Innovation Quarterly

2018 August
Volume 2, Issue 9

The Probabilities
Math, the future and the practical side of innovation

Data at Large
A global approach

Predictive Patterns
Technology strategies to change the world

A publication of The Boeing Company

Innovation
Quarterly

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ON THE COVER
Sharon Arroyo, Boeing Technical Fellow and applied mathematician in the Boeing Math Group.

PHOTOGRAPHY BY PAUL GORDON

Featured

Technical Papers

Count on this: **Math matters to Boeing**

As I approached my senior year as an undergraduate, I really didn't know what aspect of engineering I wanted to specialize in. As a result, I started taking advanced math courses and attended a seminar on the mathematics of systems and control theory. This was when I found my niche, which shaped the remainder of my academic career and a large part of my professional career.

Stories like this show how mathematics is an indispensable foundational skill in aerospace. That's especially the case in this age of the Fourth Industrial Revolution, when we're seeing breakthroughs in fields like artificial intelligence, robotics and machine learning.

Even before this, our work in aerospace has been heavily influenced by finding efficient numerical solutions to Navier-Stokes equations. But we didn't stop there, because once we had a solver, we started wrapping optimizers around these solvers to find the best aerodynamic surfaces.

Math acts as the basic building blocks for the expansive range of complex, sophisticated products and services that Boeing provides. And that's why this edition of Innovation Quarterly focuses on math.

When I joined the company in 1982, my early assignments focused on design of aided-inertial navigation systems and the first integration of GPS as part of a cruise missile guidance system. This integration was possible because of the use of Kalman filtering algorithms and the implementation of those in a real-time guidance system. This work leaned heavily on my background in applied math and numerical analysis. The bottom line is that the math made the missiles fly.

Mathematics will continue to be foundational to our work, and I believe its importance is only going to grow.

As our work becomes more and more software driven, as data becomes a critical resource that we mine for insights through analytics, and as the competition drives us to even more optimal processes and designs, this will all be fueled by mathematics. So enjoy this edition of IQ dedicated to the mathematical sciences—and thank a math teacher the next time you see one. IQ

GREG HYSLOP
Boeing Chief Technology Officer
Senior Vice President, Engineering, Test & Technology

Recognizing Advanced Developments and Research

Technology **RADAR**

People working in Boeing's Technology Intelligence and Trends community of practice are human sensors in the world of science and technology. We make it our business to watch for innovations in practice, new business models and new ways of thinking. Here's a peek at a few signals on the screen.

Homes That Monitor Your Health

LOCATION Dalmore, Scotland
PROJECT URL invernesscampus.co.uk/news
MESSAGE
FitHome, a project of the Scottish government, uses ambient sensors and interactive technology to monitor residents' health.

Underwater Adhesive

LOCATION Vienna, Austria
PROJECT URL tuwien.ac.at/en/news
MESSAGE
An epoxy resin developed at the Vienna University of Technology will cure when any part of it is irradiated, even under water.

Robots Actuated by Visible Light and Electricity

LOCATION Hong Kong
PROJECT URL hku.hk/press
MESSAGE
Researchers at the University of Hong Kong have introduced a nickel-based material that changes its volume under stimuli such as light and electricity. Such actuating material could replace bulky motors in microrobots or artificial muscles.

Atomic-Scale Manufacturing

LOCATION Edmonton, Alberta
PROJECT URL ualberta.ca/science
MESSAGE
Research scientists at the University of Alberta have applied machine learning to automate atomic-scale manufacturing.

Robots That Grab What They Want

LOCATION Brisbane, Australia
PROJECT URL qut.edu.au
MESSAGE
Roboticists at Queensland University of Technology have developed a more accurate grasp method using deep learning to allow robots to pick out and pick up independent objects in shifting or cluttered environments.

Tiny Chips for Tiny Drones

LOCATION Cambridge, Massachusetts
PROJECT URL news.mit.edu
MESSAGE
The new Navion computer chip developed at MIT—the size of a Lego figurine's footprint—can help small robots and drones navigate where GPS data is unavailable.

The future takes shape

How alloys that change shape in flight could enable new aerospace breakthroughs.

**BY JIM MABE, TECHNICAL FELLOW
BOEING RESEARCH & TECHNOLOGY**

It might be odd to think that metals that change shape can be useful in aerospace, where large vehicles fly at high speed. But that's the promise of a metals technology called shape memory alloys, which could meet the growing need for lightweight, reliable and innovative actuators.

Shape memory alloys are metals that change shape or move when exposed to a particular temperature stimulus. Although originally developed in the 1960s, the promise of this technology has recently sparked new advancements across a breadth of industries—automotive, robotics, building and infrastructure, telecommunications, orthopedic surgery, dentistry, and even optometry.

Because of their high-energy density and large strain capabilities, these alloys are particularly attractive to the aerospace industry for use in positioning flaps or other aerodynamic surfaces, morphing structural shapes, or replacing conventional hydraulic or electric motor actuators. That's especially true in instances where size and weight are critical or in environments where conventional actuators cannot survive. In fact, morphing aerospace structures represents a potentially revolutionary use of such actuators.

Boeing is currently the world leader in shape memory alloy technology and system demonstrations.

PHOTO: BOB FERGUSON

THE SHAPE OF THINGS TO COME
Technical Fellow Jim Mabe holds the shape memory alloy torsional actuator assembly that was installed in the Boeing 737 Adaptive Trailing Edge, part of the 2012 ecoDemonstrator flight test program.

Boeing is currently the world leader in shape memory alloy technology and system demonstrations. Boeing is also in the position to transition this technology from the lab and flight test demonstration to production-ready designs and FAA-approved applications.

Currently, Boeing does not have any in-production products using this technology. However, the most promising application of these alloys is compact actuators for aircraft models used in wind tunnels.

Every time personnel enter the tunnel to manually reconfigure flaps, ailerons or other model surfaces, the tunnel has to be shut down and then restarted, costing time and money.

Boeing colleagues have been building and successfully testing remotely actuated wind tunnel models using shape memory alloys for several years.

Our design tools and control methods have improved dramatically since we started, and we are close to fully capitalizing on this technology and applying it to future technology development and sensitive wind tunnel test programs.

Another application that is showing both technical and economic promise is what we are calling the "smart vortex generator." Aero devices such as vortex generators, strakes and chines are often installed to benefit one phase of an aircraft's flight segment, such as takeoff and approach. During other portions of the flight such as cruise, they may increase drag.

A smart vortex generator using shape memory alloy will react to the colder temperatures at cruise altitudes and autonomously adjust to a low drag shape. A recent study showed that for one particular vortex generator application on a commercial transport, replacing the current static devices with adaptive devices would measurably reduce cruise drag. The gains documented in this study might have been incremental. However, over the aircraft's lifetime, those gains would add to a significant amount.

Today we are collaborating with NASA's Glenn Research Center in Cleveland to develop alloys with the right thermal properties to meet the smart vortex generator requirements. Several alloys under development are showing promise both from a technical perspective, as well as a manufacturability perspective.

We've also worked with NASA to develop variable geometry engine nozzles for reduced noise and increased efficiency. We have worked with the U.S. Navy on reconfigurable rotor blades for performance optimization between hover and forward flight; we have also worked with the FAA on wing trailing edge devices to improve efficiency and reduce emissions.

We have been working with researchers at NASA Glenn since about 2008 on shape memory alloy materials and processing. That work eventually led to the Spanwise Adaptive Wing program. This two-year program demonstrated shape memory alloy-actuated wing fold on an unmanned aerial vehicle and improve manufacturing of a new a high-temperature shape memory alloy (NiTiHf) for high torque actuators. The new alloy was used successfully in a recent Spanwise Adaptive Wing UAV flight test at NASA's Armstrong Flight Research Center in Edwards, California, as well as an F/A-18 wing fold demonstration at NASA Glenn. It is also being considered for other applications.

Since improved alloys will speed the successful transition to production, we are working to develop and improve high-performance alloys such as NiTiHf. We will continue to develop and validate tools such as those for actuator simulations and, most importantly, continue to develop standards, test methods and allowables to enable production certification of shape memory alloy applications.

As we push the boundaries of existing technology, Boeing will need to make new breakthroughs in order to maintain a competitive advantage. Shape memory alloys may not address every actuator problem. But as we face stiffer competition, we need to explore every feasible technology that can realistically give us an advantage. IQ

“Kumon gave me confidence and familiarity with math. Anything that was math-related I could do, and I was excited to do.”

JAMAL MADNI

A humanity from math

This engineer applies multidimensional thinking to Boeing’s enterprise technology strategy with mathematics at his core.

BY WILL WILSON, BOEING WRITER | PHOTOGRAPHY BY PAUL PINNER AND SALLY ARISTEI

Since he was a kid, math has been another language for Jamal Madni. In addition to speaking Urdu, Hindi and English at home, his parents immersed their son in Kumon, a Japanese approach to math that emphasizes speed and accuracy in solving equations.

"Kumon gave me confidence and familarity with math," Madni explained. "Anything that was math-related I could do, and I was excited to do."

That excitement still animates Madni. As he sees it, facility with mathematics becomes more crucial as autonomy and additive manufacturing, data analytics, artificial intelligence, and machine learning and other complex technologies become increasingly prominent in aerospace.

At Boeing, Madni works with technologists and business leaders across the company to align an integrated research investment plan encompassing the current priorities and future possibilities of aerospace.

His work as a strategic integrator requires him to see patterns across broad investment portfolios, and includes plans for commercial airplanes, defense, space and services—not to mention the emergent on-demand air mobility ecosystem that will reshape and even disrupt those traditional areas of the business.

"Our job is to make sure that Boeing leaders make the right decisions and R&D investments to achieve our goals—and to do it all at a fast pace so we can shape and serve the marketplace," said Naveed Hussain, who leads Boeing's enterprise technology strategy organization, and who has long been a mentor to Madni.

For that, Hussain said, his team needs thinkers like Madni who consider a multitude of angles and perspectives, know how to find patterns, and look for gaps, which could be both opportunities and pitfalls.

Technology is one part of it. But figuring out how to deliver technologies and create an ecosystem that satisfies people's preferences—"Where is the human in the loop?" as Madni put it—is crucial to the endeavor. Strategy needs to focus on people, he emphasizes, or "eventually technology for technology's sake will overpower everything else and you'll be left with the breadcrumbs of failed ventures."

The challenges of innovating aren't solely technical ones. After earning his undergraduate degrees in computer science and mathematics, Madni focused his graduate studies at UCLA on the ties between math and basketball. He applied his biomedical engineering research to examine stress in players.

"Not everyone on the court can handle winning," he explained. "And that shows up when you measure it."

His research was part of a broader interest in wireless health approaches, ways that non-invasive body sensors could communicate information to doctors and to users. For example, could a smart cane provide feedback to help people improve their gait in order to prevent falls?

"Falls are the greatest cause of death among people over 65," Madni said. "I was centered on approaches that combined medical imaging, informatics and Bayesian belief networks."

What he really wanted to know was: How can we help people who are afraid to go to the doctor?

