Kepstrum
INVENTOR OF PRODUCT DNA™ and MODEL-BASED PROGNOSTICS

Jul 17th, 2023

THE MISSING LINK IN VIRTUAL VALIDATION

Engineering industries are undergoing a series of changes that put advancements in design technology and novel digital prototyping processes at the forefront of what they'll be able to achieve in the future. Digital management of processes, digital modeling of components, and digital tracking of design and field data are slowly becoming the norm. In this rapidly shifting and highly competitive environment, designing and developing components for emerging applications and cutting-edge technologies through continued reliance on historical data, physical testing, and multiple prototyping cycles filled with re-work is no longer a viable strategy. Companies have an incentive to pursue digitalization on the basis of achieving two distinct but related goals; increased efficiency and reduced risk.

If adopting new processes and tools to improve efficiency and reduce risk was once an amorphous goal that organizations pursued with incremental changes simply to improve their offerings and processes, it has now become imperative for them to do so in order to maintain their position in the value chain. Industry 4.0 is here, and Original Equipment Manufacturers (**OEM**s) are already openly moving to adopt 100% Virtual Validation methods, with some hoping to do so in the next five years. Moreover, they plan to rely on their suppliers to implement the necessary changes in their internal development processes to achieve this goal.

Tier suppliers are expected to:

- Establish their own internal Design Validation (**DV**) plans and new development processes that enable moving away from relying on various levels of physical testing and hardware.
- Establish systems and processes that facilitate the use of virtual tools and technologies that allow OEMs and their suppliers to leverage mathematical tools, access material data, utilize virtual models, and conduct simulations to enhance & streamline system work.

Among the goals encompassing the move to 100% virtual validation are:

- reducing development time
- improved engineering quality
- greater throughput
- reduced costs

Suddenly the two goals of reducing risk and increasing efficiency have taken a less ambiguous shape, with clearer outcomes now being defined; The ultimate result of such a complete transformation would be that the first physical prototypes to be produced would already be "good enough to sell".

This seismic shift in the market poses new challenges for OEMs and Tier suppliers. Pursuing either the goal of increasing efficiency or reducing risk in isolation will not suffice in this endeavor and will leave engineering organizations exposed to unwarranted risk or unable to remain competitive in the market. Thus, to achieve sustainable benefits and remain competitive, organizations must take an integrated approach to implementing new development processes that can achieve both goals simultaneously, and wherein the pursuit of either goal complements the other. Organizations must choose suitable methods to virtually model component behavior, ensuring their models accurately represent physical products and real-world conditions, and adopt Model-based Systems Engineering (**MBSE**) practices to facilitate streamlined system work. The ability of Tier suppliers to meet this demand will determine whether they will be able to continue receiving business from OEMs. There are bound to be many approaches to meeting this demand, but the challenges remain the same, and thanks to its robust MBSE environment, physics-based modeling, and embedded deterministic risk reduction methodology, Kepstrum's DNA Structured Platform (**DSP**) is uniquely suited to addressing them.

Virtual Validation & Virtual System Work: Traceability is the new Reliability

In order for virtual validation processes to deliver products that are good enough to sell without extensive prototyping, all steps in the production life cycle must be in lockstep. Even if the modeling that informs the understanding of a component's real-world behavior is done perfectly, it will not be enough unless the modeling delivers the intended result outlined in the product requirements. Similarly, subsequent manufacturing processes must deliver the physical product as designed. Thus, reliability goes hand in hand with traceability. In that respect, the appropriate virtual validation tool must also be the appropriate system work platform. This necessitates the implementation of model-based systems engineering (**MBSE**) processes that enable traceable management of technical data, design decisions, production procedures, and organizational knowledge.

