



SIEMENS DIGITAL INDUSTRIES SOFTWARE

Digital twins: your key to successful spacecraft design

Launch it before you build it

Executive summary

Accelerated privatization led the entire space industry into a new era in just two decades. Space 4.0 manifests itself in many ways. Launch prices drop tremendously, while space gradually evolves into a demand-driven economy. Simultaneously, public investments keep growing, and manned exploration seems to revive. This evolution has shaken up some fundamentals of space systems engineering. Besides delivering excellence while dealing with complexity, time, cost and their relation to risk are now emerging as priorities. In this white paper, we describe why both public agencies and private businesses must focus on digitalization to be relevant in Space 4.0. And we explain how Simcenter™, part of the Xcelerator™ portfolio of solutions and services from Siemens Digital Industries Software, can help space companies innovate their products and processes faster through the digital twin.

Contents

Introduction	3
Space 4.0	3
Product engineering priorities in the new era	11
Achieving excellence in a shorter time using the digital twin	14
Conclusion	27
References	27

I Introduction

“Exploration is fundamental to human nature. It is why we learn to walk before we learn to talk, because we have to explore to become well-formed human beings. And we have to have exploration as part of our society in order to be a well-formed society.” Commander Chris Hadfield, Astronaut, first Canadian to walk in space¹

1. Space 4.0

May 6, 2002 was a day that probably passed unnoticed for most of us. In retrospect, it would become a turning point for the entire space industry. An evolution that was ongoing for decades was about to make a serious acceleration.

The first seeds for space privatization were already planted during the early 1960s with the Communications Satellite Act of 1962, the regulatory framework for private companies in the United States to own and operate their satellites. Still, conducting launches and actual space exploration were the preserve of government-led agencies of a few spacefaring nations. Rather than being an economic activity, space travel was an expensive geopolitical instrument to outdo each other in military and scientific terms against the background of the Cold War.

The tide turned in the 1980s, when the U.S. gradually started to deregulate space as tension with the Soviets was cooling. As a highlight, President Reagan signed the Commercial Space Launch Act of 1984, which would allow – and even encourage – private companies to actively participate in space and space technologies, obviously within well-defined boundaries. By that time, the European Space



Agency (ESA) had already co-founded Arianespace as a commercial spin-off. Privatization of the Russian space industry followed shortly after.

This changing playing field did not cause a shock effect overnight. To be successful in the space industry required a lot of know-how and capital, at high risk. And space continued as a highly regulated environment. The conception and deployment of the International Space Station (ISS), for example, was still led by public agencies. But it was written in the stars that the moment would come when a spark of creativity would initiate a totally new era for the entire industry, as entrepreneurs were lurking.

On May 6, 2002, one of them took the risk. Elon Musk couldn't get the necessary leverage with traditional space agencies to help him progress his Mars Oasis concept, nor could he find affordable rockets to do it by himself. He surrounded himself with industry experts, founded SpaceX, and built his own. He was convinced that by transforming classic engineering approaches and by vertically integrating processes, SpaceX could significantly cut launch price, the major hurdle for private companies to step into the space business.

Six years later, after three failed attempts and close to bankruptcy, the SpaceX Falcon 1 system made its first successful launch. A big step for SpaceX and Musk for certain, but above all, a giant leap for the entire private space industry. It would be a stretch to say Musk built the foundations of Space 4.0 on his own, but he did cause the shockwave that would disrupt the entire industry.

1.1 Cheaper launch

Launching the first privately developed, fully liquid-fueled vehicle into orbit is obviously quite an achievement by itself. On top of that, the company did something very simple that hadn't been done before – it published its prices. This allowed others to put together business plans and investment proposals with real figures and a clear view on profit. That was a gamechanger for the entire industry, because not only were launch prices transparent, they were also dropping steadily.²

Today, increasing demand for launch services to support the satellite business, exploration and military and strategic programs is further leading to lower cost per launch. Again, SpaceX is putting traditional launch providers under pressure with an innovative solution. With its now-famous Falcon 9



first stage boosters, the company is hitting on reducing the cost per launch by more than 30 percent by making the platform re-usable.³ More companies, like Jeff Bezos' Blue Origin, have similar aspirations.

As a result, traditional players and alliances in the launch segment, who mainly rely on classic expendable rocket technology, will have to innovate with new concepts to remain competitive. And they will have to react fast, as SpaceX is eating ever more of their market share – almost 22 percent in 2020 (see figure 1). An enormous amount of engineering activity lies ahead in that area, including much design exploration, complex physics, new development processes and more, all under time pressure.

To put the price decrease in numbers, according to Deloitte the cost to launch a satellite has already declined to about \$60 million, from \$200 million, via re-usable rockets, with a potential drop to as low as \$5 million.⁵

1.2 The democratization of space

The enormous drop in launch cost and the positive outlook in that respect also bring the dream of space tourism closer – spaceflight by civilians for recreational purposes. Whereas space was once preserved for astronauts, cosmonauts and taikonauts who've accomplished thorough training to prepare for the rigors of space, now companies emerge that want to offer their wealthy clients a once-in-a-lifetime experience.

From simply enjoying the thrill of weightlessness to orbiting around the Moon, to spending a week in a space hotel, no idea too crazy, or at least the concept exists. Several companies are already actively working on developing the necessary infrastructure to achieve their goal. Among them are major players such as Blue Origin, SpaceX and Virgin Galactic, but also several initiatives and startups like Inspiration4, Axiom Space and many others.⁶

It will be a matter of time before space tourism becomes common. Then space democratization will be a fact – even though the term “democratization” probably misrepresents who will be able to enjoy it. The biggest challenge may be to develop a regulatory framework that assures everything will happen safely and securely, and in line with the Outer Space Treaty of 1967.⁷

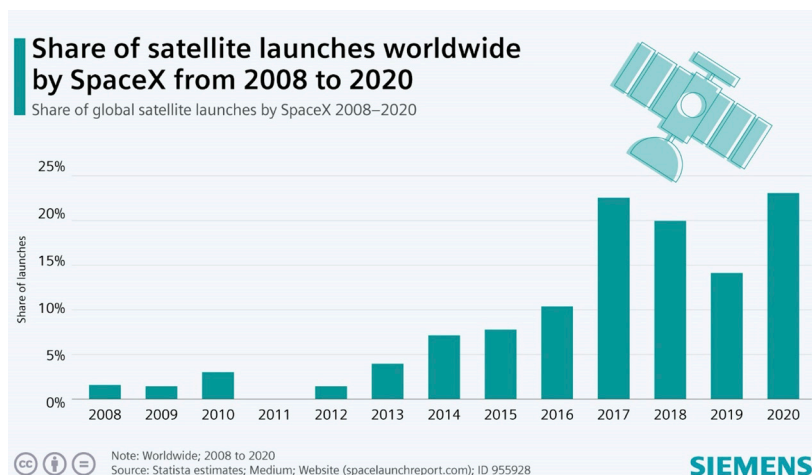


Figure 1: Share of satellites launched worldwide by SpaceX between 2008 and 2020.⁴

Also, cost and risk will need to decrease further. As a society, we won't accept that civilians who go to space for leisure will be subjected to similar risk levels as astronauts today. Simultaneously optimizing those two seemingly contradictory requirements, cost and risk, will be crucial for companies to be successful in this segment. But the technology is there, and the space economy is getting ready. Figure 2 shows an interesting price comparison. It's the estimated cost per seat on selected spacecraft over time. Slowly but certainly, we're reaching a price range that many on earth can afford.

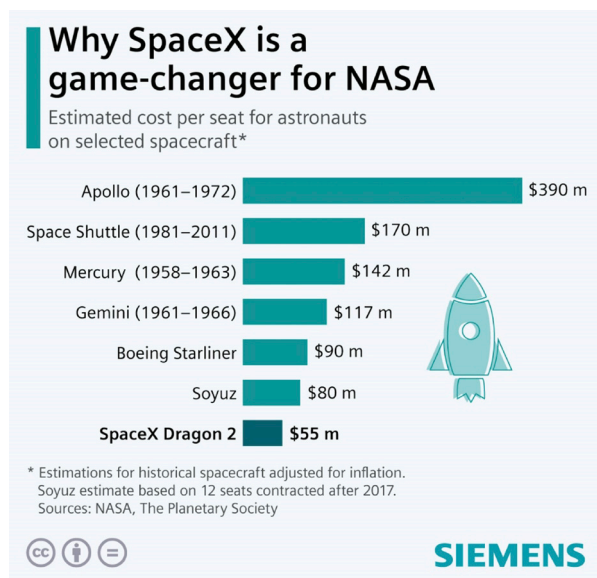


Figure 2: Estimated cost per seat on selected spacecraft over time.

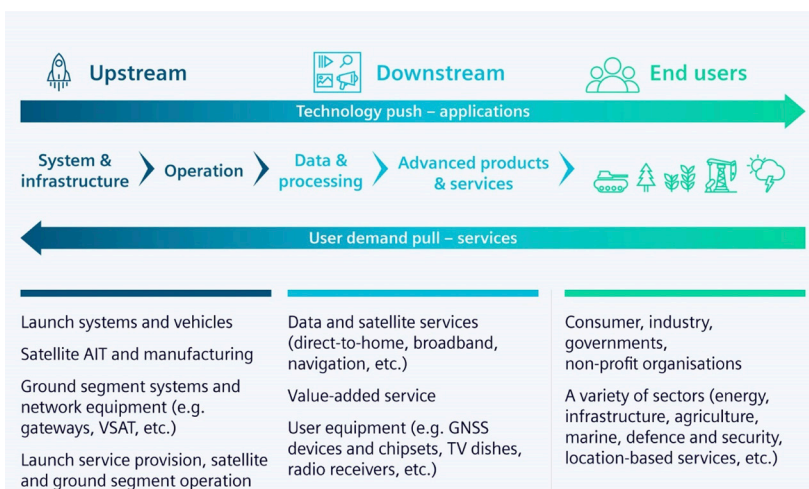


Figure 3: The space value chain.¹²

1.3 Ground-based applications increasing space demand

Like Musk and Bezos, a remarkable share of the entrepreneurs who personify Space 4.0 have their roots in the tech industry. Even companies like Google and Facebook have space on their agenda. And they have a good chance to be successful, as their core expertise is an asset. In the space industry, companies that have experience in combining multiple digital technologies such as cloud, artificial intelligence, additive manufacturing and blockchain tend to have an important competitive advantage. These technologies foster more scalable and innovative business models with customer-oriented approaches.

