White Paper

Complete Systems Modeling and Simulation for Complex Product Development

As products in the marketplace incorporate more and more complexity, the product design process must keep pace to ensure safe, efficient and reliable integration of complicated systems, subsystems and components. Few products today involve a mere single physics; most encompass multidisciplinary behaviors and interactions (with subsequent, sometimes unpredictable, cause and effect). Though simulation tools are powerful, computational restraints limit the use of high-fidelity models for every step in the design process. Adding embedded software to control product behavior further complicates development. As a result, engineering teams need specific models, simulation tools and standards that work together seamlessly to enable robust and cost-effective product development. Best-practice processes help to reduce physical testing, as well as ensure that the results can be shared across global teams and efficiently applied to future product development.

Twenty-first century products are incredibly sophisticated and feature-rich, and consumers have grown to expect advanced functionality even in simple devices. Much of this built-in product complexity comes from electrification: components that are powered, actuated, sensed, and controlled with electrical and electronic technologies. Every day, ultra-competitive product development organizations create ever-more-innovative devices to meet demand. These products deliver more content along with greater efficiency, improved safety, better performance, increased reliability, greater connectedness and more intelligence.

The challenge is to engineer these complexities within a limited development cycle, quickly assessing thousands of possible design alternatives and identifying a single, optimal solution that will have consumers marking the new product launch date on their calendars. That involves engineering systems like chip–package–board, considering multiple physics, solving advanced problems such as reduced power consumption, delivering unwavering signal integrity, and improving bandwidth.

A key enabler in electrified systems design and verification is physical systems modeling and simulation. With this virtual systems approach, the authoritative system definition resides in a living model that provides a thorough understanding of the dependencies, data and interfaces between the various subsystems — not in the traditional set of static text-based design documents.

Systems modeling and simulation represents system behavior virtually, so that the product engineering team can understand, test and optimize the interactions of a complex mix of electronic control, mechanics, hydraulics, electromagnetics and thermal effects.

The virtual systems concept is not new: It is based on techniques that have existed for decades. However, modeling and simulation tools have matured, and a great number of models and libraries are easily accessible today. With the benefit of increased computing power, systems modeling and simulation has achieved global awareness.

There is no doubt that understanding products in terms of system interactions offers great value to the product development community. The overarching concept is that any complex product must be designed and optimized as a system.

Systems modeling and simulation becomes even more valuable when engineering teams reuse/repurpose information and digital asserts — such as results of a detailed physics simulation for a component or subsystem — to apply in analyzing system behavior. Reusability is fostered by growing global acceptance, development of/adherence to standards, and built-in connections with other engineering simulation environments, particularly 2-D/3-D physics simulation.

Because the methodology is portable, models created and used in one environment/context can be easily adapted and used in other environments. Consequently, the model (rather than the specific tool used) is central to the success of systems modeling and simulation.

Even so, it’s important to choose the right tool for the job at hand. Vendors that embrace openness and interoperability (which actively support the concepts discussed) are essential in modeling and simulating virtual systems.

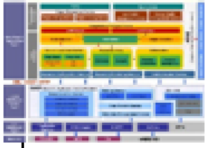
For example, computer-aided engineering (CAE) tools for 3-D simulation and analysis must have sufficient depth and breadth to ensure real-world results. Only integrated structural, fluid, thermal, electronic (integrated circuit) and electromagnetic discipline-specific tools can show the complex interactions of these physics. Traditionally disparate and disconnected models must be integrated so that, together, they can accurately represent a system.

Incorporating embedded software into the mix adds another layer of complexity to systems modeling and analysis. Smart and electrified products employ embedded code to control collaborative functions between analog and digital components. Automobiles, for example, have a number of electronic control units that execute millions of lines of code. Tools for designing, optimizing, verifying and generating embedded code must meet industry-specific standards at the highest level, especially in safety-critical applications from aerospace to nuclear.