As discussed in our white paper: "Cutting Costs Through Digitalization - Enhancing the Power of MBSE with the DSP":

> "...these benefits should be pursued simultaneously within a Model-based Systems Engineering platform; "MBSE is a formalized methodology that uses models as the center of system design, as opposed to document-centric engineering. It supports the requirements, design, analysis, verification, and validation associated with the development of complex systems."[1] MBSE enables an organization to create and manage a single digital thread, "a data-driven architecture that links together information generated from across the product lifecycle and is envisioned to be the primary or authoritative data and communication platform for a company's products at any instance of time"[2]. A digital thread "connects traditionally siloed elements in manufacturing processes and provides an integrated view of an asset throughout the manufacturing and product lifecycle."[3]"

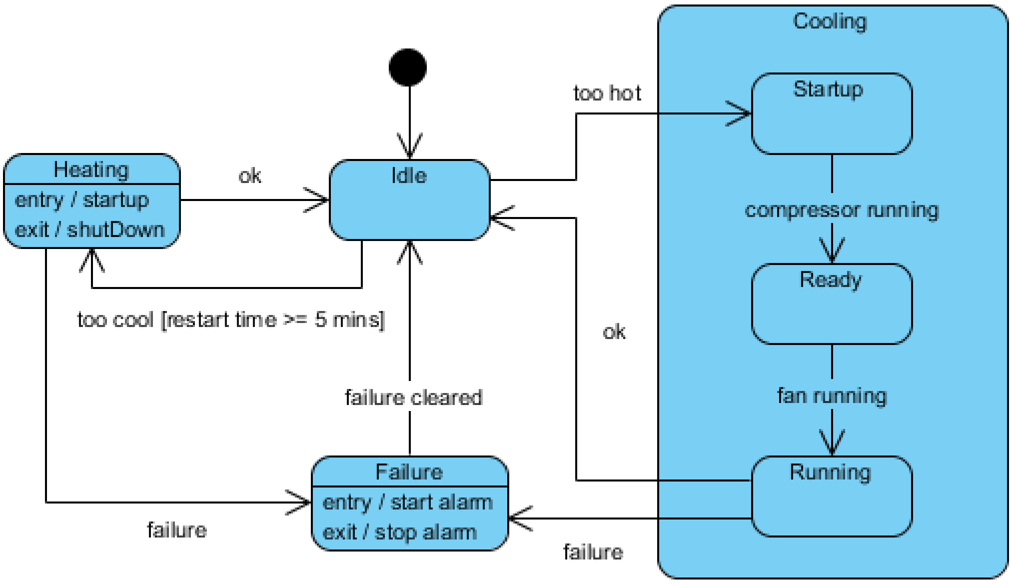
Virtual modeling, design, and validation will generate the most value with the least friction in an integrated MBSE environment that allows for the creation of digital threads, cross talk between stakeholders, collaboration between teams, and traceability throughout the development process. However due consideration to the suitability of the solutions that a MBSE enhanced process, focused on improving project delivery, delivers must be woven into every step of the development process. For engineering reliable components, the content of the digital thread and the structure of the MBSE system used to host it play a crucial role. This will be discussed in the next section.

1. Shevchenko, Nataliya. "An Introduction to Model-Based Systems Engineering (MBSE)." Carnegie Mellon University, Software Engineering Institute's Insights (blog). Carnegie Mellon's Software Engineering Institute, December 21, 2020. http://insights.sei.cmu.edu/blog/introduction-model-based-systems-engineering-mbse/. Accessed 29 Jan 2023
2. Singh, Victor, and K. E. Willcox. "Engineering Design with Digital Thread." AIAA Journal, vol. Volume 56, no. Number 11, 2018, pp. 4515-4528. Aerospace Research Central, https://arc.aiaa.org/doi/10.2514/1.J057255. Accessed 31 Jan 2023.
3. Diann, Daniel "Definition: Digital Thread" https://www.techtarget.com/searcherp/definition/digital-thread. Accessed 29 Jan 2023.

The Risks of Virtual Validation: Choosing the Right Path

Eliminating physical testing means confidence in the reliability of the models used to validate designs stands as one of the most pressing concerns around OEMs' plans to move to 100% Virtual Validation.

Typical MBSE platforms, based on UML and SysML, facilitate collaboration and traceability but exhibit limitations in modeling physical behaviors and interactions. While these platforms allow for the representation of engineered components' structures using tools like UML class diagrams and SysML Block Definition Diagrams, and their behavior using tools like UML and SysML sequence diagrams, state machine diagrams, activity diagrams, and parametric diagrams, it is important to note that these modeling tools originate from the field of software and computer engineering; they are useful for defining the conceptual nature and intended behavior of a modeled system. However, when these tools are applied in the broader fields of mechanical engineering, such as the design of dynamic and structural components, their limitations become apparent. As conceptual models that define functional behavior (the intended function of a system), they are not representative models that capture physical behaviors (real word function of a system).