A good example is the startup Astra Space, co-founded by Chris Kemp, a computer scientist with a long track record in e-commerce, open-source software for cloud computing and IT, including at NASA.¹⁰ This company specifically aims at capitalizing on the expected trend of launching smaller payloads, such as compact satellites, into space at acceptable prices.¹¹

To understand specifically why these types of entrepreneurs suddenly want to launch rockets and build satellites, we should look at how the dynamics in the space value chain evolved in our data-driven economy (see figure 3). That went from an upstream push of applications where downstream markets follow, to a downstream pull of services, where ground-based applications require the development of additional space systems.



High bandwidth requirements, continuous connectivity, easy access to earth imagery, cloud storage, global navigation satellite system (GNSS), and the Internet of Things (IoT) are examples of what tech companies are all about. Those applications require a cheap, fast and reliable communication infrastructure. And satellite-based communications are preferred because they provide wide coverage and robust data streams.

When tech entrepreneurs enter the space industry, it's not just because they can, it is also because they see value in extending their scope vertically up the value chain. New business models like ground segment as a service (GSaaS), in which activities that require lots of expertise, resources and infrastructure are shared, lower the entry barrier. Today, there is a huge demand for satellite communication from the mobility market, and from all other markets that will benefit from 5G technology.

1.4 Continued public funding

Even with ongoing privatization, public expenditure on space programs keeps growing globally. According to Statista, the accumulated total has grown from \$42.4 billion in 2014 to \$82.5 billion in 2020, with the U.S. accounting for 58 percent of that amount.¹³ That is despite the pandemic, even though that effect may still show up as governments are forced to reshuffle priorities.

The significant wider societal and economic impacts of the space sector justify this spending. For example, satellite data and services will play a crucial role in reaching the goals that were set in the EU Green Deal, a set of policy initiatives by the European Commission to make Europe climate-neutral by 2050. A significant part of the budget of the investment plans will go, directly or indirectly, to the space industry.¹⁴

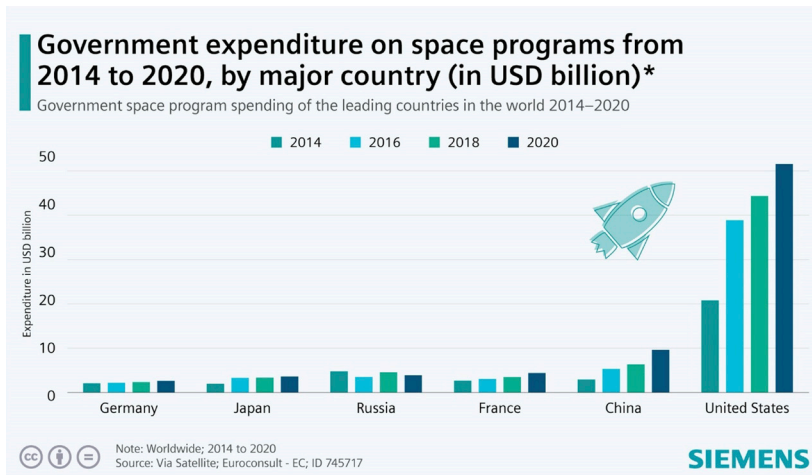


Figure 4: Government expenditure on space programs from 2014 to 2020, by major country (in billions of U.S. dollars).

For the period 2021–2027, for example, the European Commission has foreseen a total of €16 billion for the space industry. That includes €9.7 billion for Galileo and EGNOS, the EU’s global and regional satellite navigation systems, and €5.8 billion for the Copernicus, the EU’s earth observation program.¹⁵

In addition, institutional actors are expected to take the lead in defining, updating and implementing space policies that foster economic growth, but at the same time help face upcoming challenges related to the sustainability of the space environment. They must safeguard space resources from monopolization by private companies and outline a strategy that stimulates initiatives to mitigate space debris.¹⁶

Despite no longer being the primary driver, defense still represents a significant portion of space activity. Space assets play a key role in delivering crucial military requirements, such as secured communication, earth observation and drone navigation. In space, there are continuous flare-ups of militarization and weaponization, for example, in the form of space observation and other capabilities to protect these assets against malicious actions. Governments spend the necessary budgets

according to their perception of threat, in which volatile geopolitics plays a major role.

1.5 A revival of manned exploration

Space is also the environment where nations like to demonstrate their ability. Superiority in space equals power and/or sovereignty. Both Yuri Gagarin’s space-flight and the entire Apollo program were inspired by the endeavor of being first. And even though the space race ended long ago and made way for international collaboration in the international space station (ISS), we see a revival of the aspiration to impress, especially now that the ISS comes closer to its retirement and space agencies look for new challenges to push technological and scientific boundaries.

Deep space exploration, in the hope of discovering resources or finding answers to fundamental questions about our place in the universe, has never stopped. Robotic spacecraft have flown by all of the planets in our solar system. Most have been orbited, and we have landed on Venus and put rovers on Mars.¹⁷ During this decade, the race for the planets will continue, with many missions planned, but now in a different geopolitical context involving many relatively new players, and with private companies maneuvering themselves into pole position to participate.

Still, despite these great accomplishments and ambitious plans, none manages to trigger public fascination like Neil Armstrong’s first steps on the moon. Quite the contrary, it seems that in the public opinion, people are wondering why it has taken 60 years (and counting) to put a human being on another planet or celestial body. The entire space industry and all its enthusiasts are yearning for a new prestigious mission that will once again stun the world. That definitely plays a role in the renewed interest in manned exploration.

1.6 The decade of the moon

The question then arises of whether Mars or the moon should be targeted. There are pros and cons for both (see table 1). Obviously, landing humans on Mars would be an achievement that appeals much more strongly to the imagination. There will likely also be more answers to find about the origin of our solar system. And some would argue that the odds for successful permanent colonization would be more favorable on Mars. The Red Planet has much more local resources and has in many ways more similarities to Earth than the moon, in terms of gravity, temperature fluctuation and day-night rhythm. On the other hand, there are some serious objections. Risk and cost would be tremendous, and the necessary technology is far from ready.





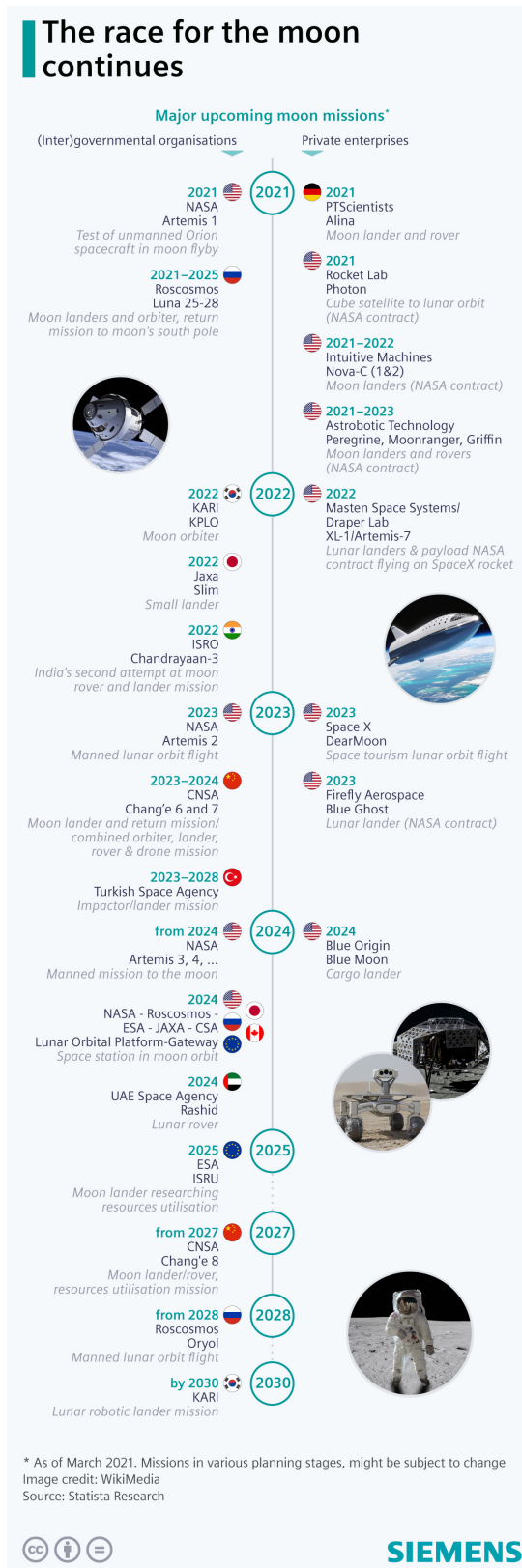
Arguments for and against sending astronauts to the Moon/Mars			
	 Moon	 Mars	
For	<ul style="list-style-type: none">– Less explored than Mars– Ideal location for testing ISRU– Close to Earth– Radio astronomy on the far side of the Moon– May spur investment from the private sector	<ul style="list-style-type: none">– Opportunity to investigate the origins of life– Similarities to Earth (24 h day, seasons, atmosphere, etc.)– Abundant local resources	
Against	<ul style="list-style-type: none">– Has already been visited six times during the Apollo era– Lunar geology is already well understood– Repetition of an accomplished task is not a great achievement– ISRU works differently on Mars	<ul style="list-style-type: none">– Not feasible with current technologies– Ethical problem of sending astronauts away for two years– Communications delay makes mission too risky– Too expensive	
ISRU = in situ resource utilisation.			