"Regardless of politics, nationality, race or income, many people are afraid to go to the doctor—even if access isn't a challenge." Elevated stress levels during physician exams can also lead to misdiagnoses, he explained.

ENVISIONING THE FUTURE
Jamal Madni (right) delivers concepts and ideas at a workshop Boeing hosted in 2016, where technologists gathered to explore the future of aeropsace. Also pictured, Boeing technologists Marna Kagele and Jim Salmon.

"He brings this philosophical, human element to everything he says. He can articulate what the future will look like and is able to tie in so many pieces of world culture."

NAVEED HUSSAIN, VICE PRESIDENT OF BOEING ENTERPRISE TECHNOLOGY STRATEGY

For Madni, the same root cause analysis and corrective action—all based in math and the scientific method—apply as much to space vehicle anomalies as to human wellness.

For others, his enthusiasm for technology and people, seeming selflessness and intuitive thinking might arouse suspicion. Is anyone that good?

It took Boeing engineering manager Jen Jacobson time to get over her initial "no one does that much and succeeds" impression of Madni.

"I didn't want to hire him!" she recently kidded with Madni outside the Boeing El Segundo, California, satellites facility. They worked together there for nearly five years. She says today that Madni is uniquely suited to help shape the company's technology strategy and the future of aerospace.

Hussain has experienced the same, describing Madni as a humanities aficionado who does engineering and science. "He brings this philosophical, human element to everything he says. He can articulate what the future will look like and is able to tie in so many pieces of world culture."

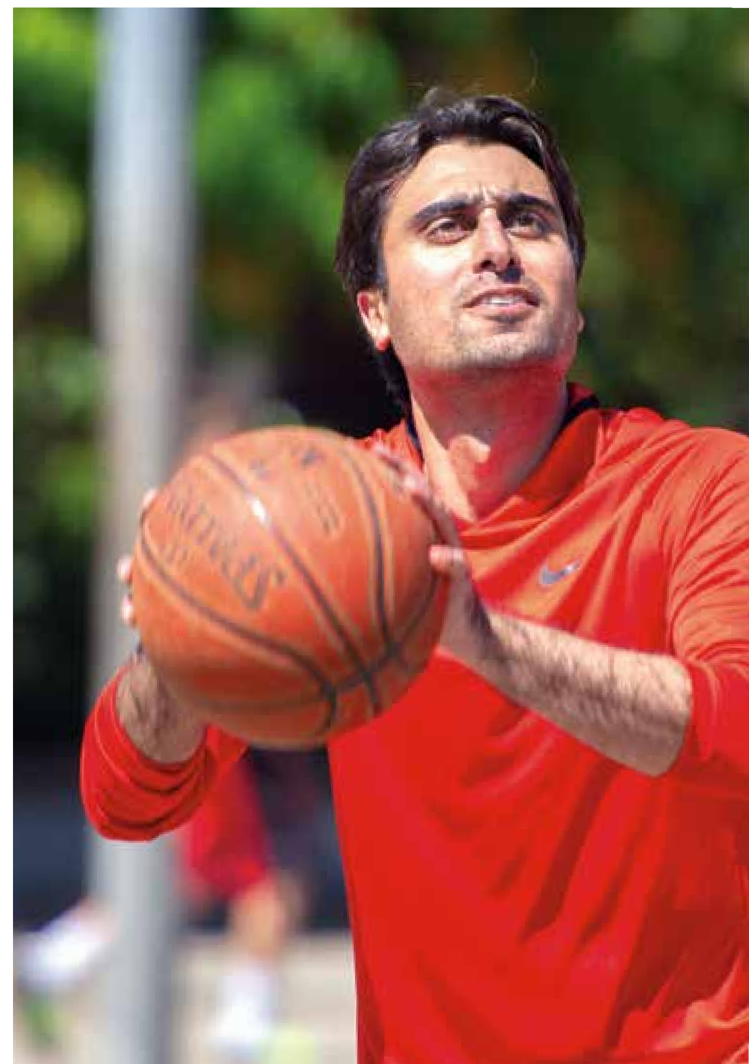
Madni's innovation philosophy is all about connections—whether the nodes are mechanical, electronic or human. And he credits his father for the "Renaissance thinking" that blends the arts and sciences, the mathematical with the human.

Asad Madni developed stability control technologies that were applied to the Hubble Space Telescope, as well as in passenger cars, providing lifesaving rollover protection that is nearly ubiquitous on the road today.

But the elder Madni is an artist at heart, according to Jamal. Born in Bombay (now known as Mumbai) in 1947, the year of India's independence, Asad won national watercolor painting competitions early in his life and always instilled in his son an appreciation of art as well as science.

In addition to his technical work, Madni would regularly come into Jacobson's office with proposals to engage teammates in development and team-building efforts. Not happy hours or softball games, but fully baked plans for what would become the "Rosen Games" (a satellite innovation competition), the Da Vinci Summit (an award-winning employee dialogue series), a STEM engagement program with local schools, and several other efforts to inspire others as thinkers and doers.

"Seeing patterns is one of my fundamental axioms of creativity. There is a real art to finding patterns. Knowing what to look for, having an intuition for the patterns, that is where the humanities comes in," Madni said. IQ

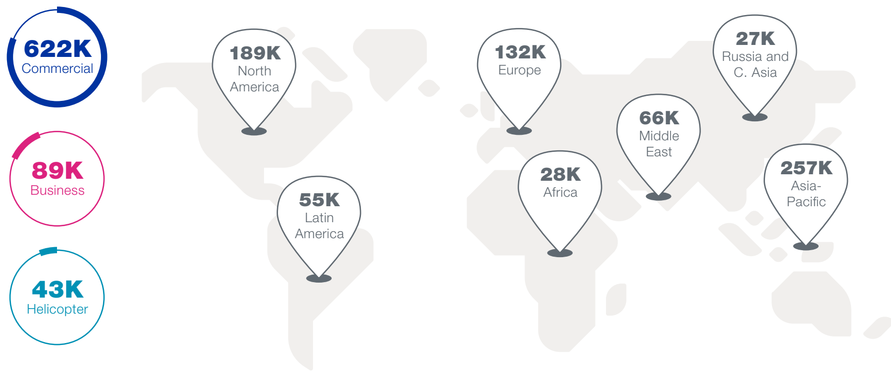


MORE THAN MATH
Jamal Madni's passion for basketball directed his graduate research in informatics where he studied how statisitcal analysis could improve helath and player performance.

New Technician Demand 2018–2037 | **754K World Demand**

THE NEED
Boeing's ninth annual Pilot and Technician Outlook shows unprecedented demand throughout the next 20 years.

GRAPHIC: BOEING



Help wanted

Pilot and Technician Outlook shows unprecedented demand.

BY ALLISON OLSON, BOEING WRITER

Nearly 800,000 pilots and almost as many technicians will be needed industrywide by 2037—double the current workforce and the most significant demand ever reported in the history of the Boeing Pilot and Technician Outlook.

Now in its ninth year, the outlook forecasts the 20-year demand for crews to support commercial airplane fleets, including pilots, technicians and cabin crew. Shared in July at the EAA AirVenture Oshkosh convention in Wisconsin, the outlook includes, for the first time, data from the business aviation and civil helicopter sectors, in addition to the commercial airplane forecast traditionally reported.

The demand is being driven by the anticipated doubling of the global commercial airplane fleet, as reported by Boeing's Commercial Market Outlook, along with ongoing record-high air travel demand and a tightening labor supply.

"Despite strong global air traffic growth, the aviation industry continues to face a pilot labor supply challenge, raising concern about the existence of a global pilot shortage in the near-term," said Keith Cooper, vice president of the Boeing global training organization. "An emphasis on developing the next generation of pilots is key to help mitigate this. With a network of training campuses and relationships with flight schools around the globe, Boeing partners with customers, governments and educational institutions to help ensure the market is ready to meet this significant pilot demand."

The Pilot and Technician Outlook also reported that demand for commercial maintenance technicians decreased slightly to 622,000, with the decrease resulting primarily from the longer maintenance intervals for new aircraft. Commercial cabin crew increased slightly to 858,000 due to changes in fleet mix, regulatory requirements, denser seat configurations and multi-cabin configurations that offer more personalized service.

Boeing provides training products and services for pilots, technicians and flight crews throughout their careers and operates training campuses on six continents. IQ

TOM GRANDINE
SENIOR TECHNICAL FELLOW

The **common** cord

As in the past, technology of the future will be driven by math.

Nearly everything that we do every day depends on advanced mathematics, but not many realize the connection.

Sophisticated mathematical algorithms are required to transform the raw data gathered by medical imaging equipment into images that a doctor can use. Telephone calls cannot be placed or received without the mathematics of networks. Starting and operating a car these days is all about the onboard software. Airport operations depend critically upon math. Onboard systems on airplanes, too. And on and on and on.

> I challenge anyone to identify some function of modern society that doesn't depend in some way on math. I can't think of any.

Each new technical advance, coupled with the speed of modern computers, has made our society more dependent upon math than ever before. As a result, companies like Boeing find themselves having to battle to attract the best mathematicians, statisticians, data scientists, and systems and software engineers the world has to offer.

Newer technologies like artificial intelligence and autonomy are both exciting, given the extraordinary potential they offer to transform society.

The problem is that no one knows why deep learning works, only that, at least for these applications, it does. There is an equally long list of applications for which deep learning doesn't seem to work at all (e.g., playing contract bridge). Unknown is why it works well for some things but not for others. On the applications for which it does work, there is no theory that predicts how well it can be scaled. The mathematics does not yet exist.

Of course, there has always been a need for the creative development and application of mathematics in the design of aircraft. The finite element method for solving partial differential equations in general (and performing structural analysis of airplanes in particular) was invented by Boeing engineer Robert Turner and his colleagues in 1952. And Boeing has maintained an active applied math group since the early 1960s to keep us at the cutting edge of technology.

Having a dedicated collection of people to understand the mathematics being used to design, build and support our products provides several benefits.

For starters, understanding the math mitigates and eliminates risk. If the calculations are understood and certifiable (by whatever means), then the results of simulations based on those calculations can be believed, trusted and built upon.

Even more importantly, understanding the mathematical details at the heart of all of our computations enables new technologies and capabilities that would not be possible otherwise. For example, Boeing developed a sophisticated means of creating mathematical models of wind tunnel and flight test data in the 1980s and 1990s. It enabled raw data to be combined with engineering insight and the laws of physics to create reliable models of the way airplanes behave in flight.

On its own, this technology was and is of great value to us. But its value was multiplied several times over when we realized that the same mathematics also could be used to enable predictive shimming to assemble airplanes in our factories. This technical replication would never have been possible without a deep understanding of the math.

The study and application of mathematics is one of the most creative endeavors of humanity. That's because math isn't just a game of numbers and calculations; it's a method of reasoning. IQ

Tom Grandine is the Boeing Senior Technical Fellow for Applied Mathematics working within the company's advanced research and technology organization.