SysML State Machine Diagram Example

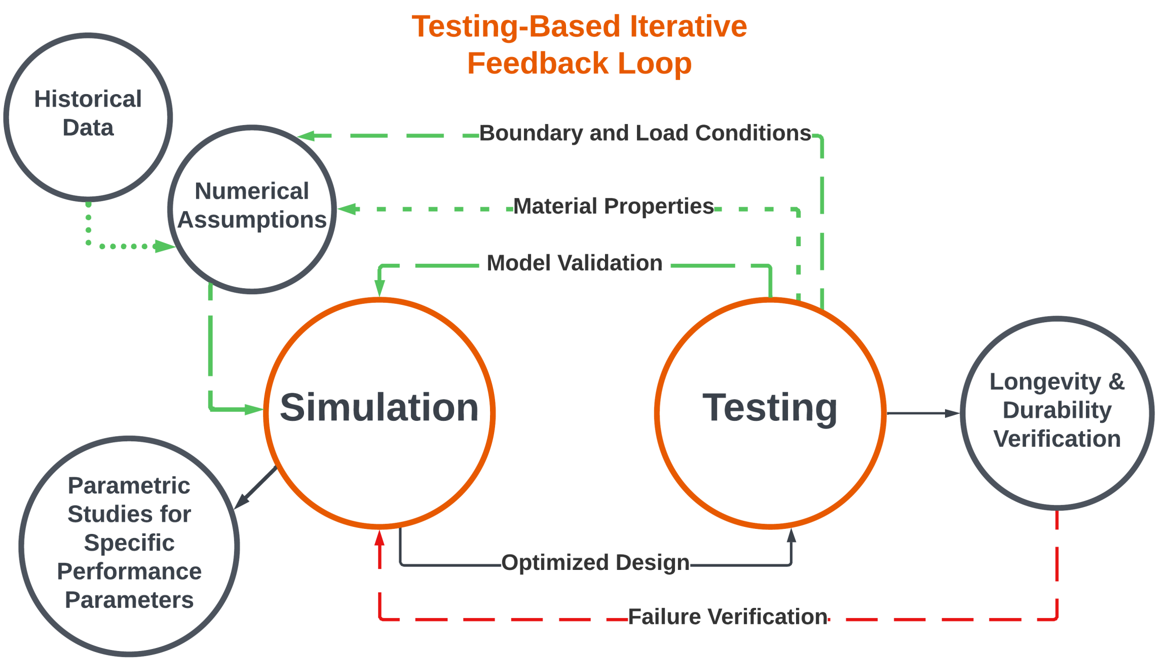
For instance, sequence diagrams represent behaviors as a single sequence of predetermined actions and outcomes. While they are suitable for capturing a linear sequence of events, they are not well-suited for modeling concurrent processes or capturing emergent behaviors that arise from the interactions between components and their environment. Similarly, state machine diagrams conceptually outline the behavior of systems transitioning between a finite number of states based on specific conditions or events. However, since they lack a built-in notion of time, they are inadequate for capturing the dynamic behavior of systems that change and degrade over time, or how they respond to multiple simultaneous stress drivers.

Activity diagrams focus on the control flow of a system rather than its data flow or physical behavior. Therefore, they are not suitable for modeling the behavior of engineered components. Parametric diagrams excel at analyzing and optimizing straightforward systems with clear quantitative relationships between components and parameters. However, they do not consider the system's underlying physics or mechanics, nor do they account for the impact of external forces or stresses on its components. Consequently, they are unsuitable for modeling complex systems with multiple components and interactions, or for design projects involving research and development to discover relationships between design parameters that will be used at a later stage.

