processing tools that are able to distinguish between different failure modes. Knowledge of the occurring failure accelerates design cycles during redesign.

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[12]Mhay A., presentation at the 'Material Intelligence Seminar', Derby, UK, October 2018

Simulating curing can predict process-induced distortion. During cooldown and removal from the tool, curved composite laminates can distort as a result of mismatches between the through thickness and the in-plane thermal expansion coefficients, as well as complex cure shrinkage mechanisms. Distorted components may cause problems during assembly, significantly increasing the overall product cost and the in-service performance of the product. Simulation can be used to compensate for process-induced distortion in advance, to meet geometrical tolerances and improve final product performance.

In aerospace applications, composites must also meet the challenge of thermal management. Composites exhibit a thermal behavior that is different from metal and requires special attention. Further, designers need to consider electrical dissipation in the event of a lightning strike or for grounding during refueling operations. This can involve embedding a metallic mesh in the composite frame.

Composites materials are now being used more and more in critical structures, where high loads are introduced. These structure domains are often very thick-walled, characterized by a fully 3D stress state that can only be captured by a volume composite (or 3D solid) simulation model. They are heavily subject to curing as well and, as discussed above, curing simulation is critical to capture and eventually optimize the process.[13]

Therefore, when considering a simulation tool set for composite materials, the tool set must be sufficiently capable of capturing the complexity of the composite – even for thick-walled parts. It must predict potential failures both in manufacturing and operation, as well as offer multiphysics capabilities (e.g., thermal, electrical), to truly deliver the understanding of the material performance in real-world operational scenarios.

/ Simulation requirements for additive manufacturing

Additive manufacturing opens vast opportunities for designers to create highly novel shapes that are topologically optimized – with just the right amount of material placed where needed. This results in many innovative configurations, such as organic and complex lattice structures. Optimizing topology and analyzing lattice structures, while accounting for practical manufacturing constraints, are essentially impossible without computational methods.

Supports are often used during the manufacturing process to ensure the part retains its shape as it is manufactured. These supports can have an impact on the quality of the final part due to their influence on, for example, the cooling rate of the part. Simulation has a role to play in helping the designer quantify this impact and optimize support placement to mitigate potential support-induced failure modes during manufacturing.

In additive manufacturing, the final materials properties are determined to an unusually large degree as the part is being created. One challenge facing the designer is, therefore, to predict the material and process parameters that will result in a part with the required performance. The key to accurate predictions is understanding the exact thermal history of the process. Each machine manufacturer uses different scan pattern logic (i.e., the collection of scan vectors the laser follows). This results in a unique thermal history that results in different strain magnitudes, defect distributions, microstructures and mechanical properties. Therefore, a simulation model must utilize the machine manufacturer's scan vectors and calculate the thermal history for every scan vector used to produce the part. Only in this way can machine-specific characteristics and their impact on part performance be captured.

Shape distortion can also be introduced during the manufacturing process and this depends on not only the materials and machine parameters, but also how the parts are distributed into the working space and the degree to which they influence each other. Distortion prediction through simulation and the capability to update CAD files before printing to eliminate it are of paramount importance.

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[13] https://www.qantur.com/wp-content/uploads/2018/01/wp-simulating-composite-structures.pdf

For each machine, there is a set of process parameters that deliver optimal performance, with a typical process map that plots scanning velocity against laser power. Too much power can lead to keyholing – a situation in which the laser power is so strong that it not only melts the current powder layer, but also melts down into the previously melted layers. A too-high velocity results in unmelted powder. And, finally, too much power applied too quickly leads to balling (instances when the bead of material is not applied smoothly). The challenge for the designer is to understand the optimal process parameters and the proximity to these potential failure modes. The right simulation tool can enable rapid and low-cost exploration of the process map to optimize faster build times and more robust builds.

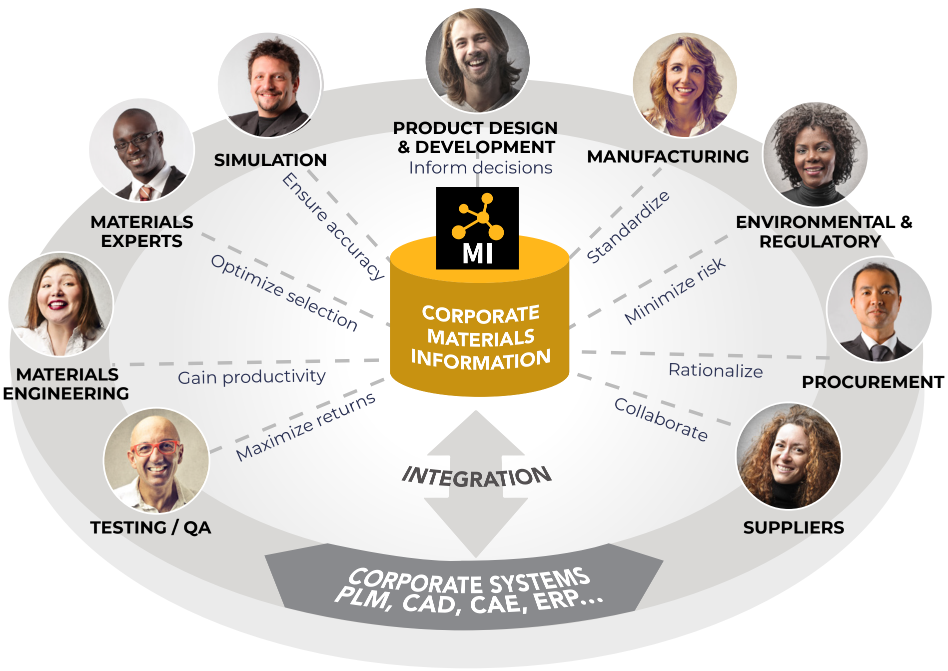
To make the most of designing for additive manufacturing, a digital workflow must be established that spans and captures the interdependencies of ideation, practical manufacturing constraints and machine characteristics, as well as helps predict the material properties of the final part.