Table 1: Pros and cons for manned missions to the Moon and to Mars.¹⁸



For the latter reasons, all eyes are on the moon in the short- to mid-term, possibly as an intermediate step for later missions to Mars. It is not clear in which constellation the next human will set foot there. Will it be part of a mission by a single nation, like NASA is targeting with its Artemis program? Or will it be in the context of another partnership like the ISS? And to what extent will private actors be involved?

Many initiatives are being conceived. ESA, for example, is fostering the idea of Moon Village, a sort of open concept in which all interested parties and nations can participate, in whatever form suits them.²⁰ It is clear that ESA envisions to extend the collaborative spirit of the ISS deeper into space.

Meanwhile, a diversity of missions is already being programmed (see figure 5). Apparently that logic will be respected. Space, whether it's low Earth orbit (LEO), the moon or Mars, is a very harsh environment. We learned how to live and work in the ISS at 400 kilometers from Earth. Before trying to do the same at 400 million kilometers, we should start at 400,000 kilometers. The 2020s will be the decade of the Moon.

"We're going back to the moon for scientific discovery, economic benefits and inspiration for a new generation of explorers. As we build up a sustainable presence, we're also building momentum toward those first human steps on the Red Planet."

Jim Bridenstine, NASA administrator²¹

Figure 5: Planned missions to the moon until 2030.¹⁹

2. Product engineering priorities in the new era

The accelerated privatization that catalyzed Space 4.0 has dramatically changed the entire space industry landscape in a very short period. It created an enormously fertile breeding ground for new applications and ambitions. The business is booming, and tremendous growth is expected during this decade, up to a tripling by 2030.²² But how does it affect the priorities in product engineering? How can traditional public agencies remain relevant, and where are the opportunities for newcomers to successfully take a share?

2.1 Reducing time, cost and risk

Where public agencies are likely to struggle most is the sudden emphasis on typical market-driven priorities like time and cost, especially in their relation to risk, which is a natural priority for space engineering that tends to become increasingly stringent in the context of manned missions.

For decades, agencies were focused on delivering excellence against certain budgets. Their primary customers were mostly public entities, such as defense departments, meteorologic institutes, large public service providers and the like. Downstream services and applications came as collateral business.²³

As mentioned, this dynamism has changed. In the new space era, the price for the end-user dictates the business. Being successful in a commercial context requires low cost, a different approach to risk and more agile, customer-oriented business models. It's typically where traditional players have difficulties, and where newcomers see opportunities.

Thorough digitalization will be crucial to achieve time and cost savings on both the product and process level. By using a digital twin, companies can dramatically reduce time-to-market by shortening the decision-making process, development time and testing loops.²⁴ More efficiency gains can be found in the way products are conceived, manufactured and used. Digital technologies can enable corporate processes that foster automation, mass

manufacturing of components, systems-driven approaches, re-usability, predictive maintenance, feedback loops, additive manufacturing and more.

All these capabilities will play a crucial role for companies and agencies to be competitive in the new space era.

2.2 Exploring innovative ideas

Driven by a commercial context, newcomers often bring ideas that question established ways of doing things. As examples, we can think of re-usable launch systems or the tendency to consider large constellations of small satellites. Materializing such ideas within the constraints of time and cost involves a lot of engineering work. That includes defining requirements, studying concepts, exploring architectures, refining designs, making them real products and following their evolution until the end of life.

Because all this work starts from a blank sheet, a large part of it needs to be done virtually and based on data. It requires powerful exploration tools and scalable simulation methods, as well as a digital platform that connects all lifecycle components.

Such digital technologies are also precarious when developing equipment in the framework of large space exploration programs. Those usually start by setting goals rather than by setting targets. Looking at what is in the pipeline to happen before 2030, there is a lot of "what" and "why." But the "how" is often still to be discovered.

Space agencies even speculate on the expected evolution in various technology fields when making plans and setting deadlines. That is what makes space an utterly interesting playing field for engineers, and why the industry is always at the forefront of innovation, even leaning very closely towards research. But it requires a strong digital backbone to capture all ideas, collect them, simulate them, develop them on time and within budget, and keep track.

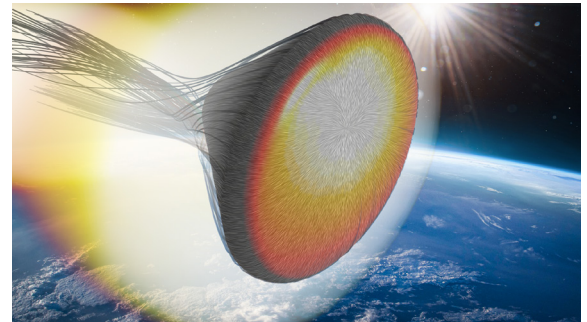
2.3 Dealing with complexity

Most space systems are very complex by nature. They include advanced materials and combine a multitude of physics. Consider highly controlled propulsion systems, for example, or robotic systems with built-in artificial intelligence. There are so many parameters involved in the development of those that engineers need a digital twin to even come close to success. At the heart of this digital twin are realistic, prediction-capable simulation models to optimize all system aspects simultaneously, from the beginning of the design cycle.

Moreover, as some of these systems are smart, they evolve over time. They include many sensors to allow further performance optimization when they are operational. Smart systems also communicate with each other and their environment, and they feed information back to design teams for future improvement and predictive maintenance. Such a system behavior requires massive use of data management and analytics in a digital solution that spans the entire product lifecycle.

In addition, space systems will operate in the harsh environment of space, where different laws of physics apply. Equipment that leaves our protective atmosphere will be exposed to different gravity

conditions, extreme temperature fluctuations, cosmic radiation and more. Any engineering work on spacebound systems needs to take that additional complexity into consideration. Applications or materials that in other industries would be labeled as advanced or exotic are the standard here.



Using a digital twin approach during product design and development requires high-performance simulation software. Only those solutions that specifically address the typical space engineering needs will comply. There are only a handful of such solutions on the market. For this reason, commercially available software is often combined with in-house tools, adding another layer of complexity in terms of tools integration.

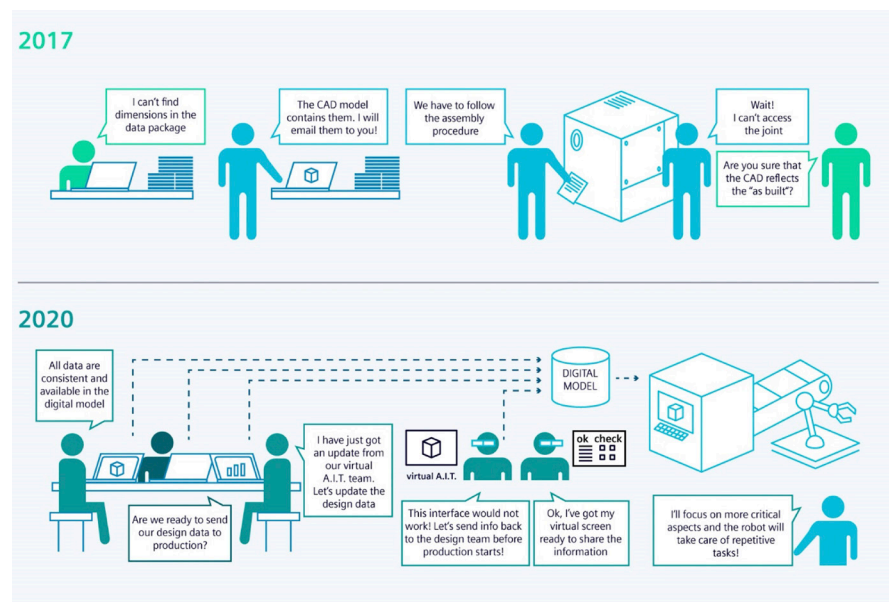


Figure 6: Engineering in 2017 versus engineering in 2020 using the digital twin (by ESA)²⁷