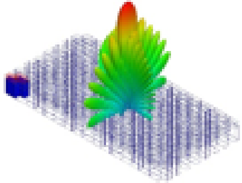
Systems Modeling and Simulation

Basic Elements

- Decompose system requirements into functional models and design the product architecture using model-based system engineering best practice.



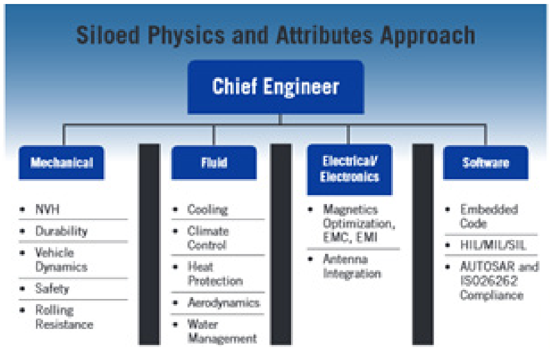
- Perform conceptual and 0-D behavioral modeling of the system to optimize and validate system architectures.



- Design, optimize and verify hardware and electronics components using 3-D multiphysics.

- Design and generate embedded control systems and human-machine interfaces that meet industry and safety certification standards.
- Perform virtual system integration and verification by combining software, electronics and hardware designs into a complete virtual system prototype.

Automotive Industry Example



In the automotive industry, mechanical strength of a brake rotor is studied separately from air flow that cools the brake, for example. Single-physics simulation studies a sole physical effect in isolation. This approach does not recognize potential failure modes when phenomena intersect. Furthermore, simulation in various disciplines is performed sequentially instead of in parallel, lengthening the development cycle.

Using another example, electrical, magnetic, thermal, fluid, structural and acoustic aspects of an electric traction motor are all tightly coupled: Coolant flow affects temperature; temperature affects electromagnetics; these, in turn, affect motor efficiency as well as structural vibrations that result in noise. For such systems, making these trade-offs in a silo-like approach is suboptimal.

Complex systems require best practices that break down the silos and span all physics/engineering disciplines.

Other enabling technologies include proven open standards for connecting models, such as the functional mock-up interface (FMI), as well as standard behavioral modeling languages like VHDL-AMS and Modelica

Why Designing in Silos Doesn’t Work

“Optimally” designing individual components and assembling them into a system/product does not result in an optimal system. It merely produces unnecessary (and costly) design iterations, product launch delay and possible product recall. By its very nature, product design involves trade-offs. When making a change without understanding all its interdisciplinary effects, the consequences can be disastrous.

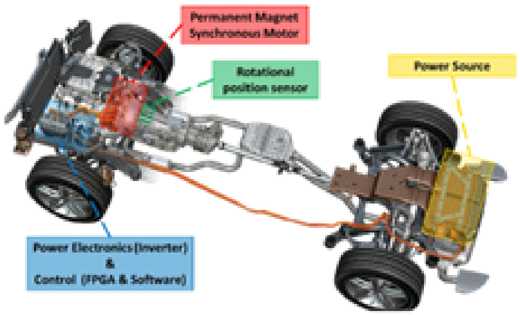
Engineering teams must have the ability to design in a particular domain within the context of the surrounding domains that ultimately influence product performance.

Designing complex products calls for a systems mindset, which is not just a task conducted near the end of the development cycle. Systems thinking must start early in the process as a discipline that informs detailed design and mitigates surprises at the component-assembly stage. The integration starts with evaluating concepts and optimizing architectures, then moves through to verifying that the combined system satisfies the intended goals and requirements.

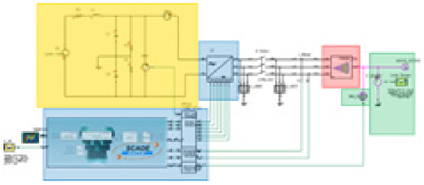
Global Applications

Product development in nearly every industry can benefit from systems modeling and simulation. Issues related to complexity (and solutions to managing complexity) apply not just to traditional complex system manufacturers (automotive and aerospace/defense) but to oil and gas production, alternative energy, healthcare, industrial equipment, and consumer products. Emerging complex applications include electric powertrains, autonomous vehicles and advanced driver assistance systems; electromechanical flight controls and electric taxiing for aircraft; and electrification of oil and gas drilling and extraction equipment.