Analytics in **Bangalore**

Tapping into data science and software talent from the "Silicon Valley of India."

BY PATTADA KALLAPPA, SYSTEM, SUPPORT AND ANALYTICS MANAGER
BOEING INDIA ENGINEERING AND TECHNOLOGY CENTER

In today's digital world, all devices, buildings, vehicles and human beings are looked upon as sources of data from which we can extract information to make day-to-day life easier, safer and more efficient.

The modern factory, aircraft and airport are equipped with thousands of sensors or other measurement devices that collect data related to its operational and environmental conditions. The Boeing 787 Dreamliner alone has more than 7,000 sensors to record parameters like flight path and cabin humidity throughout the entire flight.

PHOTO: BOEING

The advent of fast and distributed computing has enabled storage and near-real-time analysis of this data. These data analytics are focused on generating actionable insights to drive improvement.

With the launch of the Boeing AnalytX platform in 2017, the company has taken a leap into the world of data analytics and big data, with a focus on making our aircraft faster, more efficient and passenger friendly.

Across the globe, Boeing data scientists at various sites are working to develop tools and methods that will extract actionable insight from this data for Boeing and its customers. The Boeing India Engineering and Technology Center (BIETC), located in Bangalore, India, is one such site.

Launched in 2016, BIETC's access to high-end software and data analytics talent in India's Silicon Valley has made it a hub of the company's global work in these areas.

For example, using state-of-the-art big-data technology, the BIETC team has developed a data analytics framework that analyzes aircraft data at high speed to provide insights to our airlines. Collaborating with Boeing's flight data management systems and airplane health management teams in Seattle, we have deployed this framework in the computing cloud. The framework will be offered as a service to airlines, where they can use its predictive analytics service to pre-emptively repair planes and avoid costly grounded-aircraft situations. In the cloud environment, this streaming data analytics framework can be scaled up to process data from thousands of flights the moment they land—and save customers millions of dollars.

These same analytics tools are being applied internally to achieve efficiencies. For example, we have also developed an energy analytics and management software tool that has the potential to reduce energy consumption across our Everett, Washington, site. Developed using state-of-the-art data integration methods and machine learning algorithms, this software monitors and displays energy consumption patterns and provides the operations team with actionable insights to reduce energy consumption in buildings and factories.

The importance of BIETC's capacity to provide data analytics and predictive artificial intelligence expertise to partners and customers around the globe will also continue to grow as Boeing embarks on transformative air mobility endeavors—and as the world's digital transformation and Internet of Things become ever more ubiquitous. IQ

ADDING IT ALL UP
Boeing's technology team in India provides software engineering and analytics support to a worldwide business increasingly dependent on new and larger amounts of data.

Global Scale

Newton Rooms coming across Europe

In order to support aerospace-focused STEM learning and careers, a multiyear Boeing investment will establish Newton Rooms in nine countries throughout Europe. Newton Rooms are state-of-the-art classrooms where students can learn math, meteorology, climate science, navigation and other aviation-related concepts including biofuels and advanced materials.

The learning is reinforced by the experience of full-motion flight simulators. Both fixed and mobile "pop up" Newton Rooms provide free learning resources and materials to teachers and students.

Airline crew optimization for UAE's Etihad

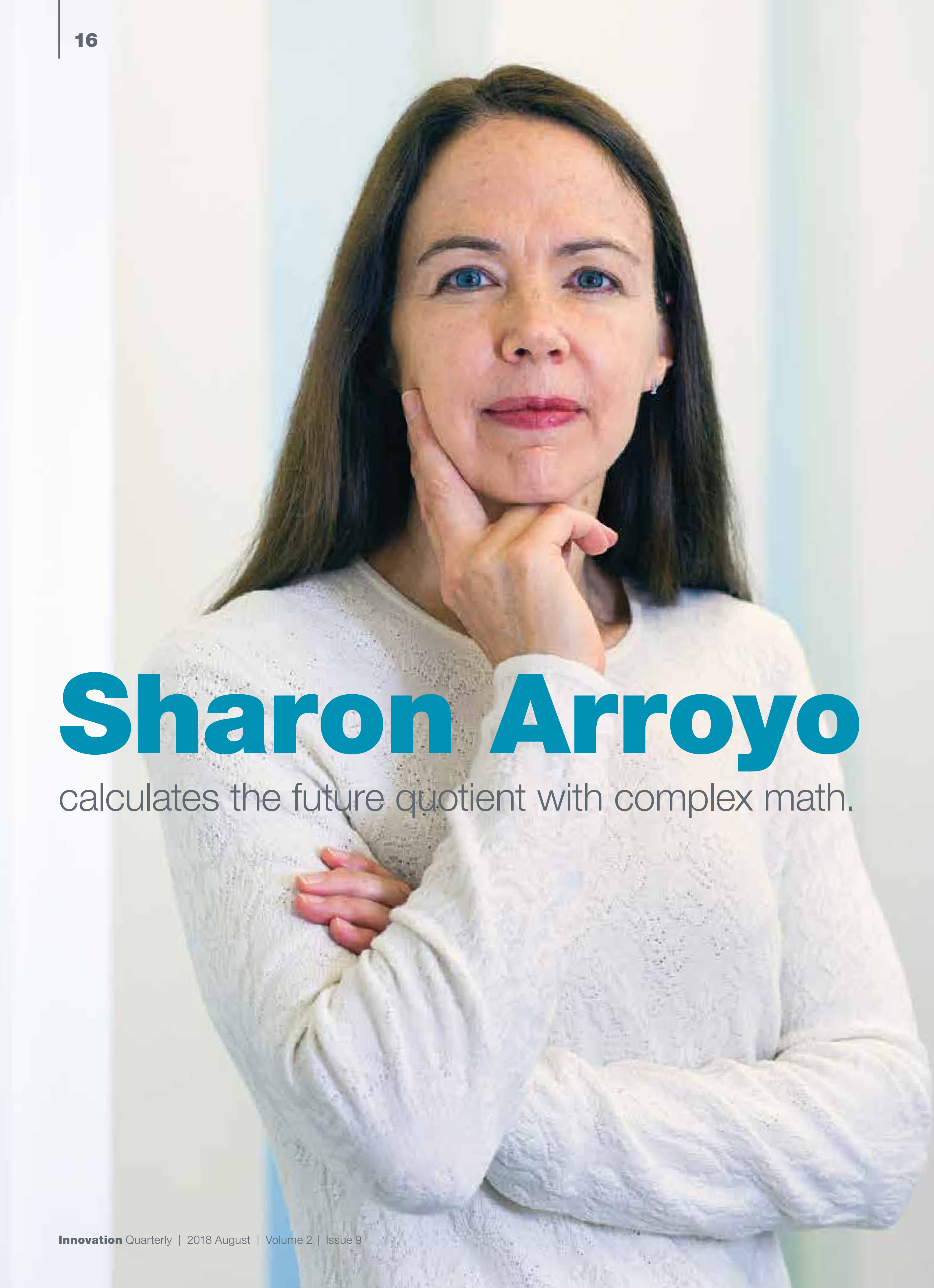
Etihad Airways, the national carrier of the United Arab Emirates, will integrate Boeing subsidiary Jeppesen crew optimization solutions. These include crew pairing, rostering and fatigue risk management that will help the airline with operational planning, crew satisfaction and cost reduction.

Powered by Boeing AnalytX, the portfolio not only increases operational efficiency while respecting crew preferences and constraints, but also builds individualized alertness modeling into rosters to decrease fatigue risk.

Data Analytics with Singapore defense partners

Boeing and the Singapore Defence Science and Technology Agency have agreed to jointly develop an information management tool using data analytics to identify trends and insights on aircraft performance.

The tool will analyze flight and maintenance data for the Republic of Singapore Air Force F-15 and AH-64 aircraft. The data will also be used to develop algorithms for predictive analytics for smarter maintenance and operations.



Sharon Arroyo

calculates the future quotient with complex math.

The marvel of flight has always been driven by a deep understanding of math. It's the job of Boeing's elite group of mathematicians to understand how it will continue to shape the future.

BY CANDACE BARRON, BOEING WRITER | PHOTOGRAPHY BY PAUL GORDON

Q&A with a Boeing Technical Fellow who practices the art of mathematics to improve the world.

Q What technologies of the future will be dependent on skilled and creative mathematics?

A In the future, automation, autonomy and data-driven systems will be even more ubiquitous than they are now. Transportation will rely increasingly on mathematical modeling and optimization of large-scale networks. Artificial intelligence will play a much larger role than it currently does. Machine learning will enable discovery of trends in data and behavior that current technologies don't see. All these technologies rely extensively on mathematics, and none will be realized without skilled and creative mathematicians developing and implementing the core algorithms.

Q Why is mathematics important to Boeing's skill portfolio? Why do we need great mathematicians in addition to engineers who are just good at math?

A The vast size and advanced nature of the engineering work that we do means that very hard mathematics problems naturally arise. It is to our advantage to maintain a staff of expert mathematicians who can roll up their sleeves to contribute specialized expertise in those situations.

> “One of the truly great things about being a mathematician at Boeing is having a front-row seat to a huge number of the many exciting problems we work on at any given time.”

SHARON ARROYO

FIGURING IT ALL OUT
Technical Fellow Sharon Arroyo discusses potential solutions with colleagues from the Boeing Math Group.

Here’s an example of practical yet difficult problem: Say we need to assign mechanics, tools and zones to different tasks to assemble a portion of an airplane. Mechanics might be qualified to perform only certain tasks, which might require more than one mechanic. Some tasks might need to be performed at the same time, while some tasks might need to be performed before others. Limited tools might need to be shared across tasks. And certain zones within the factory might allow for just one mechanic at a time. How do you schedule the mechanics and resources to assemble the airplane in the least amount of time?

Knowing how to extract a solution to the stated problem given the mathematical model can be difficult. Because Boeing maintains expertise in mathematics, we can tackle problems like this in stride.

Q What makes applied mathematics an interesting field to work in?

A Mathematics is inherently multidisciplinary, and it forms the technical basis for a huge portion of what we do.

For example, we have been working with colleagues on supply chain algorithms and tools to determine the best raw material contracts with mills. We leveraged the same technology with little adaptation to improve some of our fastener contracts. We have also been fortunate to work with our commercial marketing team, where we developed solutions to efficiently assign airplane types to airline schedules.

One of the truly great things about being a mathematician at Boeing is having a front-row seat to a huge number of the many exciting problems we work on at any given time.

Q How did you become interested in math?

A I’ve always really loved math. But I knew I wanted to focus on math as a career the day I learned about vector spaces in a linear algebra class in college.

I can still remember visualizing three vectors that could be used to represent every point in three-dimensional space. I thought vector spaces were so cool! Up until that day, the professor had been teaching us more standard math topics like adding and multiplying matrices of numbers. That was fine, but the creativity inherent in vector spaces had me looking forward to new math theories and opening and reading new math books.

Q How can someone be creative with mathematics?

A Mathematicians need to be creative in every aspect of their job. We have to design, develop and deliver mathematical tools at the right level of generality to support the largest number of applications.