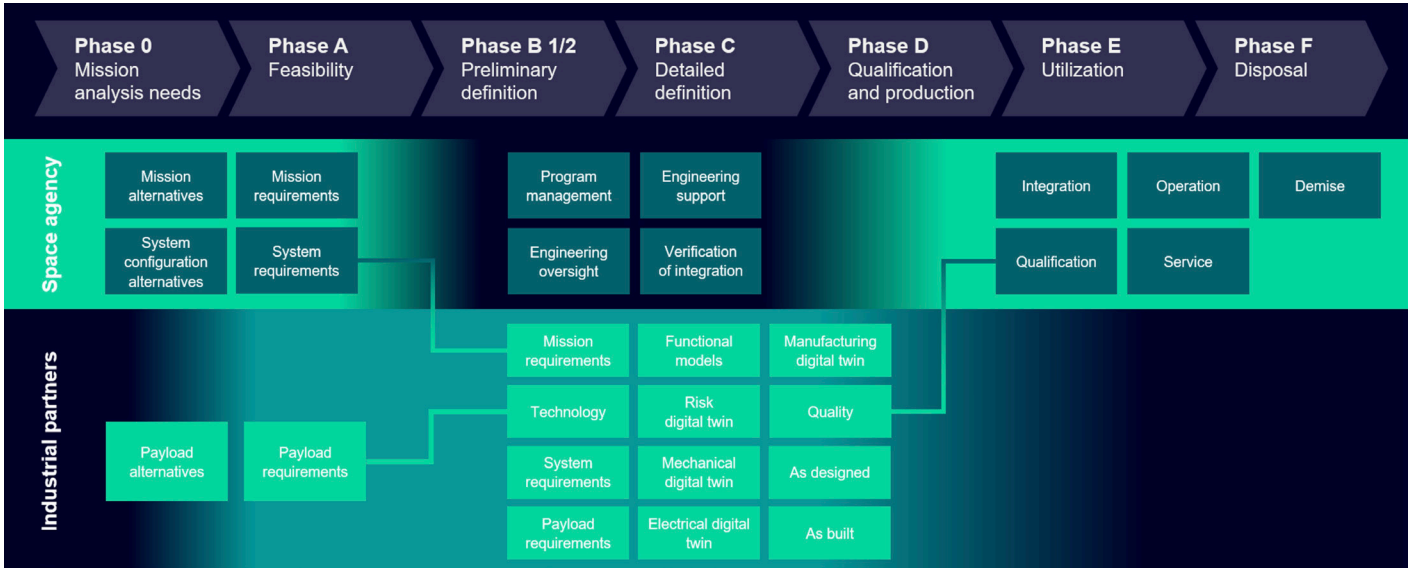


Figure 7: Space program phases and collaboration among stakeholders.

2.4 Integrating different partners

Finally, space programs, particularly the large ones, involve intense collaboration among many stakeholders in different constellations, such as alliances, partnerships and subcontracting. All of them come with their own data, processes, methods and tools. Without proper integration in a unified digital platform that manages all that data and sets user privileges, such collaborations are prone to errors.

Consider the 1998 Mars Climate Orbiter as an example – a \$327.6 million mission that was simply aborted upon arrival as the connection to the spacecraft was suddenly lost. The trajectory brought the spacecraft too close to the planet, and it was probably destroyed in its atmosphere. An investigation could attribute the failure to a measurement mismatch between two software systems. NASA used metric units. Spacecraft builder Lockheed

Martin used imperial units.²⁵ Somewhere along the process, the conversion went wrong. Such a seemingly insignificant mistake, yet with multi-million-dollar consequences, could have been easily avoided by proper data management in an integrated digital environment.

Still today, data management and integration seem challenging for space organizations. Accenture conducted a survey among aerospace and defense executives and concluded that nearly 74 percent of them feel overwhelmed by the amount of available data coming from products and services. To overcome this challenge, they will increasingly use digital threads and digital twins. Accenture concludes by saying that these technologies can help companies leverage data to generate more valuable insights, improve decision making and reduce manufacturing costs.²⁶

3 Achieving excellence in a shorter time using the digital twin

An overarching digital infrastructure, in which all data regarding the various product lifecycle phases are collected, managed, kept up to date and made accessible for all relevant program stakeholders, benefits all space system engineering priorities tremendously. That platform should weave an all-encompassing digital thread of information, from requirements definition to exploration, to detailed design, to manufacturing, to qualification, certification and beyond. It is the only way to keep a product in space connected to its original requirements, and to trace the impact of all decisions and all actions that have been taken throughout the program.

By its openness, flexibility, and ability to deliver world-class solutions for every product lifecycle aspect, and by the way all those are integrated, the Xcelerator™ portfolio from Siemens Digital Industries Software is the perfect orchestrator for any space program.

Xcelerator is a comprehensive and integrated portfolio of software, services and an application development platform that speeds digital transformation.



Figure 8: Siemens' Xcelerator portfolio.

3.1 The Simcenter solutions portfolio

Within Xcelerator, the Simcenter™ solutions portfolio for the digital twin focuses on all the engineering aspects required during space system design and development.

Simcenter uniquely integrates multiphysics system simulation, 3D CAE (structures, thermal, fluid dynamics, electromagnetics) and physical testing, and combines this with design exploration and data analytics, all in one environment. It is an open, scalable and flexible engineering platform that helps space agencies and businesses accurately predict all product performance aspects, optimize designs and deliver innovations faster and with greater confidence.

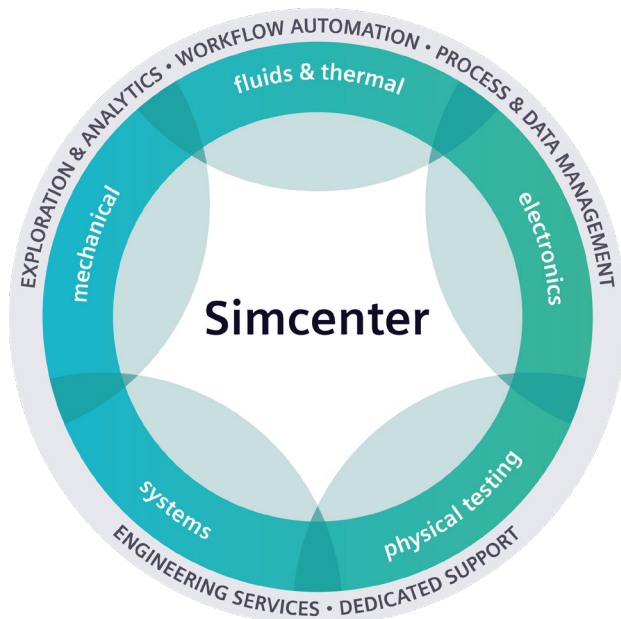


Figure 9: The Simcenter solutions portfolio.

3.1.1 Leverage engineering expertise in your development process

Becoming a Simcenter customer means more than purchasing world-class software or services; it opens the door to an unrivalled wealth of engineering expertise. Here is how Simcenter can uniquely help you improve your engineering process.

Removing silos

Simcenter coalesces and removes silos between engineering departments and/or stakeholders involved in the program. Space engineers can

benefit from the integration between all the Simcenter areas in many ways.

This integration extends from easy sharing of data and knowledge, to defining workflows for applications that involve various engineering aspects, to setting up co-simulations for the development of functions that tightly couple various physics, including software and controls. As a promoter of vertical collaboration, Simcenter also enables associative connectivity of simulation tools to Siemens' NX™ software for computer-aided design (CAD), to represent the digital mockup of the mechanical product, or to Siemens' Capital™ software, to represent the digital mockup of the electrical and electronic systems, and to Siemens NX CAM for the digital mockup of manufacturing.

Moreover, Simcenter offers the possibility to connect to Xcelerator Share, an engineering-centric cloud-based solution for ad-hoc collaboration, which will allow teams of all sizes to collaborate securely with key stakeholders, including designers, managers, test engineers, suppliers, and customers with appropriate access control. This enables scalable, project-based workspaces that deliver greater flexibility in product development. Project members can view and markup designs, share simulation templates, and review simulation results at any time, using any device.

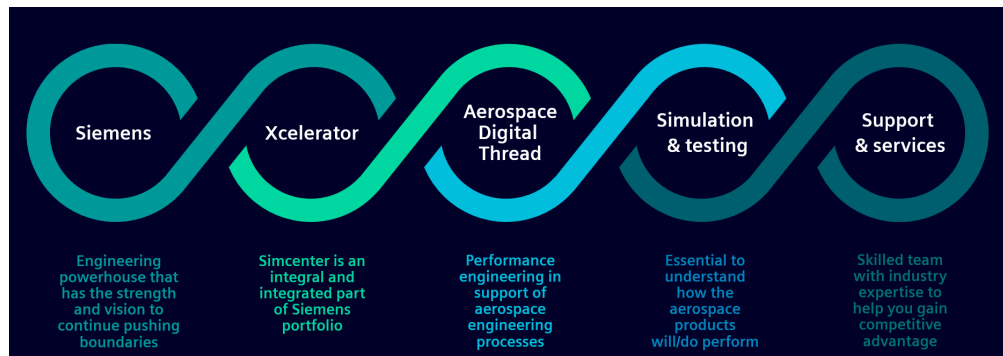


Figure 10: Simcenter, part of Siemens engineering powerhouse.

Uniquely combining simulation and test

The fact that physical testing is part of Simcenter is both unique and essential. Space engineers continuously explore uncharted areas. Physical testing plays a crucial role in pursuing the degree of realism that is necessary to achieve prediction-capable models. This goes far beyond merely measuring accurate data for standard correlation analysis and model updating.

For successful engineering of space systems, simulation and testing must go hand in hand, complementing each other. As an illustration, consider the NASA Jet Propulsion Laboratory (JPL) Mars rovers and how they landed on Mars. In preparation of such events, upfront testing can be done to a certain degree. But it's simply impossible to test the complete "7 Minutes of Terror"²⁸ – a popular way to describe entry, descent and landing on Mars combined – in all its aspects on Earth. Simulation helps to complement those tests, but also includes the results of partial tests in a more integrated process for virtual system performance testing.

Finally, any space-bound system must follow a stringent qualification and certification process in which physical testing will continue to play a crucial role. In this context, the combination of simulation and test can de-risk and accelerate that process.

Built upon decades of experience

Simcenter solutions have a long, proven track record of significantly improving space program execution. As a global industry leader and with a clear focus on innovation, Siemens strives to deliver solutions that will enable businesses in the entire space sector to take the next steps in digitalization. Siemens has achieved its stature by making substantial investments in research and development (R&D), forging strategic partnerships and acquiring technology pioneers that can provide decades of engineering expertise in the sector.