The electrification of products is a consequence of the industrial Internet of Things (IIoT), which is dramatically altering manufacturing, energy, agriculture, transportation and other industrial sectors of the economy. While it fundamentally will transform how people work through new interactions between humans and machines, most important is that the technological changes will bring unprecedented opportunities, along with new risks, to business and society. The IIOT will combine the global reach of the Internet with the ability to directly control the physical world, including machines, factories and infrastructure that define the modern landscape. All this represents an incredible opportunity to revolutionize the product development value chain.



Systems modeling and simulation is applicable to a new age of products in the automotive industry. The system-level models for this electric powertrain system include ANSYS Simplorer (a platform for assembling and testing performance of virtual system prototypes), ANSYS Maxwell (2-D and 3-D electromagnetic simulation), ANSYS Q3D Extractor (parasitic extraction tool) and ANSYS SCADE (for creating and optimizing embedded software).



Automotive Industry

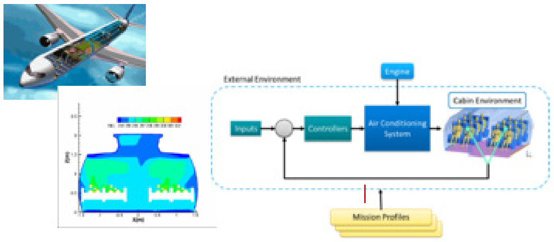
Electric Powertrain Control

System-Level Objectives

- Evaluate architectural selections and component choices to optimize fuel economy and cost
- Verify control strategies and calibrate control parameters
- Assess system reliability (worst-case analysis, fault injection)

Key System-Level Models

- Permanent magnet synchronous machine extracted as reduced-order model (ROM)
- High-voltage bus bar parasitics
- Motor control software
- High-power electronics (inverter), behavioral multi-domain sensors



The system-level models for this aircraft environmental control system include ANSYS Simplorer, ANSYS Fluent (fluid simulation), ANSYS SCADE and Modelica (modeling language for multi-domain systems).

Aerospace Industry

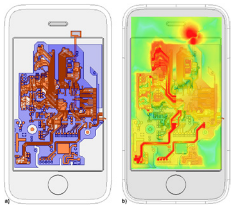
Aircraft Environmental Control System

System-Level Objectives

- Optimize component selection, sensor placement and control strategies to lower emissions
- Tune and optimize controller parameters to improve passenger comfort

Key System-Level Models

- Detailed cabin airflow model extracted as reduced-order model
- Air conditioning system components (actuators, sensors, etc.)
- Cabin pressure/temperature control software
- External conditions, mission profiles



High-tech industry product development teams routinely use systems modeling and simulation tools from ANSYS to analyze the trade-offs among speed, bandwidth, signal integrity, power integrity, thermal performance and EMI/EMC. Not only can ANSYS solutions identify obvious flaws, such as structural weakness in a tablet casing, but they can flag the more- subtle performance issues that are created when many disparate systems come together — for example, the effect of a variety of casing materials on thermal management, chip performance and electronic signal quality.