/ From Material Data to Material Intelligence

The Materials Data Management Consortium (MDMC), whose members include many leading aerospace companies, has helped define the requirements for a centralized "single source of truth" for materials and processes and their intersections – at different stages in the design process and with the different functional departments involved. [14]Key elements include:

- A single system to capture and store all corporate materials information – from R&D to in-service support
- Support for the life cycle of materials data (in the materials R&D phase) – i.e., recognizing that property data evolve as further testing and statistical analysis is performed
- Specialized data structures and tools to capture the complex test and analysis data involved in developing and qualifying composites and in AM projects
- Accessible proprietary information, along with the best available third-party reference data (e.g., composite test data from NCAMP[15]) to facilitate comparison and analysis
- Automated capture of the interrelationships between data, ensuring full traceability and a digital thread
- Integration with engineering software requiring materials inputs (e.g., CAD, CAE), and with the wider engineering and business information technology (IT) infrastructure (e.g., PLM).

The scope and some of the benefits of such a system are illustrated below.



[14]https://grantadesign.com/industry/collaborations/consortia/mdmc/
[15]https://www.wichita.edu/research/NIAR/Research/ncamp.php

The benefits of following these best practices, particularly in the context of lightweighting projects, include:[16]

AREA	BENEFITS
Development and qualification of composite systems	• Establish traceability for all analysis and testing, particularly valuable when qualifying complex multicomponent composite systems • Reuse test data in more than one project, saving cost, time and offering additional insight • Optimize performance of composites • Save time and bring composites to market faster
Implementing additive manufacturing	• Get guidance on which build, testing, feedstock and simulation parameters to capture • Gain insight into critical process/property relationships • Establish traceability supporting qualification of final parts • Save time and get AM parts to market faster
Design and simulation	• Ensure the right data are input to essential simulation tools; avoid errors and delays in design • Integrate experiment and simulation more effectively
Purchasing and supply chain	• Deploy innovations more effectively – avoid problems due to inconsistent descriptions of materials and processes
Manufacturing and in-service	• Accelerate response to customer or production issues • Feed information from in-service experience directly into R&D

[16] Warde et al. The Business Value of Material Intelligence, ANSYS Granta 2019

Conclusion and How Ansys Can Help

Delivering the lightweighting innovation the aerospace industry needs to address rising operating costs, meet environmental commitments and incorporate new propulsion systems is a significant challenge in aircraft architectures that are already highly optimized. Three levers to address these challenges have been identified and discussed in this white paper. The ongoing digital transformation of the industry will help unlock these levers and require tools that accurately predict the performance of complex materials and their manufacturing processes. It will also require data management platforms to ensure organizations maximize the return from their investments in materials development.

Ansys is unique in offering a high-fidelity multiphysics, multiscale integrated simulation tool set that spans the product life cycle from conceptual design to manufacturing for composites and metal AM. The tool set is underpinned by the industry's leading materials database and materials data management solution. This collective solution addresses the key issues highlighted in this paper. It virtually delivers rapid performance optimization utilizing high-performance computing.

As A&D continues to digitally transform, Ansys simulation will enable the industry to deliver lighter weight aircraft that will reduce fuel costs and negative environmental impacts, and provide a platform for next-generation hybrid and more electric architectures.

Access the following resources to learn how Ansys simulation addresses the three key levers of lightweighting for A&D:
https://www.ansys.com/products/structures/composite-materials
https://www.ansys.com/products/structures/additive-manufacturing
https://www.ansys.com/products/materials

Learn more about how Ansys is helping the aerospace and defense industry accelerate digital transformation and address some of its most pressing business initiatives: https://www.ansys.com/a-d

Ansys, Inc.
Southpointe
2600 Ansys Drive
Canonsburg, PA 15317
U.S.A.
724.746.3304
ansysinfo@ansys.com

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