Delivering more than just software

Siemens makes certain that its customers derive the greatest benefits from their investments in Simcenter. With an open philosophy, Simcenter works within a broader ecosystem with a unique dedicated support model, expertise and investments in engineering services, and Siemens' ability to partner with customers on technology development.

As a key part of the Xcelerator portfolio, Simcenter delivers even greater value by integrating simulation and test into the broader context for development.

Simcenter is also part of Siemens, an engineering powerhouse with the financial strength, resources and vision to continue pushing the boundaries of what is possible. Not simply a technology vendor, Siemens is also a user of these technologies and fully understands the industrial challenges its customers face, and this knowledge helps deliver impactful innovations.

Siemens understands that digitalization is not only about creating well-connected digital data throughout the lifecycle. At a certain moment, the product needs to become a reality, and that creates challenges that cannot be understood by virtual-only approaches. Siemens bridges the gap between the virtual and the physical worlds.

3.1.2 Tuned into the major space system development priorities

The benefits Simcenter brings are specifically tuned to the product engineering priorities that are necessary to make space agencies and businesses successful in the new space era. Simcenter helps them extend and mature their capabilities in the following key dimensions:

Go faster

Complexity can slow down an organization's ability to make the right decisions. Therefore, space agencies and businesses need to find ways to move faster despite the complexity. Those who manage to do this successfully can turn complexity into a competitive advantage.

Simcenter helps them by delivering solutions such as process and workflow automation, reduced-order modeling, a broad application of system simulation capabilities, fast data processing, meshing and solving, high-performance and cloud computing, AI-driven usability enhancements and more.

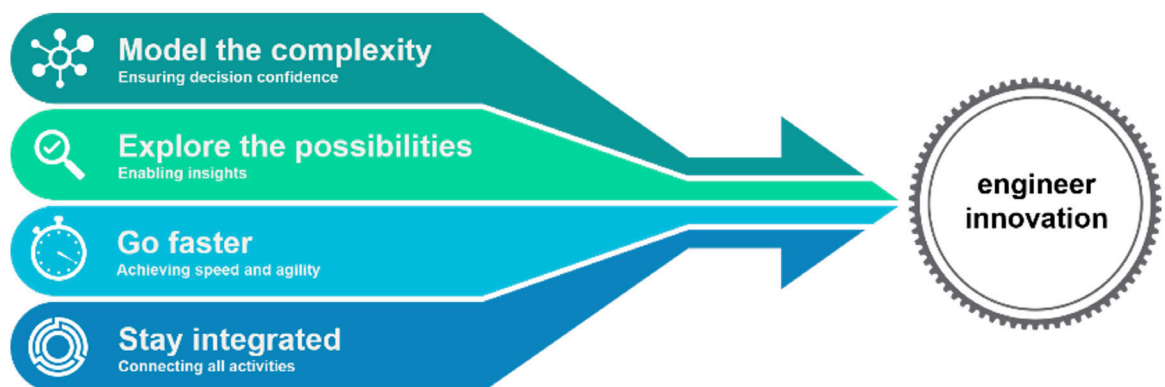
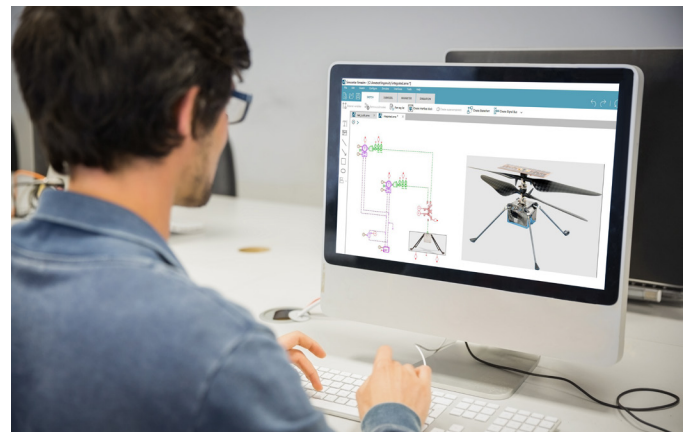


Figure 11: Engineer innovation more effectively by extending and maturing capabilities in four key dimensions.

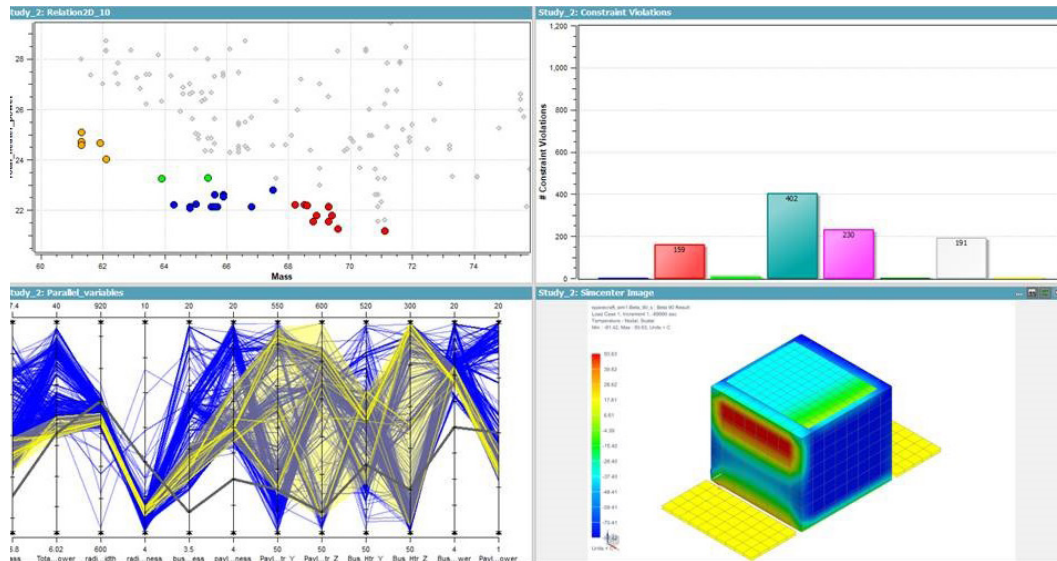


Figure 12: Multi-objective optimization trade-off study of a CubeSat .

Explore the possibilities

To truly gain advantage from their investments in simulation, space agencies and businesses need to leverage those models in experiments. Through systematic and intelligent exploration of the design space, they will discover new designs, optimize for performance and improve robustness, all in a fraction of the time it would take without these methods.

Simcenter enables space companies to make a paradigm shift in how innovation is seeded by offering solutions such as generative engineering.

Model the complexity

Predicting performance in the best possible way means capturing all complexity, whether from the geometry, the physics or the operational environment. Greater accuracy leads to greater confidence in the predictions and therefore in the decisions.

The unique combination 1D/3D/test that Simcenter delivers, along with the broad coverage of physics, is the best way to model complexity and reach the desired accuracy.

Stay integrated

Development in different functional areas happens simultaneously. An optimal decision in one area could prove to be sub-optimal for another and cause delays in development, or worse, field failures. Balancing trade-offs between performances is important but can only be achieved by having everyone aligned. Traceability is key to enabling visibility and audits on how decisions were made and who is impacted.

Simcenter helps teams involved in space systems design and development stay integrated by offering streamlined workflows that combine 1D, 3D and test. At the same time, the digital twin as delivered by Simcenter is essential for completing the digital threads for product design and engineering, making product development more agile through model-based systems engineering (MBSE), orchestrating the program and for verification management, tracking requirements verification activities throughout the lifecycle.

3.2 A wide range of dedicated space solutions

Not all simulation software is suitable to support the digital twin approach for space systems performance engineering. On the contrary, solutions that specifically address state-of-the-art space applications are required. That is a challenge, as

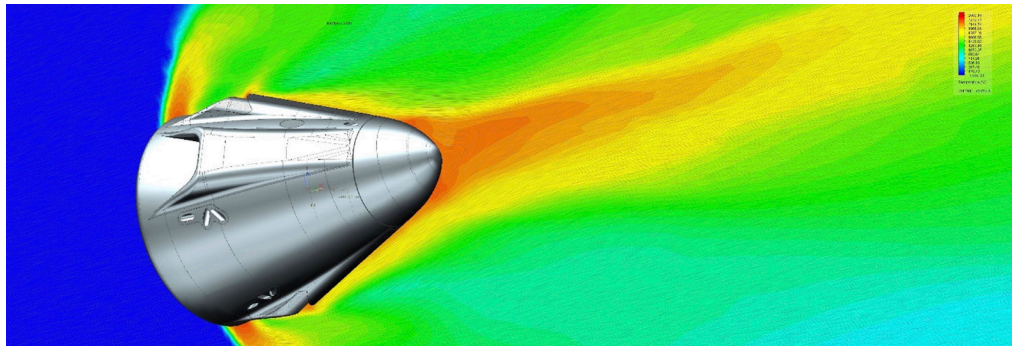


Figure 13: The flow around the capsule with temperature distribution on the capsule's surfaces. Credit: Elinter AG.

technologies in the space industry continuously evolve, and consequently so do simulation requirements.

To deliver space customers exactly what they need, Siemens has created task forces addressing identified major space engineering areas. Experts in each area follow the space technology evolutions in their domains closely, translate trending applications into requirements for simulation tools, and in reverse, combine solution components in vertical application-oriented workflows. As a result, Simcenter includes a wide range of dedicated solutions for spacecraft engineering.

3.2.1 Propulsion system performance engineering

Simcenter can help manufacturers of launch and propulsion systems more effectively discover innovative designs that are reliable, efficient and robust.