Culture Change

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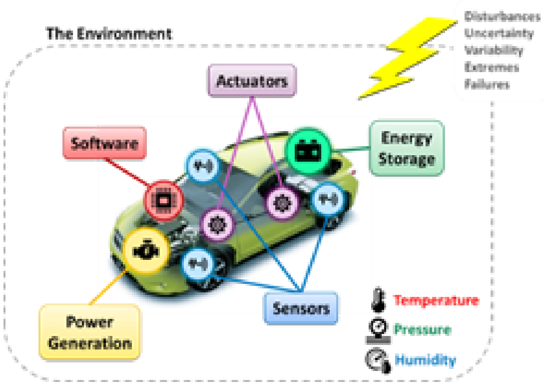
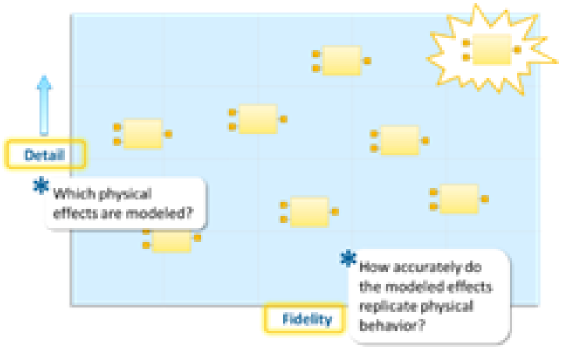
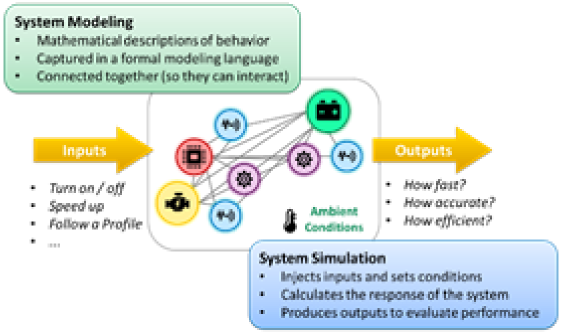


By nature, systems are complex. They involve multi-domain dynamics, multi-disciplinary interactions and a range of uncertainties.



In the fidelity/detail grid, the ideal model combines the highest level of detail with the best fidelity — as depicted in the upper right corner. In most cases, real-world product development cannot accommodate these criteria.



Systems modeling and simulation starts with models, applies inputs and then calculates the response as a way to represent performance and extract meaningful insight from the system.

Global Applications

The latest technology may be easier to adopt than the culture change that sometimes comes with using it effectively. Product development companies, especially those with a long history of product success, face tough organizational challenges. For example, the automotive industry worked for a century to design and refine vehicles with traditional internal combustion engines. But consumer, environmental and governmental pressures pushed the industry to develop mass-marketed electric vehicles in only the last decade — even though a legacy of research existed from over the past 100 years.

Once an organization commits to a systems-oriented philosophy, delivering products that better satisfy market needs, in less time, is a reachable goal.

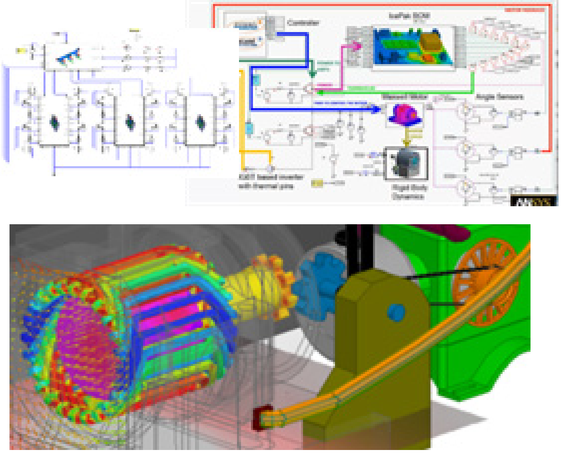
Definitions

A system, as it relates to engineering, is the an assembly of components that generate power, store energy, actuate and create motion, sense, and control behavior — all working in concert, subject to the surrounding environment (such as fluctuating temperature, pressure, etc.). The interactions and interconnections are complex, facing and can lead to uncertainties and disturbances that can result in failure or degradation of performance.