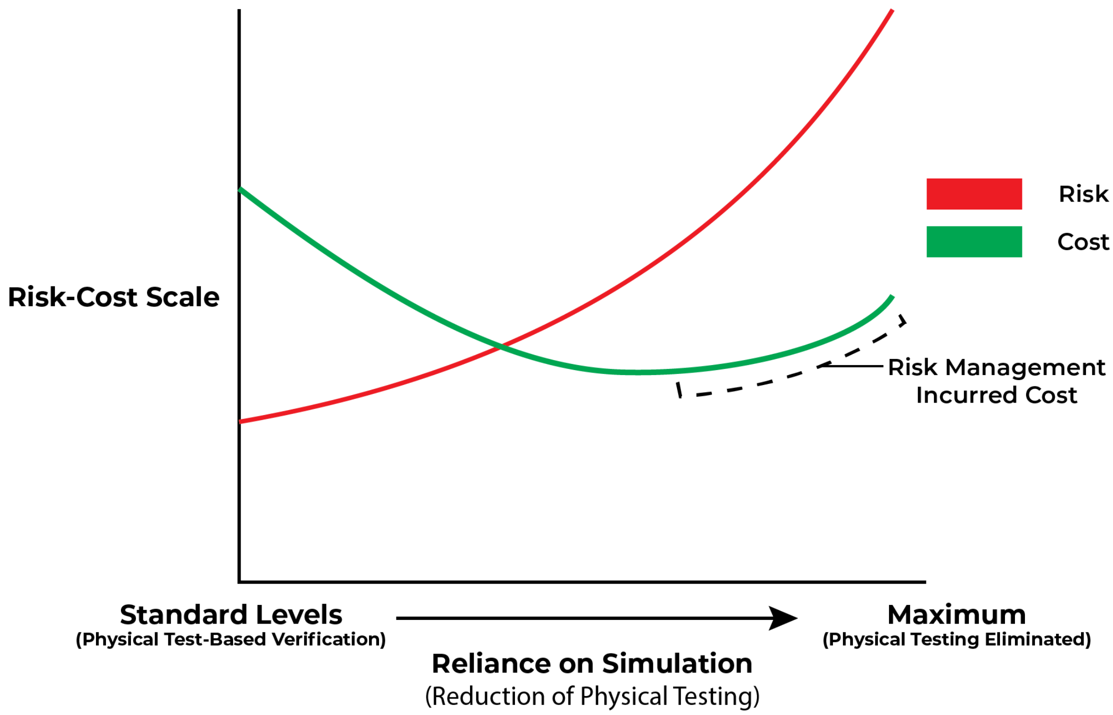
Therefore, typical MBSE tools, while beneficial for conceptually outlining intended performances, have limitations in modeling component-level behaviors and capturing the internal and external interactions of system components.

Continuous behavior, complex interactions, emergent behavior, multi-variable stress drivers, and real-time constraints must be considered when designing and validating the performance of engineered components. Without this understanding, SysML and UML MBSE languages are unable to accurately validate whether performance requirements are being met as design decisions are being made, or model the real-world behavior of a component. Thus, they cannot facilitate effective design verification or eliminate the risk of recalls. To accurately model engineered components, structure and behavior must be considered in an integrated manner in order to accurately model either. Therefore, for an MBSE-based development process to be effective in achieving 100% virtual validation, it must rely on other means of modeling components to evaluate design decisions and manufacturing processes.

Organizations that have implemented MBSE processes typically rely on simulation to overcome the limitations of conventional MBSE platforms regarding modeling component behavior. By combining streamlined system work, simulation, and physical testing, these organizations have achieved cost reductions and delivered successful products. However, there are inherent limitations to what this three-pronged approach can accomplish, and even with these processes, these environments are still prone to field failures and lengthy prototyping phases. Previously, simulation techniques complemented and improved existing development processes, leveraging historical data and physical test-based verification in order to build and validate simulation models.