When we start a new project, we need to work closely with Boeing customers to understand the problems they need solved. We figure out questions to ask to determine which details need to be included in the mathematical approach. We then write a mathematical problem formulation to make sure all the requirements are represented.

When developing a mathematical formulation, we visualize the problem in such a way that will lead to a good algorithm approach. For example, to determine how best to assign aircraft types to flight legs to optimize efficiency, we visualized the airports as nodes in a network and the aircraft flying along arcs between nodes. Developing a computer implementation of the algorithm also requires a lot of creativity, especially in constructing an architecture that might be used for other applications.

Even after all the hard work is done, mathematical expertise is still required to interpret the results. Richard Hamming, former president of the Association for Computing Machinery, said, "The purpose of computing is insight, not numbers." I love working with colleagues around Boeing to gain new insight from solving math problems.

Q Why is mathematics, in a variety of forms and disciplines, important to the technologies that Boeing is envisioning for the future?

A I view the Third Industrial Revolution, or the Digital Revolution, as the brain child of the brilliant mathematician Alan Turing. He introduced the methodology for massive computations to be performed in fractions of a second by machine. A natural evolution of this breakthrough is for these systems to perform computations even faster, learn to work together and start to approach cognitive tasks.

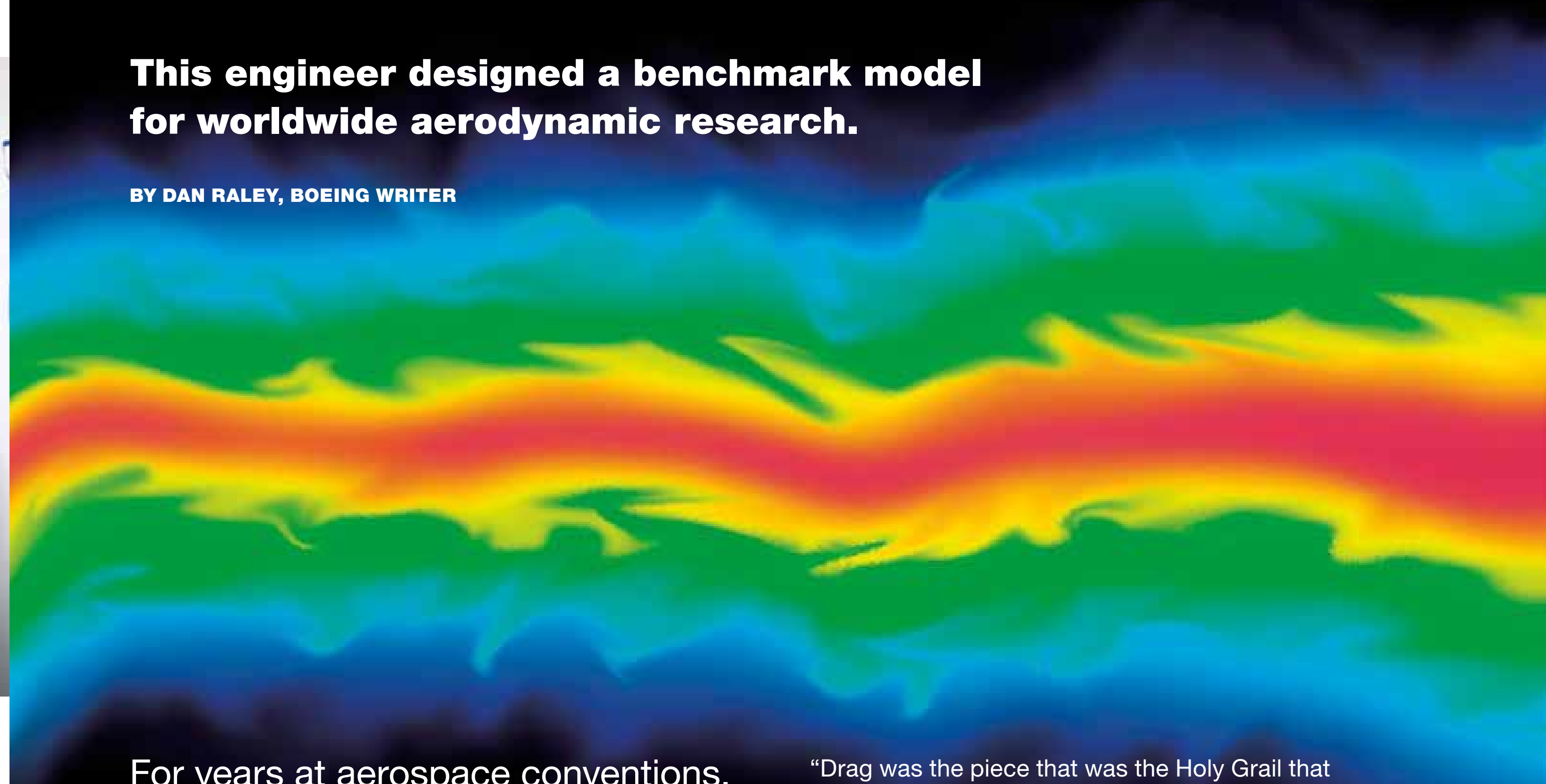
The more solutions that are linked together, the more capable the systems. For example, with prognostics, future problems can be fixed before they happen. Mathematics is a key component of prognostics because developing statistical models is a key step to identifying and predicting these potential future problems. Also, optimization is needed to determine the best approach to addressing the future problems.

Mathematics as a discipline is a common thread tying together this evolution. And it continues to evolve to address emerging technologies, as well as technologies we haven't even thought of yet. IQ

"I've always really loved math. But I knew I wanted to focus on math as a career the day I learned about vector spaces in a linear algebra class in college."

SHARON ARROYO

No drag on this



This engineer designed a benchmark model for worldwide aerodynamic research.

BY DAN RALEY, BOEING WRITER

For years at aerospace conventions, John Vassberg found himself in the middle of the same conversation: Why doesn't the industry have a standard way to measure drag?

By 2000, he and his peers began organizing workshops to address this subject. Eventually, they agreed to work more closely together to explore ways to deal with drag. To support this collaborative effort, Vassberg offered his expertise in computational fluid dynamics, where a computer initially analyzed designs and made adjustments to geometric calculations.

"Drag was the piece that was the Holy Grail that we hadn't been able to secure," Vassberg said.

Nearly two decades later, the industry relies on the result of these discussions—the Common Research Model—as a benchmark. Vassberg, chief aerodynamicist for Boeing Commercial Airplanes' Advanced Concept Design Center in Long Beach, California, designed it. NASA built it. The aerospace world studies it.

First used in 2010, the Common Research Model is a physical model—a metallic 2.7 percent scale model of an airplane shape that falls between a 777 and a 787. NASA can disassemble the 22-foot-long model, transport it around the world and test it in different wind tunnels.

PHOTO: GETTY

A MODEL FOR COMMON RESEARCH
This view of the Common Research Model with pressure-sensitive paint on it, was installed in the National Transonic Facility at NASA Langley.

Right is Boeing Technical Fellow John Vassberg. Left is Antony Jameson, Stanford University professor and worldwide expert in the fieldof computational fluid dynamics and aerodynamic shape optimization.

PHOTO: BOEING

> "I knew it would get tested. It's good to see that a seed I planted out there is proliferating like crazy. There was a need for it."

JOHN VASSBERG

"It has taken off in directions I never imagined," Vassberg said. "I knew it would get tested. It's good to see that a seed I planted out there is proliferating like crazy. There was a need for it."

Common Research Model results were public domain because drag was considered an industry-relevant issue. Engineers discovered how much variation in test data existed from using different wind tunnels as well as in the interpretation of computer results.

"We needed maximum sharing to see what everyone else was doing that was good," Vassberg said. "People could adopt practices. People could see what they were doing wrong."

> Drag is difficult to measure because flying objects come in different shapes and move through the air in different ways, plus air molecules can stick to a surface and change object shapes.

The Common Research Model collaboration sparked so much interest that dozens of similar models have been constructed by aerospace organizations or universities globally for further study. To fit into their respective wind tunnels, ONERA, the French aeronautics, space and defense research lab, built a bigger model than NASA's. JAXA, the Japan Aerospace Exploration Agency, designed a smaller one.

In honor of his work on the Common Research Model, Vassberg was part of a three-person team that received an International Cooperation Award in 2017 from the American Institute of Aeronautics and Astronautics.

"I think of John as a true applied aerodynamicist," said Rich Wahls, NASA strategic technical adviser for advanced air vehicles. Wahls and his NASA colleague Melissa Rivers shared the AIAA commendation with Vassberg.

"He has a feel for everything aerodynamics and can explain it well to people. I've seen him explain it to students, other experts and people around the world. He can use the tools," Wahls added.

The various aerospace groups protect their experimental work involving drag as proprietary, but they welcome any Common Research Model inroads that provide a baseline and will lead to another 1 or 2 percent in fuel consumption savings. They're now discussing lift. They could use the Common Research Model for this project, too. Vassberg remains deeply involved.

"This is a very unique opportunity," said Joe Morrison, NASA's associate project manager for transformational tools and technology. "We were able to combine the efforts of John and Boeing and do the design. John has been a critical element in what we've been trying to accomplish." IQ

Selections from the **Boeing Technical Journal**

The Boeing Technical Journal is a peer-reviewed periodical for Boeing subject matter experts to capture and share knowledge. Research coverage includes all manner of commercial and defense product development, and products and services spanning land and sea, to air and space, and cyberspace.

Contributing Authors

Environmental Impacts of Aerospace Batteries

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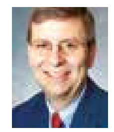
leads tools and data for commercial product development environmental performance and integration.



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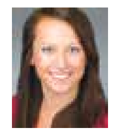

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Monte Carlo Simulation of Large-Scale Complex Life-Cycle Product Patterns for Program Management

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The Journal is a proprietary publication, but the articles on the following pages are summaries of technical papers approved for public release and available online at Boeing.com.

Environmental Impacts of Aerospace Batteries

Summary

BY NIKLAS HANSSON | MARTY BRADLEY | MATT CAMPBELL | DE'ANDRE J. CHERRY | KELSEA COX
DUSTIN D'ANGELO | JOSEPH GONZALEZ | CURTIS MOORE | JEREMY ZEE

Boeing needs batteries today for energy storage in nearly all of its platforms, including airplanes, helicopters and satellites. But to prepare for a future of more aircraft electrification, we must determine a better battery chemistry for the aerospace industry that provides a combination of superior technical performance and minimal environmental impact, ensuring a sustainable and responsible use of energy and its storage.

A commonly used process for evaluating environmental impact is life-cycle assessment (LCA) as described in the International Organization for Standardization (ISO) 14040. The LCA method is used to quantify material and energy flows of a product system, and the subsequent waste and emissions generated throughout the product's life cycle.