By combining scalable multiphysics system simulation with design exploration, engineers can explore various concepts and predict launch and propulsion system performance starting from the very early development stages. That capability is very useful in the current context of companies exploring re-usable launch systems and new propulsion methods for smaller spacecraft.

In addition, Simcenter includes all the tools required to further refine, optimize and ultimately qualify the chosen concept, both as a structure and as a system. In Simcenter, engineers can find end-to-end solutions for a large variety of propulsion applications, including the design of complex rocket motors or optimization of thrust vectoring controls and flight dynamics including mechanisms and structural details. With Simcenter, engineers can optimize the detailed structural design of the system throughout the entire mission profile.

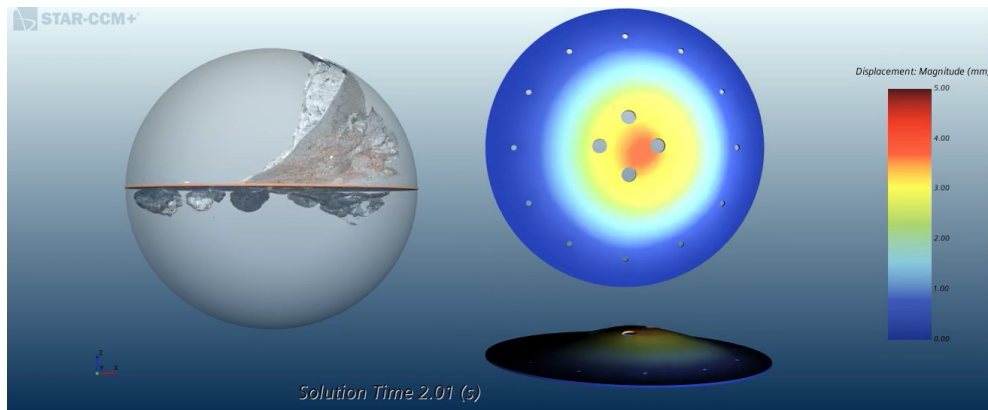


Figure 14: CFD simulation of fuel sloshing and fluid-structure interaction in a satellite tank.

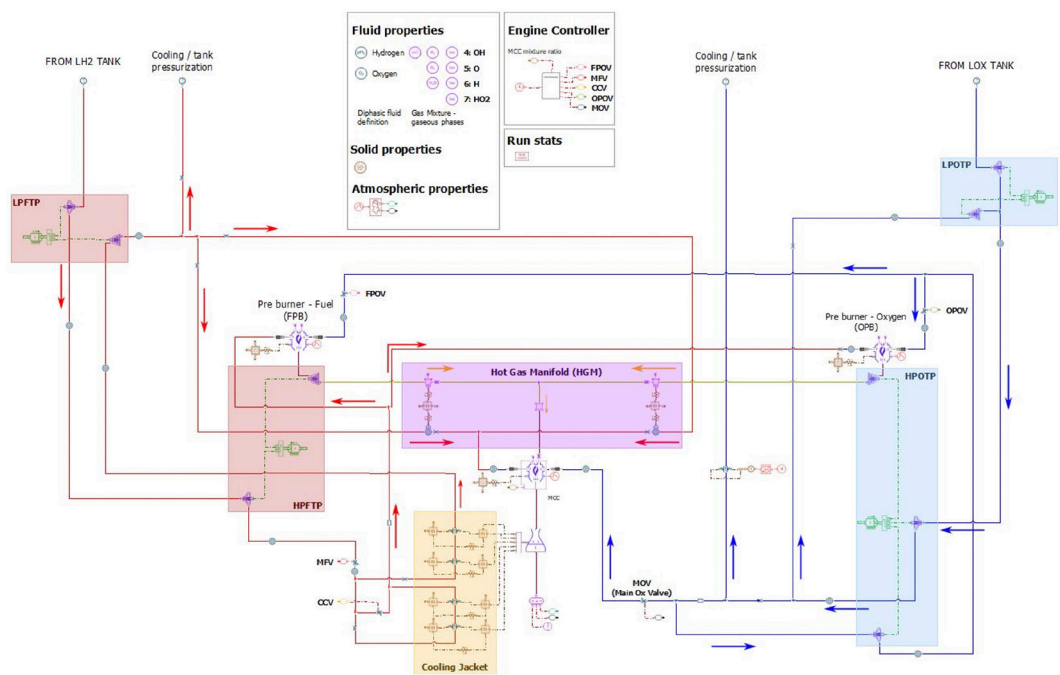


Figure 15: In the context of launcher re-usability, there is a need for higher fidelity in the simulation of rocket engine startup and shutdown.

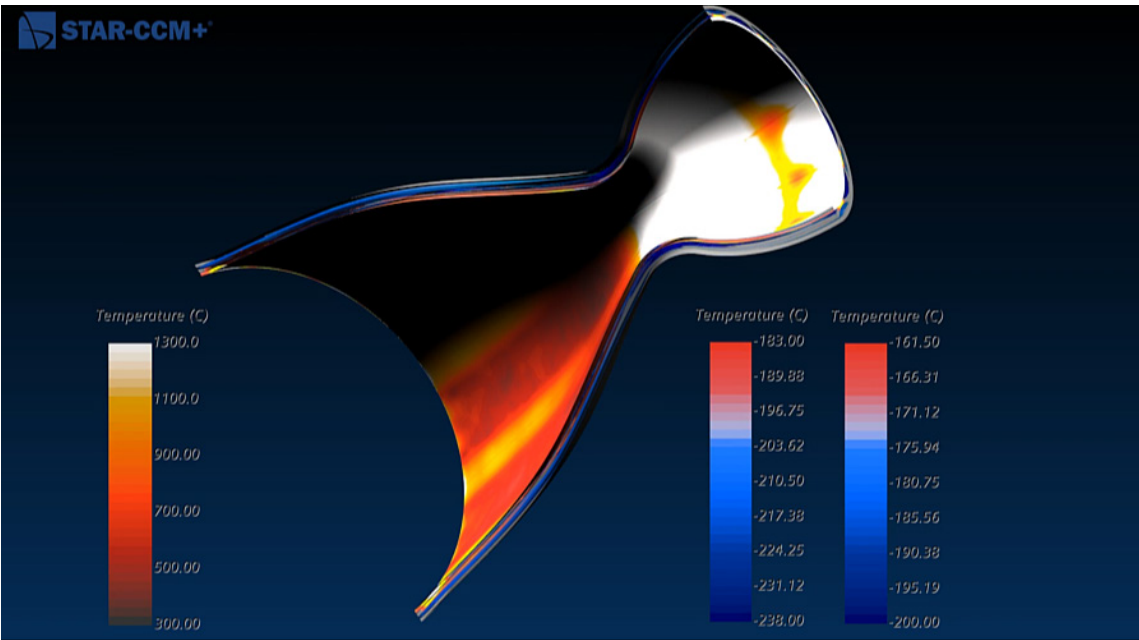


Figure 16: Conjugate heat transfer simulation for solid and coolant temperature predictions in a 3D printed rocket nozzle.

The software also enables them to design the entire fuel delivery system, from tank to pump to rocket nozzle, including the study of fuel sloshing and its impact on vehicle control.

3.2.2 Fluid dynamics and heat transfer

Simcenter features an exceptional breadth and depth of solutions for realistic simulation of various fluid conditions, related heat transfer and the impact of those on structural strength. These solutions are particularly useful for virtually evaluating mission-critical design requirements for launch and re-entry vehicles as they experience a tremendous range of aerodynamic conditions in operation.

Simcenter offers a wide and diverse range of applications, including external aerodynamics, low-speed to hypersonic flight and aerodynamic loading, to help understand the structural forces in the system during launch and separation events to make sure these happen safely. Other applications relate to performance, such as rocket plume and combustion, fuel pump design and nozzle cooling (important when considering re-usability) and the design of cryogenic systems.

3.2.3 Structures, systems and robots

Space vehicles, launch platforms and payloads experience extraordinary forces during launch. Many space systems are complex mechanisms with numerous control systems that must operate in conditions that cannot be tested on Earth. To deal with all these engineering challenges, Simcenter includes a comprehensive set of simulation solutions specifically fit for design of structure and mechanisms, including controls.

To support space engineers throughout the entire process, from concept design to qualification, Simcenter solutions are scalable, capable of delivering both reduced-order models for real-time controls validation and ultra-high-fidelity models for advanced analyses. Simcenter solutions include tools for structural design, coupled loads analysis to understand the loads in different configurations, processes to study the mechanisms involved in docking, deployment of solar panels and robotic arms, designing high-precision instruments, analysis of pyrotechnic separation systems and many more.

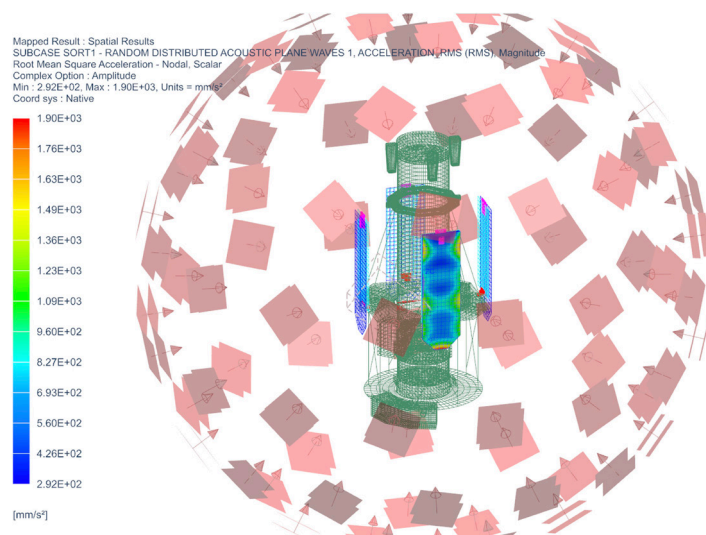


Figure 17: Acceleration results on the solar panels under random acoustic loading.