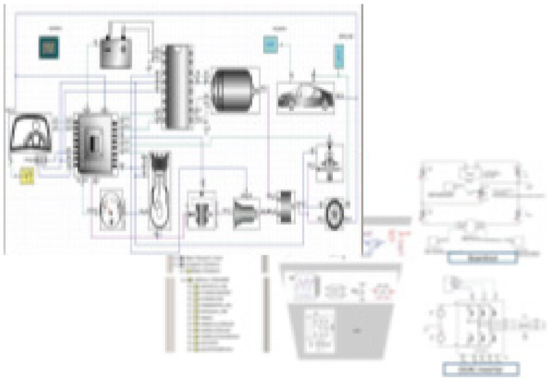
A model is an abstraction of selected aspects of structure, behavior and/or operation of a real-world process, concept or system. It is an approximation or representation of a problem and its objectives (in this case, a complex product with requirements, parameters and limitations related to cost, size, time, consumer demand, etc.).

Two important concepts influence how a system model is assembled: level of detail and fidelity. Detail refers to which physical effects are modeled. Fidelity describes the accuracy with which those details replicate actual physical behavior.

In an ideal world, development teams would create system models at the highest levels of detail and fidelity. However, the result is unnecessarily complex, and there is usually not enough time or available information to actually create the models. In practice, engineering groups apply an array of system models to assemble virtual system prototypes. The choice of which model to use depends on the type of questions that need to be asked, analysis being done, stage in the development process and information available.



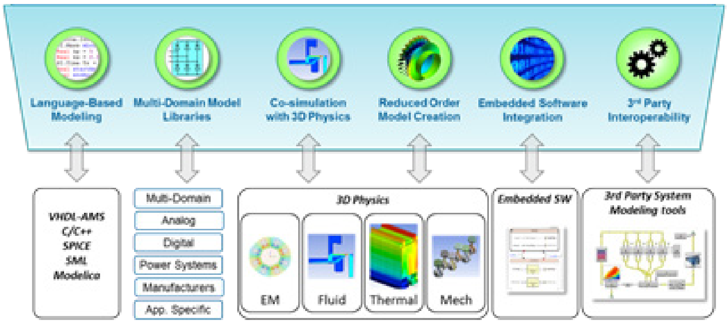
The ANSYS systems modeling and simulation capability is based on ANSYS Simplorer, a comprehensive platform for building virtual system prototypes. Established as a tool for analyzing power electronics and electromechanical systems, Simplorer has been enhanced to support combined electrical, electronic, fluids, mechanical and embedded software systems.

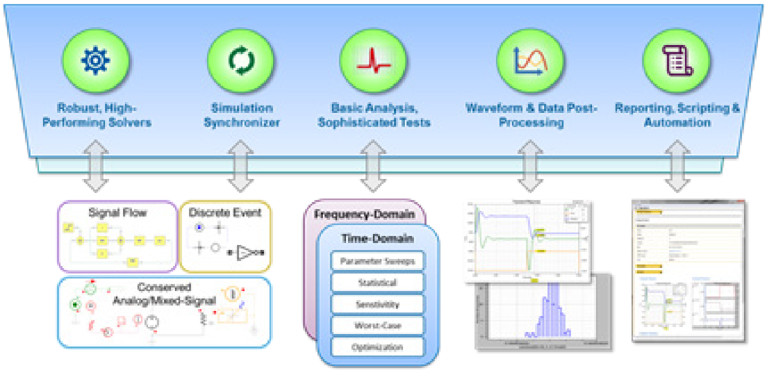


VHDL-AMS support is included as standard in ANSYS Simplorer, enabling easy exchange of models between tools used in industry. Standard model libraries for the automotive industry support system simulations of hybrid electric vehicles. By integrating these libraries, engineers can perform a simulation of energy consumption in an entire vehicle.

Ecosystem

The best systems modeling and simulation tools provide the ability to create models, access existing models and libraries, assemble those models, and perform simulation-based tests in a robust and efficient manner.



