ESI BLOG ARTICLE

SCIENCE TALK

A walk around the ESI arts of modelling, simulation and decision-making

In a world where technology and science intersect, ESI Group is redefining the landscape of engineering practices. Prof. Francisco Chinesta, ESI's Scientific Director, unveils his groundbreaking approach for modern development engineers to surpass the limits of modeling, simulation, and decision-making. By following his innovative formula—selecting the most advanced physics-based model, gathering the most relevant smart data, merging the two to closely replicate reality, and utilizing this hybrid model to make precise predictions rapidly and at scale—engineers can achieve unprecedented accuracy and efficiency.

FIRST ACT: Prelude

At the beginning was science. Modern science, as we know it today, was still some time away. From the very start, humans created technology to master and benefit from the natural environment. As time passed, the desire to surpass the status quo and break limits led to the birth of engineering. Leonardo da Vinci's dream of flying exemplifies this drive—his wings were simply an inevitable means to an end.

As Theodore Von Karman said, "Scientists study the world as it is; engineers create the world that never has been." The first industrial revolution, powered by steam, transformed industry. Later, electricity sparked the second revolution, enabling faster and more efficient production, which transformed both industry and society.

About two centuries ago, Alessandro Volta was invited to the French Academy of Sciences in Paris. He demonstrated the effect of applying electrodes to a frog, causing it to jump, much to the audience's amazement. Napoleon then asked Volta if electricity could ever serve a purpose beyond making frogs jump. Today, it's impossible to imagine a single day of our lives without electricity. Later, electronics and automation ushered in the third industrial revolution, allowing not only faster but better production. Despite these advances, engineering remained product-based. Society sought performance, and products were merely a means to that end. When we buy a drill, we're essentially trying to buy a good-quality hole. Yet, engineering remained product-oriented. Why?

The limitation lay in the difficulty of addressing products within their complex, uncertain, and fluctuating environments using physics-based models. Additionally, solving these models in real-time for optimal decision-making in design or operation was challenging. How did ESI address these challenges throughout its accomplished history?

SECOND ACT: ESI ARTS

ESI tackled these challenges by mastering three major arts:

1. **The ESI Art of Modeling**: This art encompasses all physics across all scales of description related to materials, processes, and structures. It provided a rich and holistic physics-based approach, enabling ESI already back in 1985 to master materials, manufacturing processes, and structural analysis, even under extreme conditions with computational resources far less powerful than today's smartphones. Despite these limitations, ESI simulated a crash test involving complex dynamics, multi-contact, plastic deformation, damage, and rupture.

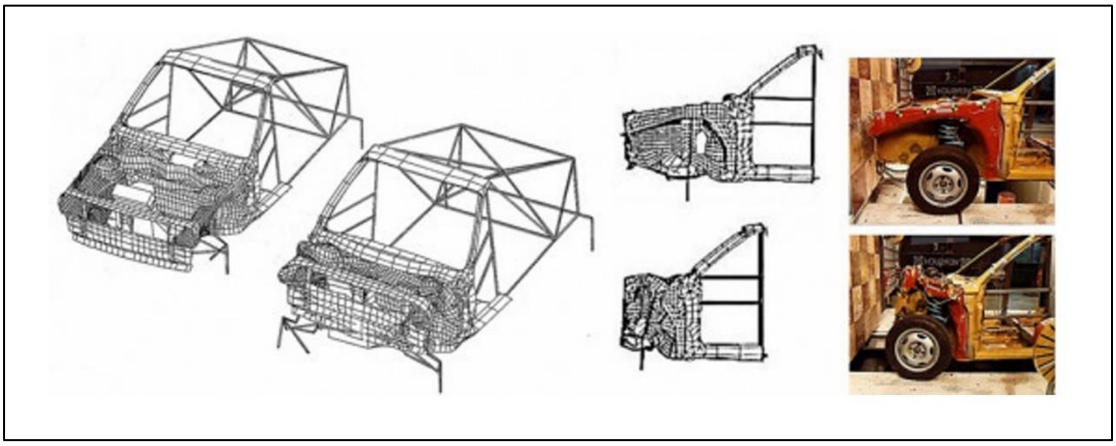
   

   Image 1: The first ever crash simulation conducted with ESI together with Volkswagen in 1985

   The ESI art of modeling was capitalized in its numerous products that enable the exploration of materials involved in manufacturing processes, as well as the virtual analysis of structural performance. However, the potential accomplishments were limited by the available computational resources and the computational time required for calculations and responses. Transitioning from product management to performance management requires faster predictions to facilitate quicker and more efficient designs and decisions.

2. **The ESI Art of Simulation**: To address the limitations of computational resources and the need for faster predictions, ESI enriched its modeling with the art of simulation. This involved applying the best numerical techniques to each problem, ensuring accuracy and efficiency. The need for real-time, or faster, simulations led to the development and deployment of advanced Model Order Reduction (MOR) techniques, particularly the Proper Generalized Decomposition (PGD). This enabled creating computational vademecums[1] that provided

[1] technical references

responses to various conditions in almost real-time, embodied in the ESI AdMoRe platform.