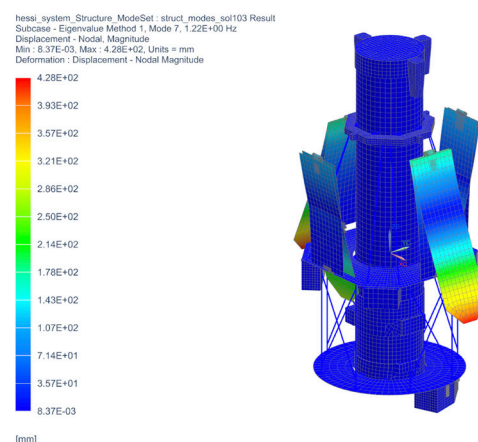


Figure 18: Modal analysis of a spacecraft.

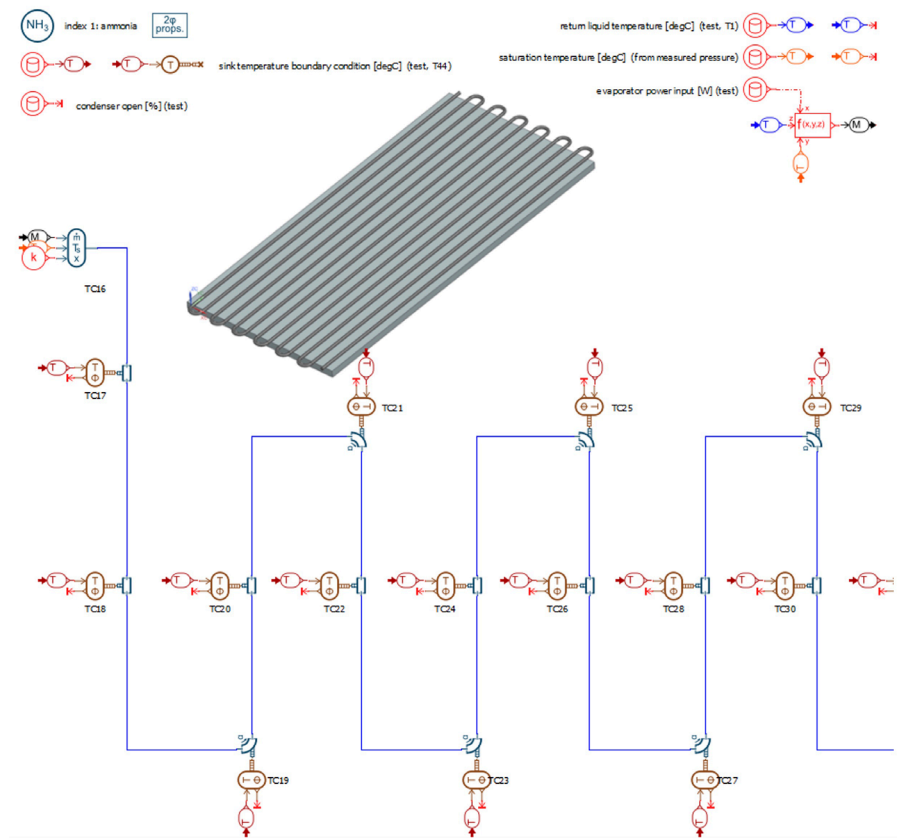


Figure 19: Condenser system simulation model of a loop heat pipe passive cooling system.

3.2.4 Thermal management

Space systems design always involves many engineering challenges related to thermal management. Any space environment is already thermally harsh, and space systems require additional effort in that respect. Rockets, for example, produce so much heat that they need to be cooled appropriately in order to avoid catastrophic failure. Also, powerful avionics require a well-designed cooling system to function properly and safely.

Simcenter includes a wide offering of solutions for thermal management, including passive and active cooling design of the spacecraft, thermal analysis in multiple environments and flight phases, tools to develop materials and structures for heat shields, and vertical solutions that address the specific needs for Mars, Moon and Earth orbits, and for thermal management on other planets or celestial bodies.

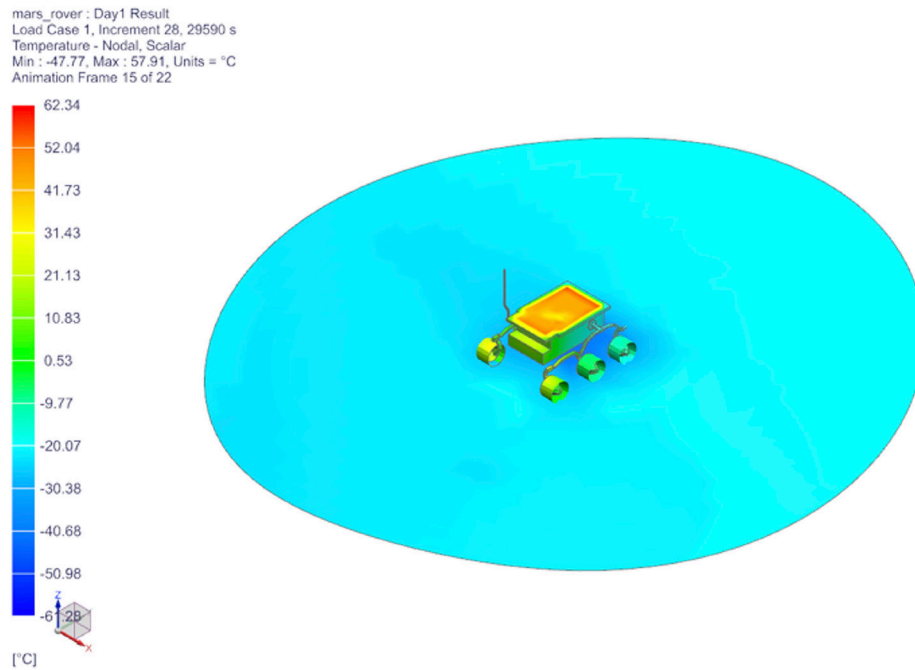


Figure 20: Simulation of the solar heating environment during a mission.

3.2.5 Electromagnetic performance engineering

Simcenter helps engineers understand all the necessary details of electromagnetic transmission, reception, propagation and interaction to conduct proper design and siting of antennas and arrays. No spacecraft could function without myriad electrical and electronic devices on board. But those may cause interferences that could ultimately degrade overall performance. With Simcenter, engineers can design all electronic units in, for example, a satellite, for mutual electromagnetic compatibility (EMC).

In addition to EMC within the spacecraft, electromagnetic interference (EMI) with sources in the environment is also a challenge, especially considering the current massive introduction of broadband satellites. Space is already a hostile environment for electronics, with lots of radiation – from the Earth's radiation belts, from explosive events on the Sun, and from cosmic rays. And plasmas can cause high levels of electrostatic charge on a spacecraft structure, which can lead to electrostatic discharge.

With Simcenter simulation, electronics and electromagnetics engineers can calculate conducted and radiated emission, study harnesses, metamaterials, shielding, electrostatic discharge and plasma charging, and more, all with the objective to reduce risks related to EMC and EMI, and to protect electrical devices from the hostile environment of space.

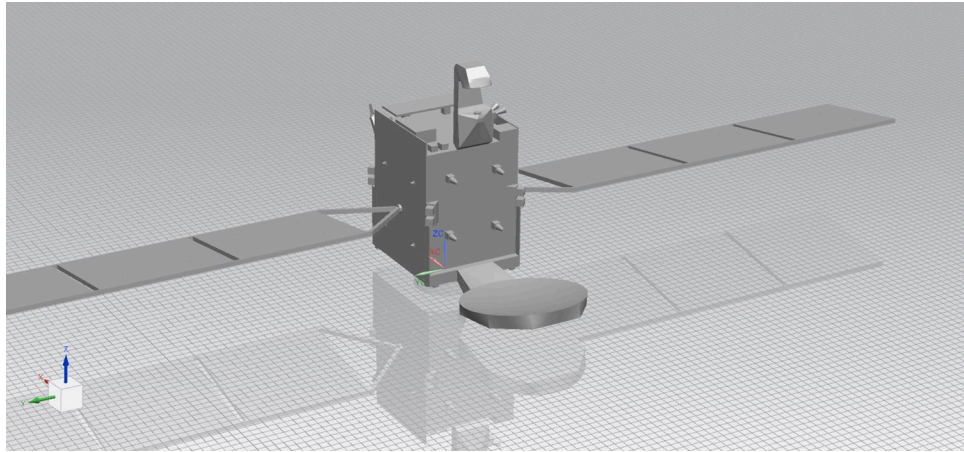


Figure 21: When designing space systems, electromagnetic simulation helps understand and reduce risks related to EMC.

3.2.6 Spacecraft safety and mission assurance

Despite emerging priorities, including time and cost, the overall quality perception of space products will to a large extent depend on safety and reliability (technical risk). With those priorities weighted against each other, it becomes increasingly important that space organizations follow a more rigorous approach to risk assessment during design to analyze and understand the potential impact of decisions on safety, reliability and operational availability.

Simcenter provides an integrated digital risk twin approach that allows engineers to continuously evaluate the reliability, availability, maintainability and safety (RAMS) of spacecraft designs against cost and operational efficiency, from the very early stages of the design process. This digital risk twin combines modeling with analysis to identify the expected behavior and the impact of potential failures and risks associated with a design configuration in an objective, repeatable and traceable process.