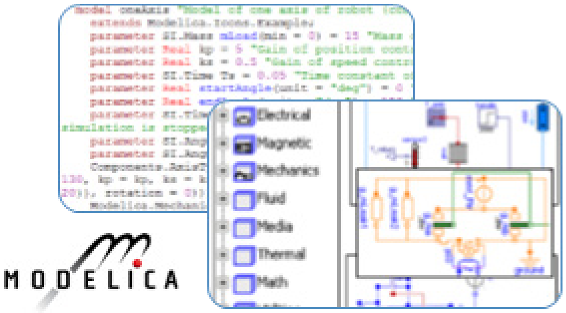


Standard Modeling Languages

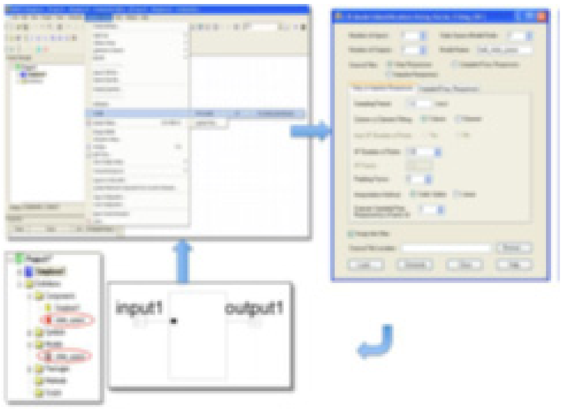
Standard modeling languages make it easy to create and exchange physical system models and model libraries.

Among several conventions and approaches for modeling the behavior of multi-domain systems, formal language standards are an important underpinning of model reusability and portability. Two of the most prevalent are VHDL-AMS, used especially in the electronics/electrical/high-tech sectors, and Modelica, highly applicable to mechanical and fluid modeling. Both languages offer the same fundamental capabilities, but adoption has been concentrated in their specific arenas.

VHDL-AMS is an extension of the IEEE 1076 standard VHDL modeling language, which incorporates support for analog, mixed-signal and multi-domain descriptions. This standard was created to enable designers of analog and mixed-signal systems and RF integrated circuits to create and use modules that encapsulate high-level behavioral descriptions as well as structural descriptions of systems and components.



By combining support for popular modeling languages in a single environment, ANSYS technology is able to more broadly and more effectively support the virtual system prototyping needs of product development organizations. By partnering with the premier Modelica provider, Modelon, ANSYS is integrating Modelica technology into ANSYS Simplorer to provide seamless support and capabilities.



ANSYS software provides reduced-order modeling interfaces with all the core physics disciplines (mechanical/structural, fluids, electromagnetics) to address a range of modeling needs at the systems level. The methodology also leverages/reuses the effort applied during detailed design steps.

Modelica is an object-oriented language for modeling complex multi-domain systems. The language standard, along with a library of models (called the Modelica Standard Library, or MSL), are freely available, developed and maintained by the Modelica Association — comprising users and contributors in industry, research and academia. Automotive, aerospace, industrial equipment and energy companies use Modelica libraries as standard tools in their systems modeling efforts.

The Modelica ecosystem is vibrant and growing, due in part to a rich set of available model libraries used to describe systems in all engineering domains, with applications spanning a broad range: fluid power, vehicle dynamics, cooling and thermal management, and industrial processes.

3-D Analysis

Detailed 2-D and 3-D simulation is applied broadly in the detailed design stages of product development: structural, fluid dynamics, thermal, and high- and low-frequency electromagnetics analyses, as well as multiple physics simulation that integrates physics disciplines. Such software not only shortens the design cycle and delivers efficiency, it drives innovation. The technology reduces or eliminates physical constraints, enabling simulated tests that might otherwise not be possible. It fosters what-if thinking so engineers can readily explore design alternatives for an optimal solution.

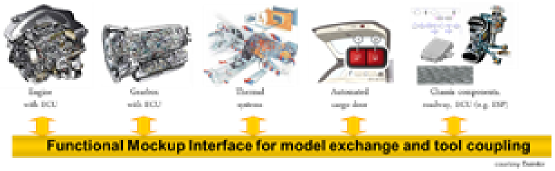
Because today’s 3-D simulation software delivers incredible fidelity, it can be challenging to apply virtual analysis at the system level. Computational requirements are prohibitive and unrealistic. Therefore, a premier systems modeling and simulation solution includes reduced-order modeling (ROM) methods that enable effects of a sub¬component to be represented within an assembly without loss of accuracy — while greatly increasing computational speed.