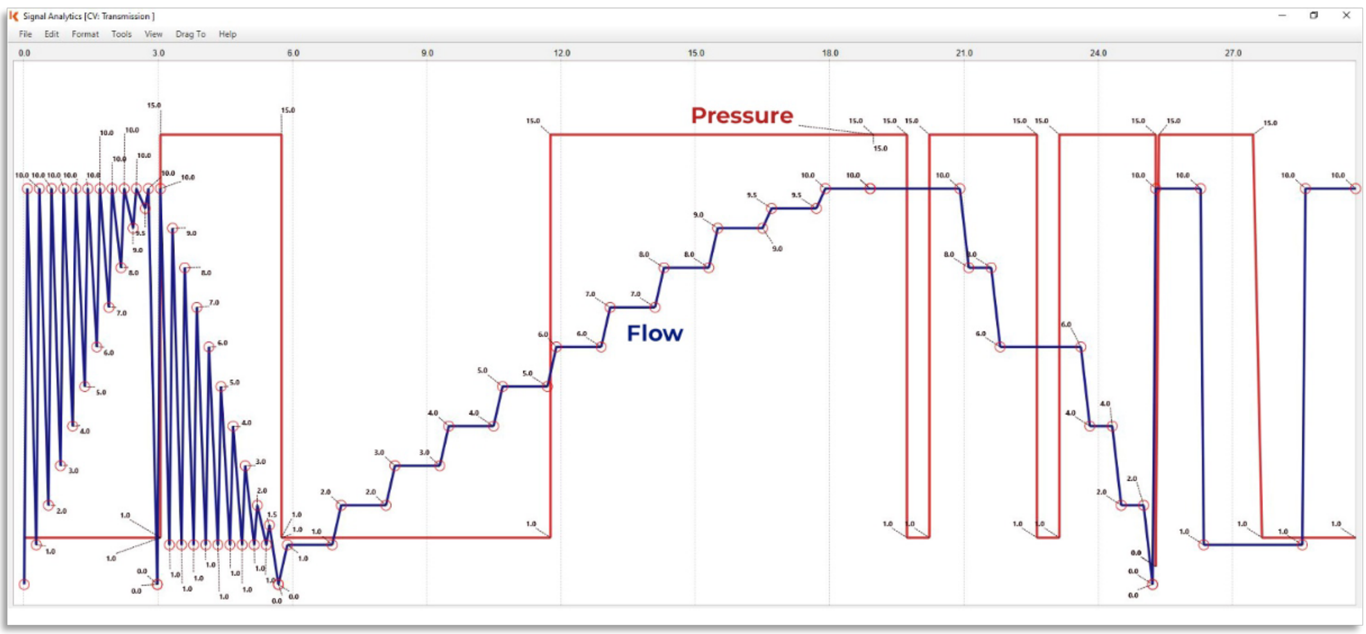
With the elimination of physical testing from the development ecosystem, MBSE processes reliant on simulation will become even more shorthanded. Simulation teams will no longer be able to iteratively inform the numerical assumptions of their models, validate their models, or rely on testing to identify any potential failures that may have been missed in simulation. This will introduce an unacceptable amount of risk as organizations will not be able to verify that their product meets safety and performance requirements. This challenge is particularly prominent in new developments lacking sufficient historical data to inform the assumptions of numerical simulations. Furthermore the specific nature of parametric simulations means that produced results cannot be extrapolated beyond a narrow range of specific conditions. The heavy reliance on simulation in virtual validation can lead to misguided mistakes if an open system of definition, analysis, cycles, and stress drivers is not properly defined. The weight of this risk will only increase as organizations are pushed to supplant their physical testing processes with more simulation. This increased risk will also result in new costs associated with risk management and reputational damage, rendering the cost savings derived from the elimination of physical testing insignificant or even outweighing the initial benefits.



A successful 100% virtual validation process cannot be developed by simply increasing the investment in, and strain on, simulation teams, and instead requires the inclusion of an additional ingredient: physics-based analytical modeling.

DSP: MBSE & Virtual Validation the Right Way

What differentiates DSP from other MBSE offerings is the embedded methods of capturing functional requirements and modeling component behavior. UML and SysML-based MBSE systems' standardized methods of capturing product requirements are heavily text-based and ultimately require diligent and manual validation throughout the design process. DSP provides the capability of capturing product requirements and then graphing them as signals on a single plot to create the component's "**Digital Spec.**" functional profile. For modeling components, we rely on analytical models as the best tool for truly understanding the capabilities, behaviors, and limitations of engineered components. To employ these models, DSP uses Digital Spec. profiles, which include the signals defining functional requirements, as a foundation and expands them to include calculated signals whose values can be related to one another and are calculated using physics-based closed-form equations. Digital Spec enables a clear visual understanding of the product requirements in the same format as the calculated signals that model the component's complex interactions, performance, and exposure to stress. This simultaneously eliminates the ambiguity and complexity of capturing complex product requirements in a text-based format and enables real-time design verification, ensuring those requirements are being met as development progresses. Furthermore, DSP allows the same models and equations to be used on these profiles to calculate the component's trend-to-failure to determine the design limit and avoid unforeseen field failures, in addition to verifying whether the product requirements have been met.