The ESI Art of Simulation allows addressing sophisticated physics (stemming from the Art of Modeling) within their environments, leading to the ESI concept of the "**Augmented Virtual Prototype**" (AVP), a virtual replica of a real system.

With an operational AVP, one might think the story ends here, but as Winston Churchill said, "This is not the beginning of the end, but perhaps the end of the beginning." AVP enables rich descriptions of physical systems in almost real-time, but are these descriptions and associated predictions consistent with real-world observations? In some cases, they are, but in many others, significant deviations arise and grow over time, limiting predictive capabilities. An epistemic ignorance seems to persist in our conceptualization and description of physical reality. Models are models, but sometimes reality contains elements that our models overlook—this is the so-called "ignorance" (the part of reality our models ignore).

The greatest obstacle to discovery is not ignorance.
It is the illusion of knowledge.

Stephen Hawkins

3. **The ESI Art of Decision-Making**: As models sometimes deviated from real-world observations, a new protagonist emerged: the art of decision-making, central to the fourth industrial revolution. At it's core is the question: How do we realize that a model is not accurate enough? By collecting data and comparing these measurements with the predictions based on existing knowledge and state-of-the-art models. In today's fully interconnected global world, facilitated by the Internet of Things (IoT), collecting abundant data is often possible and relatively easy.

   When these measurements, even when adequately assimilated into the models (model calibration), fail to represent observed reality accurately, it indicates a gap in our representation of reality that urgently needs addressing to improve designs and decisions. One solution is offered by Artificial Intelligence (AI), which has become integral to our lives, technology, and social activities since the end of the second millennium. Machine Learning (ML) can create predictive models from available or collected data and provide predictions in almost real-time.

   However, creating models from scratch because existing physics-based models are not accurate enough is not ideal. Building a model solely based on data requires a vast amount of data, which in engineering and technology equates to high costs. Additionally, data collection often involves ethical considerations, regulatory compliance, and technical challenges.

At ESI, we advocate for an alliance between the traditional world of knowledge and physics-based models and the new digital world of data, leveraging increasingly powerful AI techniques. This alliance is embodied in the ESI Hybrid Twin, which enriches physics-based models by addressing their intrinsic ignorance through data that highlights the deviation between predictions and measurements.

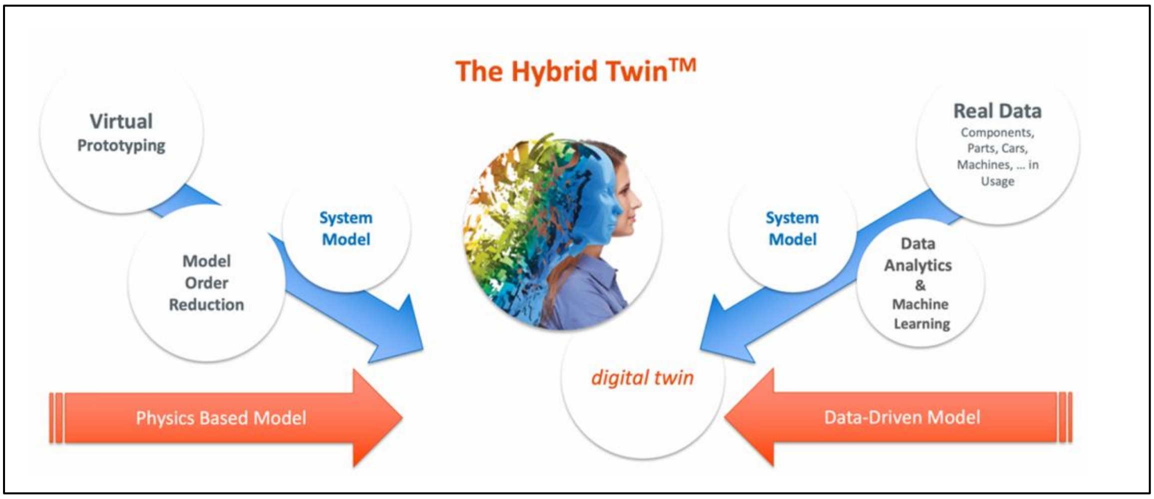


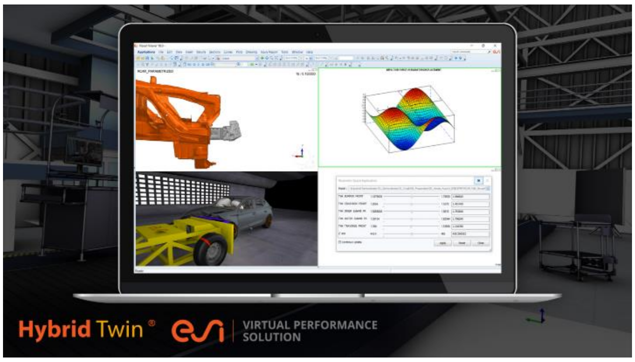
Image 2: The ingredients to build a Hybrid Twin; © ESI Group 2024

This approach reduces the amount of data needed, constructs models in real-time, and certifies designs and decisions. Even though the explainability of the AI component can be challenging, the physics-based contribution is well understood, having been verified and validated over the centuries.