Using data provided by the Green-house Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model database, we explored four key life-cycle phases and five impact categories across each battery chemistry:

1. Resource extraction phase explores the energy and environmental impacts associated with the acquisition of raw materials for each battery chemistry and processing the materials into useable forms, such as metal ingots.
2. Manufacturing LCA analyzes the energy and environmental impacts associated with converting the required raw materials into the necessary components to construct a functional battery of each discrete chemistry.
3. Use LCA then accounts for the total energy, emissions and waste associated with the operation of each battery chemistry during in-service or active conditions.
4. End-of-life phase evaluates the energy, emissions and water consumption associated with the separation and recycling of each component of the exhausted battery.

Impacts to the environment from wastes and emissions are used to characterize the "footprint" of a product's life cycle.

This summary represents a literature review and analysis of the battery technologies of both conventional and advanced cell chemistries, the methodology of the LCA approach, the LCA results and a comparison of each LCA metric to determine the optimal aerospace battery.

The conventional battery chemistries included lead acid (Pb-acid), nickel cadmium (NiCd), and nickel metal hydride (NiMH). These batteries are used throughout the aerospace industry and are well established in other industries. Literature and data regarding the conventional battery chemistries and their respective life cycles is abundant, and provided the framework for the other batteries considered.

Advanced batteries included lithium ion (Li-ion), lithium sulfur (Li-S), lithium air (Li-air), and zinc air (Zn-air). These batteries are relatively newer in comparison to the conventional technologies and have promising improved performance.

These batteries exist at a range of technology readiness levels. Li-ion batteries are already being used in aerospace applications, Li-S is under active research, and secondary Zn-air or Li-air batteries are at low technology readiness levels. In fact, use of metal-air batteries in the aerospace industry could be considered only speculative. Information regarding these newer chemistries was limited, and theoretical data was used and assumptions were made to complete the evaluation.

A literature survey was conducted to capture relevant inputs to the LCA study. In all cases, information regarding the system-level battery

Battery Chemistry	Pb-Acid	Ni-Cd	Ni-MH	Li-Ion	Li-S	Li-Air	Zn-Air
Single Battery Weight (lb)	77.18	86.83	47.19	65.12	6.51	10.42	9.30
Number of Batteries per Life Cycle	2.86	2.86	2.86	1.00	1.43	40.00	40.00
Total Life-Cycle Weight (lb)	220.51	248.08	134.82	65.12	9.30	416.77	372.11

TABLE 3.1
Battery weights.

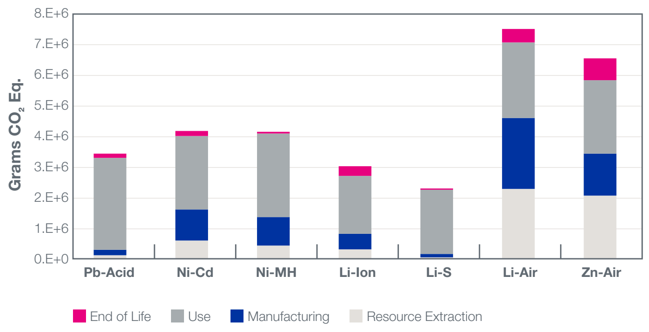

FIGURE 3.1
Life-cycle greenhouse gas emissions.

was used over information for individual battery cells. The 787-8 Li-ion battery was used as a baseline with other chemistries scaled to its performance requirements. Key properties of each chemistry included the materials and relative compositions of each chemistry; the manufacturing process; end-of-life scenarios; and performance attributes such as specific energy (Wh/kg), discharge cycles, depth of discharge and charge efficiency.

Differences in battery weight within the use phase are also a critical consideration for aircraft performance. Increased weight results in greater fuel burn, resulting in emissions and upstream fuel production impacts. For this, information regarding the impacts of a 787-8 was taken from quickLCA, a software tool developed by Boeing to conduct aircraft-level LCAs.

Table 3.1 shows calculated weights of each battery chemistry needed to complete the performance requirements of the aircraft. Included are the single battery weight (the weight aboard the aircraft), the number of batteries used over a five-year period, and the total battery weight (all the batteries used in that period).

Figure 3.1 shows the total greenhouse gas (GHG) emissions represented in grams of CO2 equivalents. Figure 3.3 shows the total life-cycle water consumption of each battery for similar life-cycle phases represented in Figure 3.1.

Results for CO2 emissions generated and water consumed by each battery, follow similar trends in terms of relative performance to other batteries. When excluding impacts to aircraft performance, each of these environ-mental performance measures is driven by total battery weight. Li-S and Li-ion consistently outperform other chemistries, while Li-air and Zn-air perform significantly worse than the other batteries.

Figure 3.4 shows the total life-cycle solid-waste-to-landfill of each battery for similar life-cycle phases represented in the previous figures. These results are significantly different from the other environmental performance measures.

Here, resource extraction dominates over the other life cycles. Li-S and Li-ion perform the best while Li-air and Zn-air perform orders of magnitude worse.

Figure 3.5 shows the total life-cycle energy consumption of each battery chemistry with the same life-cycle phases represented as Figures 3.1, 3.3 and 3.4, with the exception of the use phase. The use phase is divided into the energy actually used for the aircraft mission and the energy lost to charge inefficiencies. Results of Figure 3.5 demonstrate the dependence on

To prepare for a future of more aircraft electrification, we must determine a better battery chemistry for the aerospace industry that provides a combination of superior technical performance and minimal environmental impact, ensuring a sustainable and responsible use of energy and its storage.

Aviation Batteries

LEAD ACID BATTERIES

The Pb-acid battery chemistry is an established technology that was invented in 1859, making it the oldest rechargeable battery. The Pb-acid battery can be found in various aerospace applications. The components of the Pb-acid battery cell include a cathode comprised of lead peroxide, an anode made of sponge lead, electrolyte of sulfuric acid and a fiberglass separator.

The advantages of the Pb-acid battery are its manufacturing simplicity, mature technology, dependable service, low maintenance requirements and low cost. Additionally, processes have been established to make the Pb-acid battery highly recyclable. It is estimated that 95 percent of all Pb-acid batteries produced are recycled, and new Pb-acid battery materials range from 60 to 80 percent recycled content.

NICKEL CADMIUM BATTERIES

Although the basic chemistry for NiCd batteries has been used for some time, there has been continuous development on the electrode, electrolyte and packaging technologies to enable a wide range of applications. The components of the NiCd battery cell include a cathode composed of nickel hydroxyl oxide, an anode made of metallic cadmium and an electrolyte of potassium hydroxide.

NiCd cells come in all forms for many applications, such as small cylindrical cells for lower power, pocket-plate for high mechanical and electrical abuse, and sintered plate for higher-rate discharge. The flexibility of NiCd batteries is why they are used on many Boeing defense and commercial products with specific power requirements. Besides the wide range of applications that NiCd batteries have, other advantages include reliability, long battery cell life, low maintenance, long storage life and a wide range of operating temperatures.

NICKEL METAL HYDRIDE BATTERIES

NiMH batteries are commercially available batteries that are widely used in hybrid vehicles and portable electronics. The NiMH battery originated as the successor to the NiCd battery and exhibits a higher energy density and specific energy when compared to Pb-acid and NiCd. The components of the NiMH battery cell include a cathode composed of nickel hydroxyl oxide, an anode of mischmetal (Me) hydrides, electrolyte of potassium hydroxide and a separator of a porous polypropylene membrane.

Recyclable materials are used in the construction, and the battery does not contain hazardous materials such as cadmium, mercury or lead. The batteries are also maintenance free, and are safe during charging and discharging.

NiMH batteries are not historically used as a primary source of power in aircraft applications, although the NiMH cells are used within other aircraft equipment or systems, such as the emergency door and floor escape path lighting, as well as portable entertainment devices and electronic flight bags.

LITHIUM ION BATTERIES

Li-ion batteries provide energy on a vast array of programs across Boeing. The designs for each of these platforms include either small- or large-cell formats making up the battery pack. Small-cell batteries offer many advantages over large cells, including high reliability, high-volume manufacturing, high-volumetric efficiency and reduced likelihood of cell-to-cell thermal runaway propagation.

A Li-ion cell comprises a cathode that contains lithium composite oxide materials (LiMnO, LiCoO2, etc.), while the anode is graphite-based composite. The electrolyte varies in composition but is commonly a combination of ethylene carbonate [solvent], diethyl carbonate [solvent], and lithium hexaflurophosphate [salt]. Li-ion batteries are sealed cells, requiring no maintenance, and the chemistry offers high specific energy and low discharge rates, thus providing an extended cell life cycle.

Environmental impacts are minimal in the production of lithium, and extraction processes are not energy-intensive. However, recycling standardization is challenging due to the variation in materials within the cathode, anode and electrolyte used to construct Li-ion batteries, as well as diversity in shapes and sizes.

LITHIUM SULFUR BATTERIES

The Li-S battery is capable of revolutionizing the battery industry. With a theoretical energy capacity of 2600 Wh/kg, it has an energy capacity, five times higher than Li-ion batteries. The battery is lightweight, inherently safe (doesn't make use of flammable solvents), durable and maintenance-free. The battery has a low cost in comparison to anode- and cathode-based materials such as graphite and LiCoO2, respectively. For comparison, the cost per capacity ($/kAh) is 110 (LiCoO2) versus 1.9 (graphite) versus 1x10-3 (Sulfur).

As with all lithium battery chemistries, there is a risk of combustion if lithium is exposed to the air. The primary weaknesses of the cell chemistry are the formation of lithium dendrites and dissolution of sulfur active materials from the polysulfide shuttle effect, ultimately limiting the charge-discharge cycle life.

Advancement in this technology is showing the likelihood of the Li-S battery becoming the battery of the future. The current industry leader in Li-S technology is Oxis Energy, which currently produces the rechargeable Li-S Rack Mounted Battery for European consumers.

LITHIUM AIR BATTERIES

Li-air, also called a Li-oxygen battery, is typically designed using a lithium metal anode, a porous carbon cathode and an electrolyte (typically lithium salt). Metal-air batteries have the highest energy density because the cathode active material (oxygen) is not stored in the battery, but can be accessed from the environment. Currently lithium batteries are the subject of Advanced Research Projects Agency-E efforts, but are not mass produced commercially. The theoretical capacity of Li-air batteries makes them very attractive for aerospace and automotive applications; however, several technical challenges need to be overcome.

One of the major drawbacks of this technology is current Li-air batteries lose 25 percent of their original capacity after only 50 discharge cycles. Charge efficiency with a carbon cathode is only 57 percent, which falls well short of the typical aerospace efficiency of >90 percent. Use of platinum or gold catalysts can improve this to 73 percent; however, this is not likely to be a commercial solution due to the cost of platinum and gold.

ZINC AIR BATTERIES

As mentioned earlier, the greatest benefit provided by metal-air batteries is their high energy density compared to other battery chemistries. The Zn-air configuration represents a safe, environmentally responsible and potentially inexpensive option for the storage of electrical power. Because of this fact, a recent surge in research efforts has developed in Zn-air battery chemistries for potential usage in both portable (cellphones, laptops) and stationary devices (power grid), as well as electric vehicles.