Simplified Digital Spec. Profile Example

At its core, DSP is an enterprise level database-structured software that facilitates the computer aided implementation of our patented "Method for deterministic stress based risk reduction" (Patent No. US20140081583A1), known as Intelligent Reliability Methodology (**IRM**), to generate a product's "**DNA**" (**D**esign Limit, **N**ature of Failure, **A**ctual Life). **Product DNA** is the culmination of the use of analytical-models and closed form equations in conjunction with deterministic analyses based on IRM. This analytical stress-life model is used to predict product failure modes (why it fails, how it fails, when it fails), and understand product capability far more accurately than conventional methods. It represents the organization's highest level of understanding about their product, and it is the tool by which organizations can understand their component's limits, safety margins, and maintenance requirements, and deliver confident predictions of a product's true life expectancy to their customers. (Diagram on the following page)

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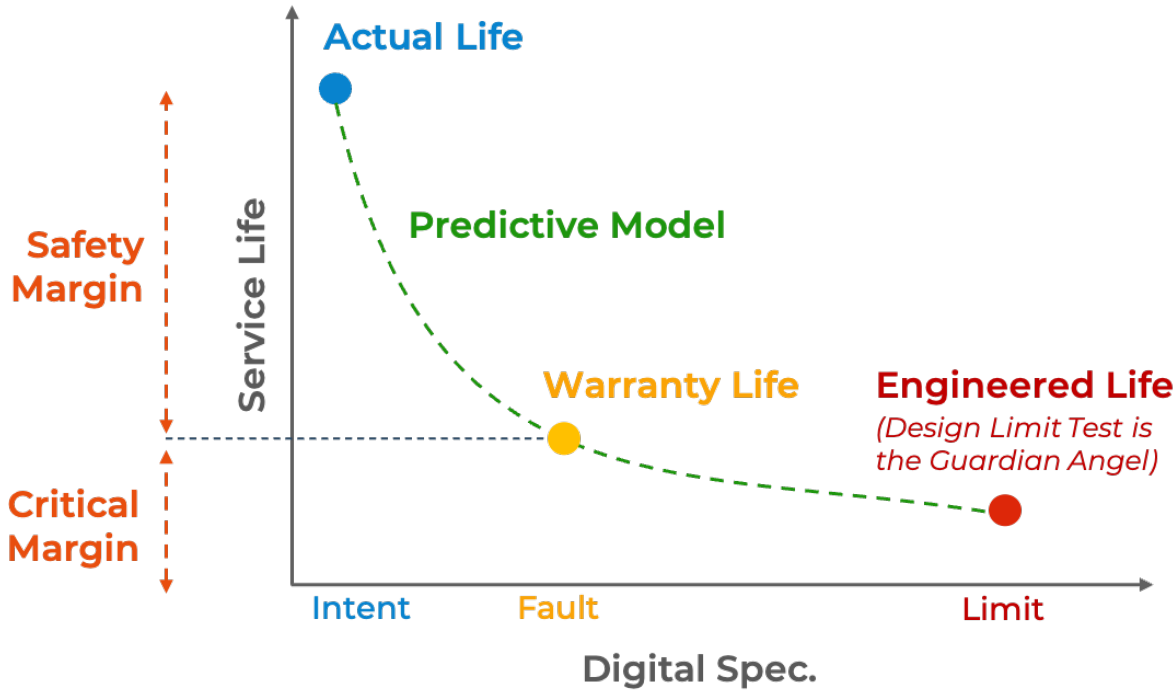
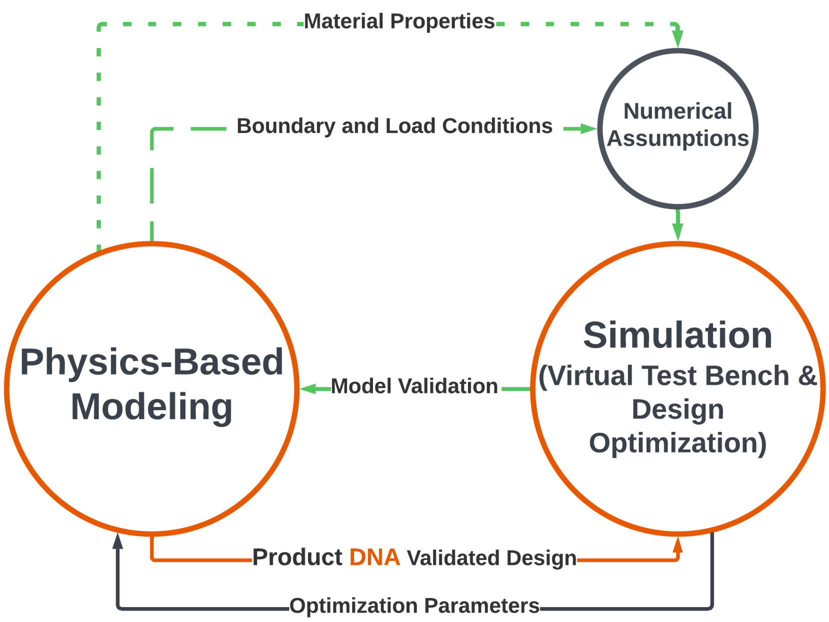