Reduced-order modeling enables reusing the results of detailed 3-D simulations in an integrated system context. It generally refers to the generation of compact, computationally efficient models from a much -more detailed description. The simpler models can represent some behaviors of a component that are then connected with other systems-level models to form a complete picture of system behavior.

Standard Open Interfaces

Open interfaces play a large role in enabling a flexible, inter-operative platform for virtual system prototyping at every point in product development and production cycles.

The functional mockup interface, or FMI, allows manufacturers to gather and connect various models into systems. These models come from many places, both internally (different engineering departments within a company) and externally (equipment and component suppliers).



The FMI was created as a tool-independent standard for exchange and cosimulation of dynamic system models between suppliers and OEMs in a number of sectors, including automotive, aerospace and energy. It is a primary interface in ANSYS Simplorer for integrating models of physical hardware and embedded software.

ANSYS provides several means of incorporating embedded control into the context of system models, to support a number of X-in-the-loop methodologies, including model-in-the-loop and software-in-the-loop validation. ANSYS SCADE products for safety-critical embedded software design are tightly integrated with ANSYS Simplorer; they also support the FMI.

For this unmanned airborne vehicle, ANSYS SCADE automatically created a program source code with over 100,000 lines compliant with the aerospace safety standards.

By providing a standard for connecting simulation models and tools, the FMI results in earlier integration and evaluation of designs. It also improves communication among all parties involved, engineering or otherwise. Finally, it protects the intellectual property contained within models exchanged among suppliers and manufacturers. Today, nearly 70 simulation software vendors support the FMI, contributing to a thriving community of highly collaborative development.

Embedded Software

The process for incorporating embedded code that controls systems faces similar pressures: iImprove design quality, reduce development costs and shorten development time. Embedded systems and software utilization is emerging as a major differentiator in most product industries. Yet adding embedded code increases system design challenges and complexity.

Embedded software is increasingly becoming the source of product failures. Some industry leaders claim that every 1,000 lines of embedded software contains eight bugs. This means that a premium-class automobile with 20 million lines of the code, could contain 160,000 errors. To manage this quality risk as well as meet tighter standards for software certification, embedded software engineers must leverage software simulation tools and certified code generators.

The appropriate tool for modeling and generating embedded code is one that integrates with systems engineering tools, virtual prototype generation and multiple physics simulation. Model-based design methodologies enable system and software engineers to model each function autonomously and then collaborate with different disciplines to ensure that the model meets specific requirements. The tools used must allow for early verification and validation of the code, often before the actual target is available.

Certified code generators play an important role in speeding product development cycles. Code generators must guarantee that the code generated is an exact replica of the model developed. Tools that generate code should meet stringent industry standards, like DO-178C for aeronautics and ISO 26262 for automotive.

There are still many challenges that companies need to manage. Systems modeling and simulation is applicable to all of them:

- Anticipating increasing complexity
- Incorporating more content, more variants
- Seeking out and applying new technologies and processes
- Understanding multi-domain interactions
- Adjusting views related to quality and reliability
- Dealing with new government and industry regulations
- Hitting ever-shorter market windows

Summary

As products become smarter, more connected, increasingly electrified and consequently complex, systems modeling and simulation provides enabling technologies for robust and cost-effective product development. Model-based development can also help to ensure design quality, functional safety verification and reuse of design assets.

Furthermore, organizations are now leveraging virtual systems methodologies to evaluate and demonstrate compliance/conformance with industry standards for performance.

The most-successful product development companies apply modeling and analysis of systems at start of the process — designing from requirements (power, load, features, reliability) — incorporating systems modeling and simulation as early as possible and throughout component design, then integrating the information gleaned to address the full system.

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ANSYS, Inc.
Southpointe
275 Technology Drive
Canonsburg, PA 15317
U.S.A.

724.746.3304
ansysinfo@ansys.com