Zn-air batteries are composed of three main components: a zinc anode, an alkaline electrolyte (potassium hydroxide), and an air cathode usually made of a porous and carbonaceous material.

When comparing Zn-air batteries to other metal-air chemistries, there are several potential advantages that can be exploited in the battery manufacturing process. One example is the abundance of zinc metal as a raw material. This key benefit potentially provides an advantage in the hypothetical expense of the mass production of Zn-air batteries. With respect to the environment, zinc, as a raw metal, is a safer material than lithium and can be fully recycled.

BOEING SUGAR VOLT

The SUGAR Volt, which would use a hybrid-electric propulsion system, is one of several notional concepts for the 2030-2050 time frame that a Boeing-led team studied for NASA as part of the Subsonic Ultra-Green Aircraft Research (SUGAR) project.

ILLUSTRATION: BOEING

total battery weight similar to the results of Figures 3.1 and 3.3.

The life-cycle energy storage performance of a battery can be characterized by the total energy stored by the battery over its lifetime compared to the total energy consumed by the battery over its life cycle. Batteries that have a percentage of 50 percent or greater use more energy to perform the function of the battery (energy storage) than is needed to generate and dispose of the battery. Table 3.2 shows this "energy-use" percentage of each respective battery in this study.

Li-S is the best-performing battery by this metric. However, Pb-Acid and Li-ion are both near the 50 percent target. Given the assumptions made and fidelity of the data, they could also be considered high-performing. Alternatively, the metal air batteries show very poor performance.

When aircraft performance is considered, each of these four environmental performance measures are driven by the weight of a single battery. Li-S again outperforms all other batteries, while the performance of the two metal-air batteries greatly improves, as shown in Figure 3.10. Because additional weight to the aircraft contributes negligibly to solid waste generated during use, the solid-waste results remain constant whether considering aircraft performance or not.

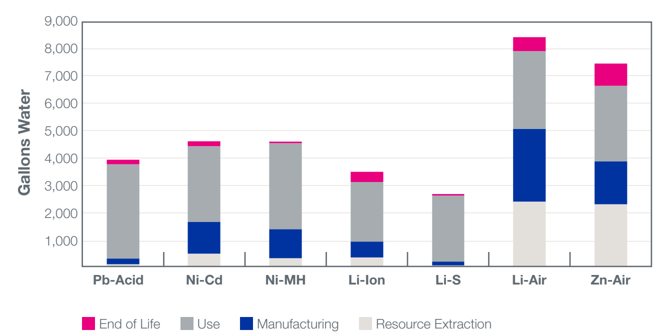

FIGURE 3.3
Life-cycle water consumption.

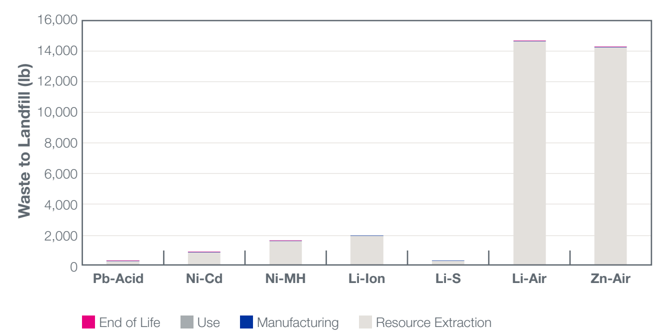

FIGURE 3.4
Life-cycle solid waste.

When taking into account aircraft performance, the results show the energy intensity of materials and manufacturing processes are less significant than the overall technical performance of the battery. This is true for each measure except solid-waste-to-landfill. The high volumes of waste generated by the metal-air batteries are driven by the limited number of discharge cycles, requiring the batteries to be replaced more often.

Recycling measures are a classic method to reduce impacts to resource extraction. However, it is evident that recycling measures could greatly reduce the amount of solid-waste-to-landfill for every battery chemistry.

In every metric of this study, Li-S batteries outperformed the other chemistries. Li-S low weight overcame perceived shortcomings such as low charge efficiency, poor recyclability and energy-intensive manufacturing processes.

Not only do Li-S batteries have the lowest environmental impact potential for aerospace, they also promise significant advantages in technical performance. However, the technical maturity of this technology will need to improve further to realize some of the life-cycle benefits outlined in this study. IQ

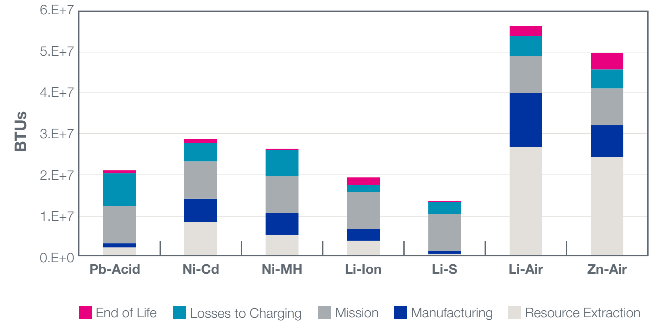

FIGURE 3.5
Life-cycle energy.

Pb-Acid	Ni-Cd	Ni-MH	Li-Ion	Li-S	Li-Air	Zn-Air
43.49%	31.79%	34.70%	47.49%	68.06%	16.14%	18.32%

TABLE 3.2
Useful energy percentage.

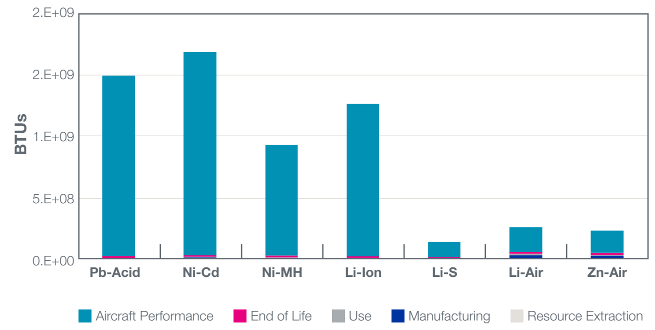

FIGURE 3.10
Life-cycle energy.

To read and download the complete Boeing Technical Journal paper titled:

"Environmental Impacts of Aerospace Batteries"

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Monte Carlo Simulation of Large-Scale Complex Life-Cycle Product Patterns for Program Management

Summary

BY SCOTT D. BUTTON | JOSHUA W. BROWN | TEK D. KIM | THOMAS E. SHERER

Cognitive bias unfavorably affects how we make decisions under uncertainty. This is exacerbated with the increase in scale and complexity of systems that are affected by those decisions.

Methods are needed to provide decision analysis support for program managers and other engineers faced with allocating scarce resources for large-scale, complex product development.

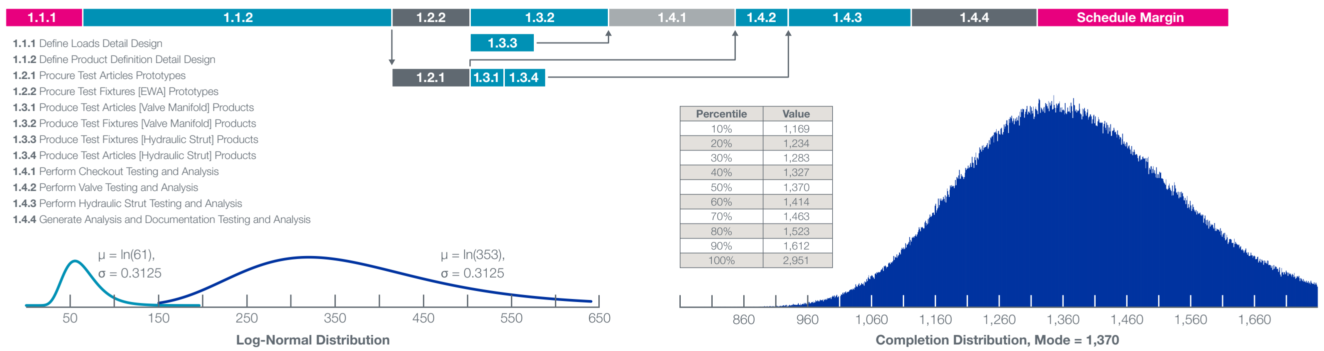
The approach described in this summary extracts a life-cycle thread from an overall product development network and uses Monte Carlo analysis to simulate options for resource allocation. By doing this, we can then describe the trade-offs between the resource allocation choices. Expected benefits are reductions in the cost and the elapsed time from beginning to end of programs that contain significant product development.

This approach starts with Lean+ Systems Integration Management (LSIM), a set of tools and methods demonstrated to increase productivity and improve affordability of product development. The principle objective of LSIM is to perform the right work in the right order to reduce unplanned and out-of-sequence rework. This model-based approach improves the quality of deliverables, increases throughput, facilitates cross-functional integration, and provides management a predictive model with regular feedback on focus areas requiring their attention.

In 2015, we started developing life-cycle threads from our LSIM integration models. The context of a thread is the life-cycle maturity of information for a few functional groups—for example, how the Flight Controls team and the Stability and Control team interact to mature information from concept to deliverable. These thread features enable the use of statistical clustering to extract a life-cycle pattern of products and inputs, and to apply this life-cycle pattern to other products to establish similar patterns of inputs, without manually selecting these inputs. This has the potential to significantly speed up our modeling process.

In 2016, we enhanced these features to provide network diagram plots. We created the ability to add to a thread from a tree view of the product hierarchy, produce a network diagram with nodes and edges colored according to the responsible organization, and populate the nodes with additional helpful information.

Expected benefits are reductions in the cost and the elapsed time from beginning to end of programs that contain significant product development.



Percentile	Value
10%	1,169
20%	1,234
30%	1,283
40%	1,327
50%	1,370
60%	1,414
70%	1,463
80%	1,523
90%	1,612
100%	2,951

FIGURE 2
Semi-levered landing gear thread, horizontal axis in units of days.

PHOTO: GETTY

Probabilities and Randomness

Monte Carlo analysis is a simulation method named after the famous Mediterranean gambling resort. These methods are a broad class of algorithms requiring repeated random sampling, essentially using simulation to solve probabilistic problems.

In 2017, we added a Monte Carlo analysis of these threads. This new approach enables functional managers to understand the expected completion distribution of their function, in the context of the overall program.

To conduct a Monte Carlo simulation, a sample is drawn from a defined distribution representing each task. Each sample from the defined distribution constitutes a trial, and 100 to 1 million trials are typically evaluated to determine the results.

The mainstream approach to simulation of project duration is by assuming a shape for the task distributions, then aggregating the tasks according to the project network to form a project completion distribution.

For this Monte Carlo analysis, we selected the log-normal distribution to use as the shape of the distribution for task duration. We favor the log-normal distribution, as it only requires our program sources to estimate the average duration and validate our assumption that the safe duration should be two standard deviations longer than the average duration.

Figure 2 illustrates a network thread for the 787 semi-levered landing gear.