By correlating stress-drivers with how and when a product will fail, Product DNA empowers engineering teams to reveal product weaknesses and generate design solutions in the early stages of development, validate designs, and detect material variation in manufacturing. Thus, random failures become a thing of the past, and the design process becomes more effective and efficient, allowing for the actualization of the goal of producing reliable components good enough to sell at the first production batch.

DSP's physics based modeling and DNA technology has the power to enhance and complement numerical simulation models to establish a healthy Virtual Validation process. By using DSP's physics-based modeling, engineering teams are able to provide simulation teams with deterministic boundary conditions grounded in real-world physics. These boundary conditions provide essential parameters for numerical simulations, thereby ensuring the assumptions used generate reliable results. In this process, the focus shifts from CAE to Concept-to-CAD, ensuring that new products

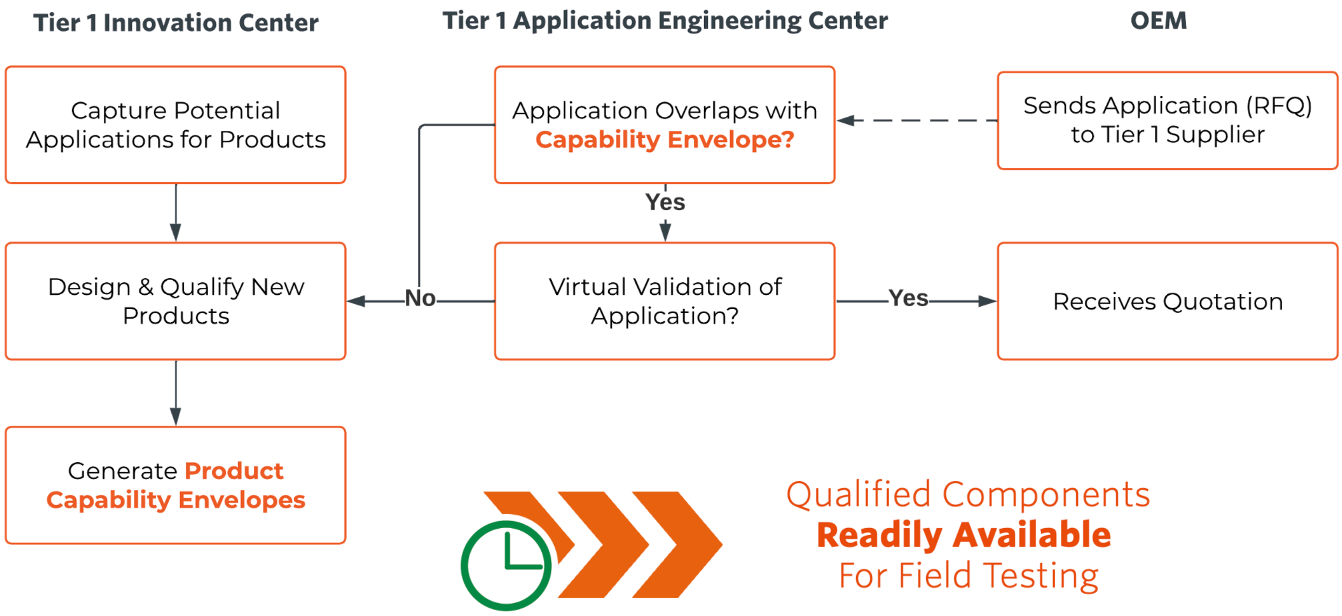
Physics-Based Simulation Enhancement



are qualified in the conceptual stage for sizing and service life before reaching the CAD stage. Our platform's concept-phase physics-based analytics offer unlimited capacity for involving any kind of deterministic boundaries. With these deterministic boundaries in place, simulation teams can greatly enhance the reliability and applicability of their simulations and are empowered to optimize designs that, thanks to DSP's DNA enhanced design process, are already capable of delivering the intended performance. By defining physics-based boundary conditions, the DSP system elevates the trustworthiness and effectiveness of simulation results to new levels, an important benefit in pursuing 100% virtual validation.

Qualifying Product Capability Envelopes: Respond to RFQs With Speed & Depth

Through the same modeling tools that generate product DNA, DSP is used to generate Product Capability Envelopes, profiles that provide a comprehensive definition of a product's capabilities. This unique feature allows tier suppliers to qualify the Product Capability Envelope for new products without historical data and match existing products to new applications, enabling them to be ready for OEM applications and respond to request for quotation (**RFQ**)s with speed and depth. A DSP enhanced process grants tier suppliers the ability to confidently understand and convey their components' capabilities, allowing OEMs to purchase them with the confidence that they will do the job "straight off the shelf", and if not, collaborate to draw a clear path to developing a component that will. With Product Capability Envelopes, suppliers' application engineering centers can quickly determine if an existing component is qualified for an OEM's provided application.