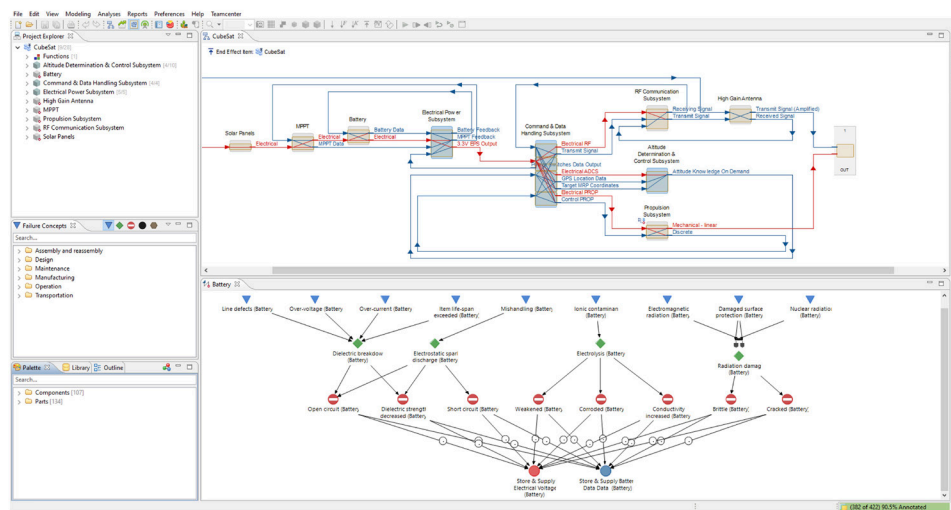
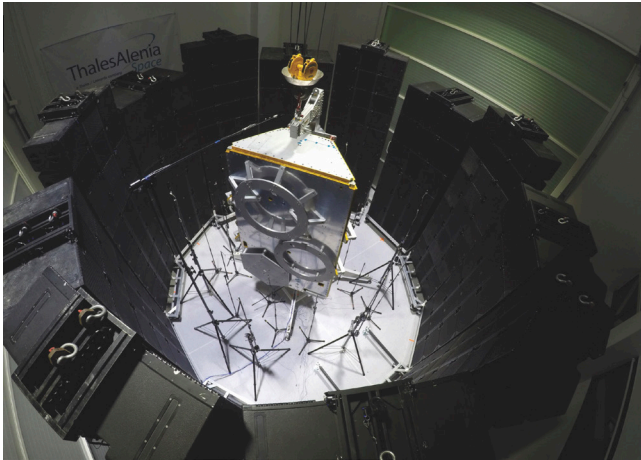


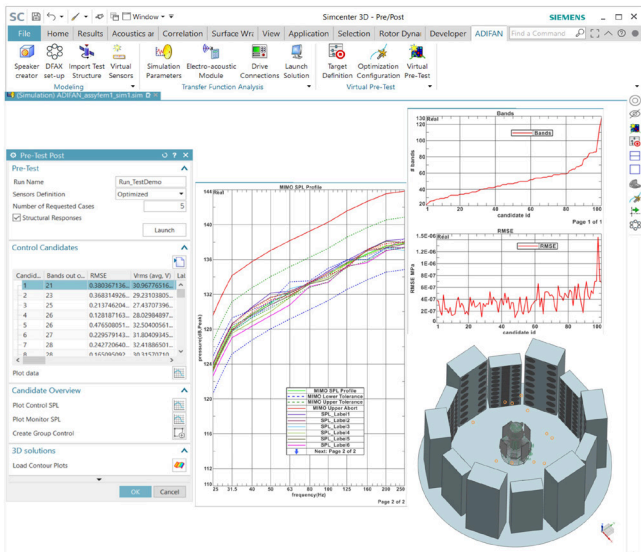
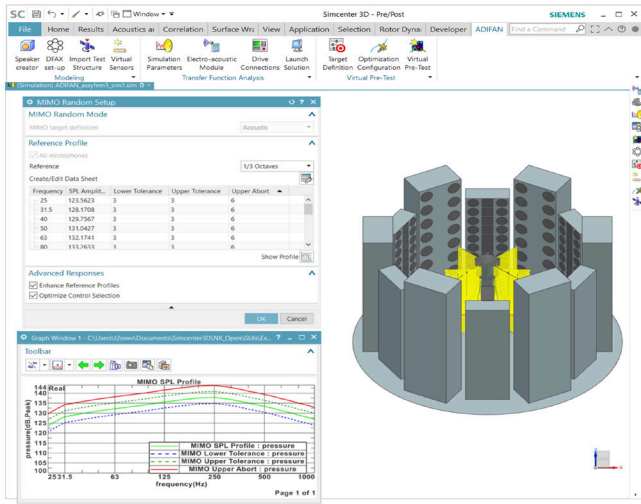
Figure 22: Model-based RAMS analysis.



3.2.7 Integration, verification and qualification

Finally, any space-bound system must pass an extensive dynamic qualification testing process, to affirm that the structure can withstand all the launch conditions. That is risky business, as space systems are often one-of-a-kind. In space engineering, there is seldom room for prototyping. It is crucial to have these qualification testing campaigns fully under control. Over-testing a structure above its specifications could lead to component failures or, even worse, a launcher explosion.

Simcenter has an enormous legacy in space qualification testing. The Simcenter environmental testing solutions, whether based on vibrations, acoustics, or shock, are renowned in the industry for their efficiency, robustness and precision. Simcenter offers unique capabilities that engineers can use to de-risk qualification tests by preparing them virtually, on the digital twin. It is an application in which simulation and test are very complementary, and where combining them can be very valuable. Similarly, Simcenter can also be used to test the thermal reliability of electronics.



Conclusion

This white paper describes the priorities that are driving product engineering in Space 4.0. The benefits that can be delivered by Simcenter through the digital twin are perfectly aligned with those. Simcenter also includes a wide range of dedicated solutions that are specifically designed to support various areas of space engineering. Simcenter helps space agencies and businesses move faster, effectively explore innovative solutions, handle process and product complexity, and integrate all stakeholders.

The Simcenter digital twin is an essential component of Xcelerator, the Siemens portfolio that accelerates the digital transformation required to be relevant in the new space era.

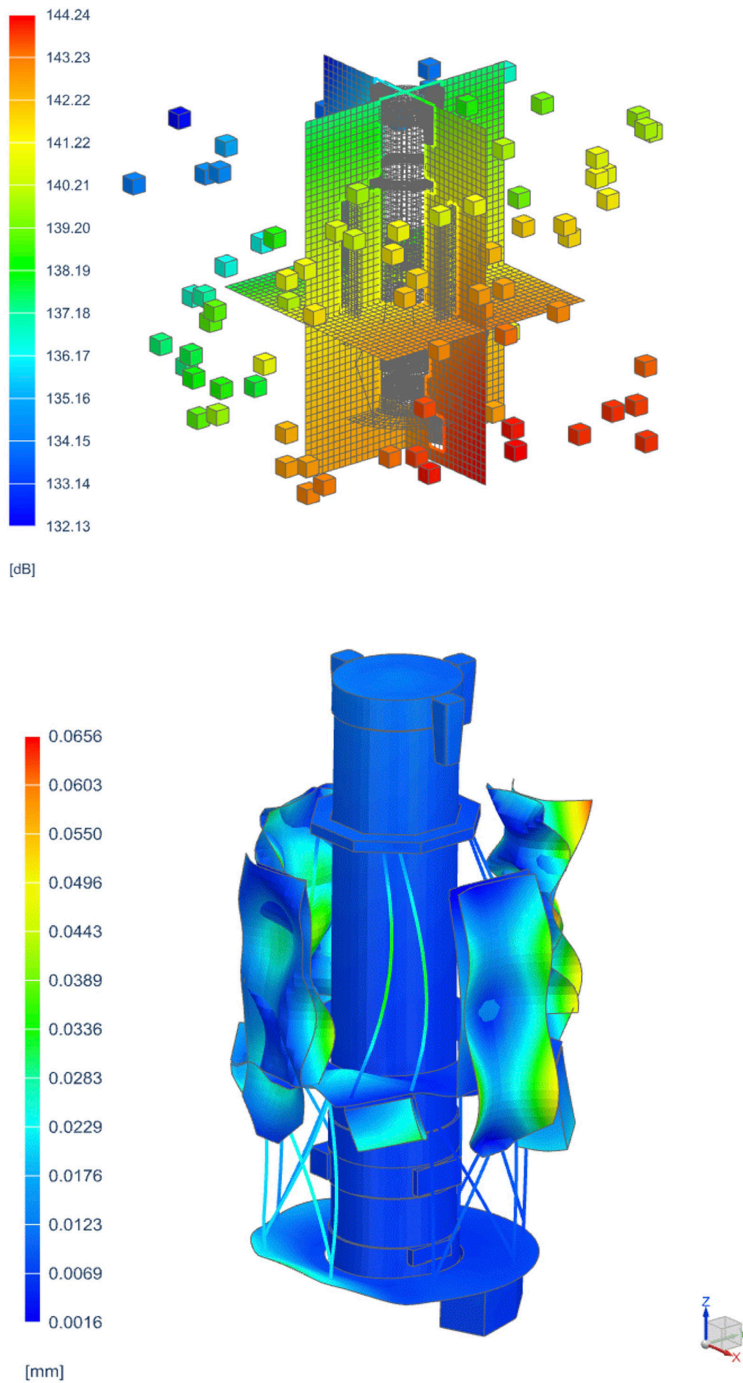


Figure 23: Virtual pre-test analysis for vibro-acoustic qualification tests.

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