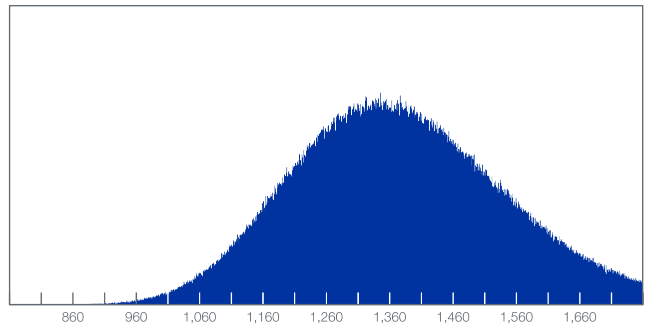


FIGURE 5
Completion distribution, mode = 1,370 days.

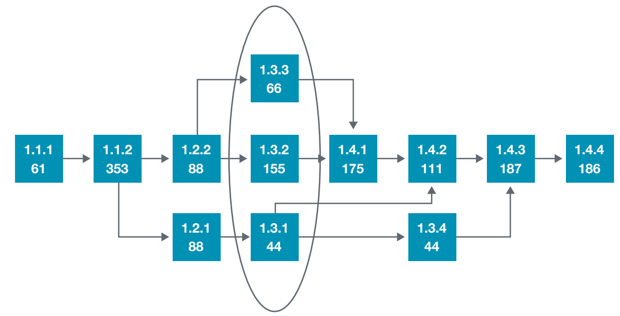


FIGURE 8
Landing gear network diagram.

This is a thread excerpted from a larger, airplane-level integration model. The curve below the first two tasks in the thread represents the log-normal distribution of durations for each task.

For each task in the network, a random sample is taken from the probability density function representing that task. A finish time is computed for each task, which is the sum of the sampled task duration and the finish time of the latest predecessor to that task. The finish time of the terminal product in the network represents the finish time for the thread, for one run of the Monte Carlo analysis.

This is repeated numerous times (1,000 to 100,000) to form the completion distribution of the thread. Figure 5 shows the histogram for the completion distribution of the terminal product in the thread. Note the completion distribution shifts toward a more normal distribution, due to effects predicted by the Central Limit Theorem.

The network diagram is shown as Figure 8: Landing gear network diagram. The upper number is the uniform resource identifier; the lower number is the duration in days. The three tasks involved in the trade-off are indicated with an ellipse.

We find it rather interesting that by moving resources from 1.3.1 to 1.3.2 in this example, the project duration is reduced approximately the same amount as if you doubled the resources on 1.3.2 in isolation. This is due to sufficient slack in the noncritical path feed from 1.3.1 downstream. Although this effect is somewhat obvious for this simple network, the technique will provide non-obvious results for more complex networks.

This shows that Monte Carlo analysis methods are useful to demonstrate the trade-offs between time and resources for life-cycle threads in a commercial aircraft program. And it allows program managers and engineers to understand the role of variation and uncertainty in large-scale, complex, life-cycle product patterns. This understanding is central to meeting the flow time and cost improvement necessary to remain competitive. IQ

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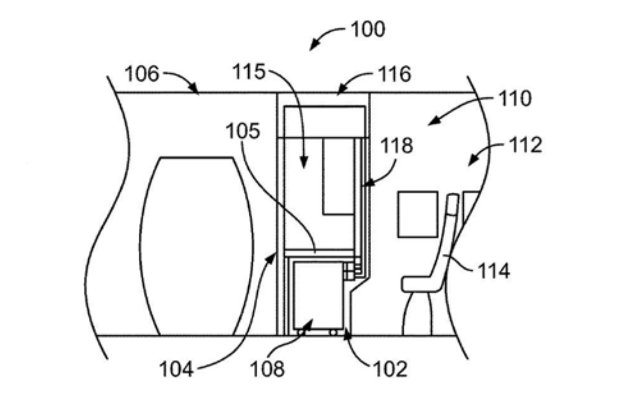
Patent **spotlight**

Check out a few of Boeing's latest ideas and technical breakthroughs recently granted or published by the U.S. Patent and Trademark Office.



Galley Cart and Galley System of an Aircraft

U.S. PATENT 9,957,050
INVENTOR: THOMAS JOSEPH MORAN

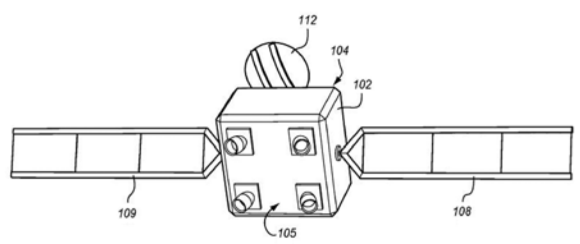
Efficient use of cabin floor space directly influences airline operational costs. Galleys, while necessary to safely manage food and beverages, occupy significant cabin floor space because of the carts and the refrigeration system.

The refrigeration system's airflow ducts typically connect to the back of the carts at the galley rear wall and consume about 4 inches of the galley depth and the associated cabin floor space. Considering that some aircraft can have up to eight centerline galleys, this takes up a lot of space.

This newly issued Boeing patent describes a galley refrigeration system and cart compartment that eliminate the typical return duct at the back of the cart without requiring a new cart design. With this new configuration, the cabin floor space traditionally occupied by galley refrigeration system ducting can be repurposed.

> "The U.S. is the largest world contributor in important innovation inputs and outputs, including in investment in R&D, and patent applications, and scientific and technical publications."

GLOBAL INNOVATION INDEX 2018, A PUBLICATION BY CORNELL UNIVERSITY, INSEAD AND THE WORLD IINTELLECTUAL PROPERTY ORGANIZATION, JULY 2018



Spin Stabilization of a Spacecraft for an Orbit Maneuver

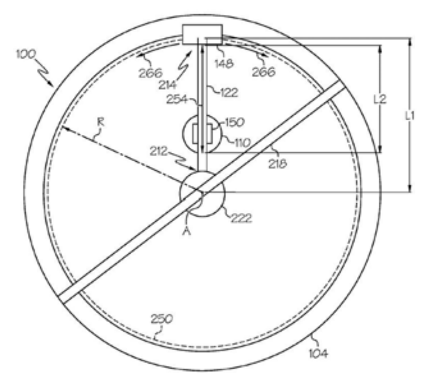
U.S. PATENT 9,963,248
INVENTORS: QINGHONG W. WANG, ALEXANDER JACOB SOBEL, GARY LEMKE, TIMOTHY LUI, KANGSIK LEE, GLENN N. CAPLIN, TROY ALLEN FONTANA

A geosynchronous satellite follows the direction of the Earth's rotation as it orbits. To put it into a geosynchronous orbit, the satellite is loaded into a payload of a launch vehicle, which then carries the satellite into space. The launch vehicle may not carry the satellite all the way to the geosynchronous orbit, however, releasing it instead at a lower orbit. The satellite then maneuvers itself with its onboard thrusters to complete the transfer to its geosynchronous orbit.

Torques on the satellite make it difficult to maintain attitude control when passing through low perigees. Torque can spin the spacecraft up or down, and the spinning might require frequent adjustments of spacecraft momentum using thrusters.

This recent Boeing patent describes how to stabilize the spinning satellite in the transfer orbit and increase efficiency of thrusters used in the orbital maneuvers.

This patent claims a method and the hardware to align each thruster force parallel to the spin axis, and to use wobble and nutation control with wheels (momentum wheels, reaction wheels or control moment gyros) to stabilize the satellite's spin. Because the thruster force is parallel to the spin axis, it produces near-zero torque about the spin axis. Therefore, thruster firing for an orbit maneuver will not cause the spacecraft to spin up or spin down, but will maintain the spacecraft total momentum near constant.



Appartuses And Methods for Additive Manufacturing

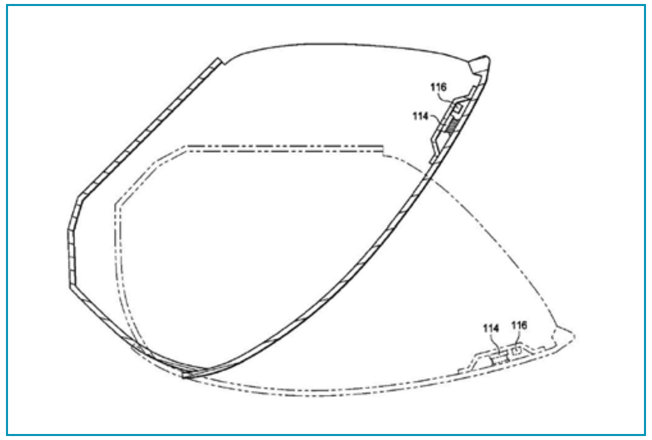
U.S. PATENT PENDING
INVENTOR: ADAM R. BRODA

Conventional manufacturing techniques for large-scale assemblies generally require the interconnection of various parts, using lots of fasteners and other associated hardware to form the final structure. Existing manufacturing techniques for large-scale structures are labor-intensive, increase manufacturing cycle time and cost, and limit design freedom.

This application, recently allowed by the United States Patent and Trademark Office, describes a 3D metal printer for large aircraft structures.

The proposed apparatus would fabricate an entire large structure in one piece.

The apparatus comprises a linear rail that can rotate or revolve in a horizontal plane about a vertical axis. An electromagnetic energy source is coupled to the linear rail and is movable in a polar coordinate system. Metal powder is used in the build. The powder can also be contained and discharged through vents.

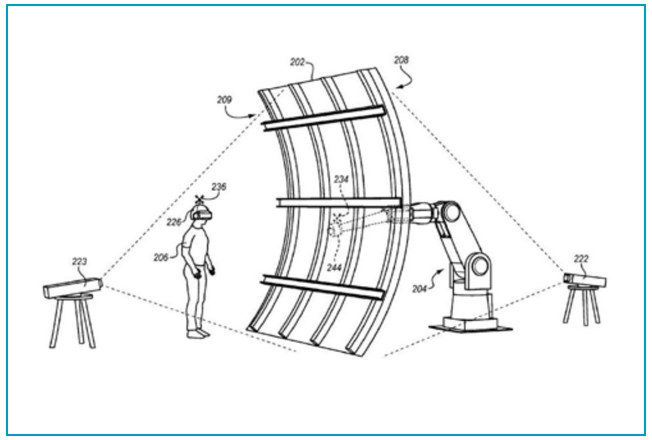


Apparatus and Methods for Acoustically Exciting a Face Panel of a Stowage Bin Inside a Vehicle

U.S. PATENT 9,936,272
INVENTORS: YAKENTIM IBRAHIM, KEVIN S. CALLAHAN, MICHAEL ALAN FEINBERG

Flat-panel speaker technology is often used to provide audio for environments like the inside of airplanes, where space and weight are priorities. This recently issued Boeing patent suggests a method for using flat-panel speaker technology to turn a stowage bin into an audio source using resonant vibration. An electroacoustic transducer is integrated into the face panel of the stowage bin, thus enabling acoustic excitation of the face panel.