DSP: The Ideal Platform for Virtual Validation and Virtual System Development

Kepstrum's DNA Structured Platform (DSP) simultaneously addresses the risks of transitioning to 100% virtual validation and provides a MBSE environment that enables comprehensive and integrated virtual system work. It provides engineers with a collaborative platform wherein they create a single digital thread to connect all the aspects of product development in order to give the entirety of the organization an integrated view of their products throughout their life-cycle.

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DSP enables faster and more reliable design validation, faster responses to market demand & shifting regulations, faster validation of individual components for modular inclusion in larger complex systems, and faster iterative product development to meet new requirements for new applications. DSP's integrated environment both guides progress and serves as a repository for tracking an organization's decisions, systems knowledge, and engineering know-how. This comprehensive approach gives our clients a competitive edge in today's rapidly changing markets, enabling them to reduce time-to-market, costs, and achieve stable production. By leveraging DSP, tier suppliers can embrace the OEMs' vision of transitioning to 100% virtual development and validation processes. Our platform's comprehensive capabilities, focus on accurate modeling, concept-to-CAD approach, knowledge management features, and alignment with OEM requirements make it the most suitable platform for this transformative initiative.

Author's Note:

This whitepaper was written in response to the emerging 100% Virtual Validation trend in various engineering industries, however not all OEMs are shifting to this paradigm rapidly (some are implementing it gradually). While DSP is uniquely positioned to address the needs of 100% Virtual Validation processes, it is also intended for full PLM integration in development processes that still use physical testing. DSP allows for the direct export of Digital Spec. profiles as test protocols to test machines and the direct import of test results back to DSP for analysis and comparison against the intended performance and modeled behavior of engineered components. In such use-cases, DSP is a valuable tool for enhancing physical testing processes. In addition, the use of Product DNA in the development process can allow for the replacement of lengthy durability and longevity tests with model-based design limit tests, and the reduction of prototyping iterations by revealing product weaknesses in early design stages. DSP is a robust tool that can complement or transform your development processes depending on the degree to which your organization leverages its capabilities. Please visit kepstrum.com to learn more about how you can use DSP to enhance your development process at any stage.

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