Using an exciter instead of the conventional speaker cone is also more efficient. Positioning the electroacoustic transducer in such a fashion in a stowage bin instead of a conventional speaker frees up additional space. This enables other surfaces, such as the ceiling panels of the passenger compartment, to be used for other functionalities like a high-definition display system.



Virtual Display of the Real-Time Position of a Robotic Device to a Human Operator Positioned on an Opposing Side of an Object

U.S. PATENT 9,964,765
INVENTOR: JIM GARDINER

Humans use robotic devices to assemble and fabricate objects and structures, including really large objects such as fuselages. However, sometimes the human operator cannot see how or where the robotic device is operating. For example, if a robot is drilling a hole through an object, the human operator will not be able to see where the robot is drilling until the drill bit pierces the object. This may slow down manufacturing and may also be dangerous.

So how can the human operator "see" through the object? This recently issued Boeing patent suggests using augmented reality (AR).

The invention is a system where the human operator wears an AR headset, while a robotic device operates on the other side of an object. The system tracks the position of the robot and displays it to the operator using the AR headset.

This invention both improves the speed of manufacturing processes and the safety of people in an automated environment.

College **signing** days

Students pledge to study STEM in celebrations across the United States.

BY KATE EVERSON, BOEING WRITER

PHOTO: BARBARA FREEMAN

LOOKING TO THE FUTURE
Mark Cassel (right), director of Boeing's global engagement strrategy, poses with one of the 50 students recognized at the Chicago STEM Signing Day held at City Hall.

Just as athletes sign letters of intent to play college sports, high school students are increasingly signing "STEM Letters of Intent" to pursue their education at some of the nation's top colleges and universities.

Boeing sponsored five events this spring in Chicago, South Carolina, Alabama, Southern California and Seattle recognizing more than 240 students across the United States.

STEM signing days, which started last year in South Carolina, are modeled after sports signing days, complete with pumped-up music, photo ops and addresses from company and community leaders. Students sign letters of intent to continue their education and seek a career in STEM, from medicine and civil engineering to computer science and aerospace.

Among the Chicago crew was Sydney Wilson, who graduates soon from Jones College Prep and will be studying aerospace engineering to pursue a career in space and satellites. She and the 49 other signees applied through Chicago STEM Pathways Cooperative, a community-based effort aimed at addressing inequities in the STEM learning landscape.

Supporting primary and secondary education is part of Boeing's global engagement strategy, which focuses on improving access to globally competitive learning, contributing to workforce and skills development, and supporting military and veteran communities.

At the Seattle event, Chris Reykdal, Washington superintendent of public instruction, praised the discipline that lead the students to their academic success. "We want to elevate you and let you fly in any way that you want," Reykdal said.

It's advice America Sevilla, from Pasco, Washington, plans to follow. She is the first member of her family to attend college and plans to become a pharmacist. Being recognized at STEM Signing Day was validation for all of the work she has put into her studies.

"I want to help others with new medications we need to find in this world," Sevilla said. "It's an important step because they can see how much I value school and how much I value my education and how important college is for me." IQ

MODEL REFERENCES
Morgan Langston, quality assembly inspector, discusses the current configuration on an aircraft using the latest patented technology, linking two visualization systems together.

PHOTOS: BOEING

The **new look** of innovation

Photographers and computer engineers come together from different parts of the company to invent a more efficient design process.

BY JEREMIAH SCOTT, AUGMENTED VR TOURS TEAM LEADER
BOEING ENTERPRISE SERVICES

When you think "aerospace innovation," images probably come to mind of satellites and space planes, sleek airliners and autonomous aircraft. But the realm of invention isn't ruled solely by rocket scientists and advanced research and development. The truth is that innovation in a company as vast as Boeing can come from anywhere—even from a photographer like me.

A couple of years ago, the Boeing Everett Modification Center asked my group, Scientific Imaging, to fully document the flight test configuration of one of the early 787 flight test airplanes. Their request was to photograph both the main and cargo decks of the aircraft, as well as all of the exterior areas, providing a complete visual record of the current condition of the aircraft.

The photographs would be used to reference the current condition of the aircraft and compare it to the design configuration. This process would support building an estimate of the work necessary to reconfigure the aircraft to be sold as a Boeing Business Jet.

In order to streamline this process, I recommended using virtual tour technology, a photographic, interactive computer walk-through of an airplane's exterior and interior, similar to a real estate tour of a house. This "as-built" interactive record has a myriad of uses both inside and outside the company.

In order to determine the required configuration, the 787 Program used Boeing's own patented Integrated Visualization Technology (IVT) that provides a 3D rendering of all (available modeled) systems and parts installed on every commercial airplane. The user can pan and zoom through layers of modeled data, and click to view part information.

And so it struck me: What if we tied the IVT and virtual tour technologies together? Networking these technologies could streamline Boeing's current process, allowing modification engineers to quickly compare the as-designed models to the as-built configurations. Could the solution really be that simple?

With the help of IVT experts, Associate Technical Fellow Jim Troy for IVT and industrial engineer Katherine Meza from the Boeing Visualization Center of Excellence, we joined these two systems in order to support Boeing's needs. We built the: "Synchronized Side-by-Side Display of Live Video and Corresponding Virtual Environment Images."

The process allows users to display a panoramic image captured for a current environment and then display a visualization of the corresponding 3D model at the same viewpoint. Communication between the computer applications—a panoramic image viewer application and a 3D model visualization application—provides the ability to synchronize viewpoints and information relative to engineering and the real-world environments.

Program managers estimated the new technology saved thousands of labor hours in only its first year of use. Since its initial deployment on 787 in 2016, the technology has been used for the 737, 747, 767, and 777, and is driving additional applications and replication across Boeing defense programs.

Turns out, even the simplest solutions can become valuable innovation. The U.S. Patent Office granted the patent for this new invention in February 2018. IQ

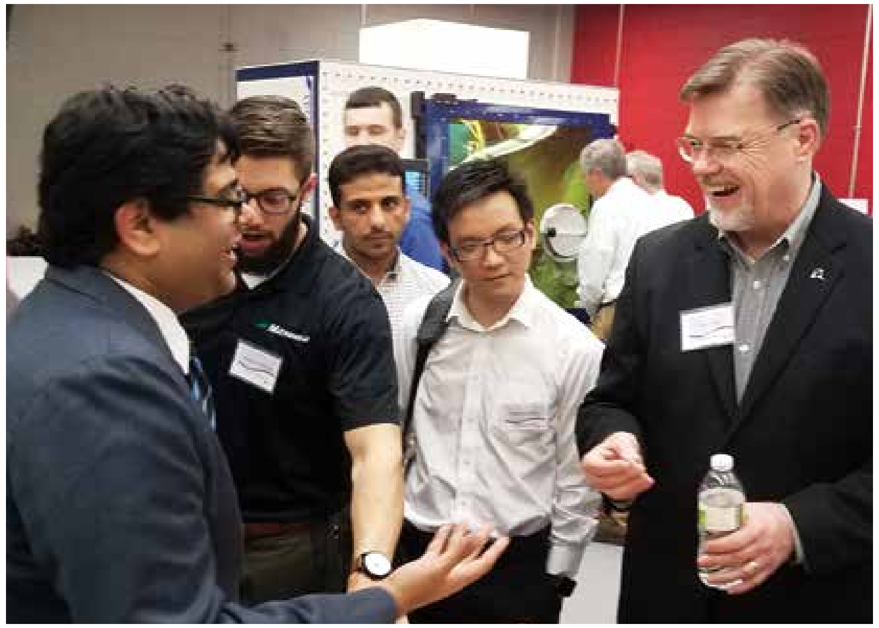


PHOTO: BOEING

PHOTO: BOEING

PHOTO: BOEING

PHOTO: BOEING

Spreading the word and wonder of engineering

From the top, left to right:

ADDRESSING ADDITIVE MANUFACTURING IN THE GREAT PLAINS
Greg Hyslop (right), Boeing chief technology officer, shares a moment of levity with Prahalada Rao (left), of the University of Nebraska, as they look over 3D-printed parts at an open house of the school's additive manufacturing lab.

ENGINEERS OF THE YEAR
Boeing Engineers of the Year celebrating their awards with a selfie. From left, Peter Kamber for Global Services, Marilyn Aarnio for Commercial Airplanes, John Mc Tigue for Engineering, Test & Technology, and Raenaurd Turpin for Defense, Space & Security.

BEING TECH AT BTEC
Nearly 1,200 people met in St. Louis in May for the largest annual gathering of the Boeing technical community. The Boeing Technical Excellence Conference brings together engineers, scientists and technologists from across Boeing's businesses, subsidiaries and international offices to share knowledge and discuss ongoing projects and R&D.

WAY MORE THAN SUPERSONIC
Boeing's Mike Sinnett (left), vice president of commercial product strategy and future airplane development, and Senior Technical Fellow Kevin Bowcutt, Boeing's chief scientist for hypersonics, shared a passenger-carrying hypersonic concept design at the AIAA AVIATION Forum in Atlanta in June.

The virtual history of computation

How fast we do the math

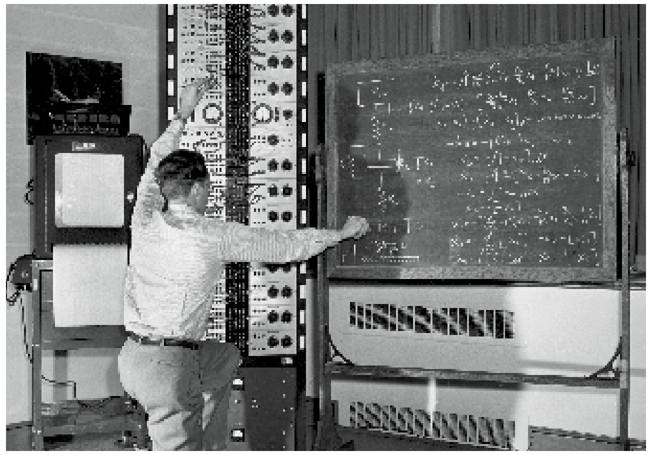
Computer technologies took off nearly as fast as the aviation industry itself. First by transmitting data via telegraph to the electronic methods used to break World War II codes, the ability to process large amounts of data was key in developing the systems that would herald the jet age.

Of course, digital technologies and machine computation are universal now; most people today carry more computing power in their pockets than NASA used to put men on the moon. Today's aircraft are, indeed, flying computers with complicated electronic systems and subsystems operating on digital technologies throughout the platform.

Boeing has been at the edge of these technologies for all of its 100-plus years—building the machines to do the math, while also employing the best human mathematics experts to invent the machines of the future. IQ

–CANDACE BARRON

PHOTO: BOEING



FROM THE DAWN OF MACHINE COMPUTATION
A Boeing engineer uses chalk and a computer simultaneously to run advanced calulations in 1949.

PHOTO: BOEING

TO COMPUTERS THAT FLY
Pictured here on a world tour, pilots fly the Boeing 787 Dreamliner, which features one of the most advanced networked flight systems available.


BREAKING
BARRIERS
TOGETHER
BOEING