Just as data can enrich existing knowledge (physics-based models), existing knowledge and physics-based models can transform the big-data paradigm into a smarter data paradigm by answering three main questions:

- What data to collect?
- When to collect the data?
- Where to collect the data?

For example, to estimate the temperature in Paris, you can use two thermometers: one in your room and one on the balcony, taking measurements at midnight, early morning, and noon. With just two thermometers and three measurements, you get a reasonable approximation of the daily temperature evolution. This decision, based on your knowledge, avoids the impracticality and expense of using millions of thermometers across Paris. This illustrates the difference between big data and smart data. Smarter data collection is clearly better.



Thus, the **ESI Hybrid Twin** constitutes a digital replica of a material, process, structure, component, system, or system of systems.

Image 3: Hybrid Twin Technology used in a crash simulation to study weld rupture, © ESI Group 2024

It can replace or substitute the real system to anticipate future responses and access its intimate state, while retaining the following features, qualities, and functionalities:

- Accuracy guaranteed by the hybrid approach
- Frugality, based on the smart-data paradigm
- Holistic coverage of all involved physics and description scales
- Real-time responses through advanced model order reduction techniques
- Explicability and certifiability
- Adaptability
- Reliability
- Resilience
- IoT-informed
- Systemic approach to address the system within its environment
- Usability

Success stories include collaborations with Dassault aviation and Thales for aircraft Hybrid Twin, EDF EN for wind farm twins, and CNRS@CREATE for the DesCartes programme in Singapore and Paris as well as numerous awards and recognitions.

Yet, it doesn't stop here, because the Hybrid Twin (HT) of a component, system, or system of systems can and must interact with humans, who remain the primary contributors in many areas. This requires imagination, intuition, complex abstraction and interpretation, qualitative reasoning, and an emotional dimension. People remember what they learned very differently after two weeks: 10% to 20% of what they heard or read, but 90% of what they did (acted upon) in a real or virtual experience. Thus, we as humans must experience physics as protagonists, not just as observers.

Data produced by the HT must be contextualized to be useful, interpretable, and exploitable by humans. New human-centric facilities have emerged and combined with the hybrid paradigm. Among them are immersive virtual reality (VR), augmented reality (AR) in multiphysics evolving settings, and hybrid reality (HR), where humans interact with the virtual world (a digital replica of reality) in the form of holograms that can be experienced visually or through touch. These interactions can even integrate other sensory experiences such as smell and taste while recording emotions to better adapt products to each specific user. For example, adapting a car to the driver, a textbook to the reader, or a cosmetic cream to the customer.

This **human-centric Hybrid Twin** is a key player in the emerging ESI Augmented Intelligence, which does not aim to replace humans but to enrich their capabilities in facing the ultimate art: the Art of Decision Making. This art goes beyond simple reptilian pattern recognition like "I'm hungry, I eat," which is necessary but primitive. We are discussing a more elaborate dimension of decision making that utilizes both sides of the brain—the rational and the creative.

THIRD ACT: EPILOG

We recently experienced the impact of a pandemic everywhere and adapted to it in an active and constructive manner. Some activities have proven resilient enough, while others, such as production machines and supply chains, remain less adaptable.

Without a doubt, a resilient, human-centric world that combines the real and virtual, cold digital data and warmer emotions—all harmoniously integrated—will constitute the new revolution. This revolution will be more than just industrial; it will have a significant human and societal dimension. ESI is succeeding in this new framework, sculpting a new world with major components such as:

- Hybrid Twin (combining real-time physics and real-time physics-informed AI),
- Blockchain,
- Quantum computing,
- Multisensory and emotional human-centric technology.

This rich and complementary ecosystem empowers human creativity and imagination, enabling progress that is further, better, and faster. This is not a distant dream; it is already real through the intimate combination of the three ESI arts: the art of modeling, the art of simulation, and the art of decision making.

ESI is committed to empowering humanism, both technically and societally, without venturing into transhumanism. Each step must be taken at its proper time. The world will emerge from our actions, and everyone should assume their responsibility. ESI takes an active and constructive role in this globally sculpted new world, and its continuous and responsible innovation is the best proof of its involvement and major contribution.

Author

Prof. Francisco (Paco) Chinesta, Scientific Director at ESI Group

Francisco (Paco) Chinesta is full professor at Arts et Métiers Institute of Technology in Paris, and ESI Group Chief Scientist. He has a recognized expertise in hybrid modelling (physics-based and data-driven), allying physics, applied mathematics and artificial intelligence, the main components of the so-called hybrid twin. He received many scientific awards, he is honorary fellow of the "Institut Universitaire de France", fellow of the Spanish Royal Academy, Honoris Causa Doctorate from the University of Zaragoza, Silver Medal of the French CNRS, French academic palms, French order of merit, ... He is the Director of the DESCARTES that CNRS develops in its hub at Singapore, on Hybrid Artificial Intelligence for Decision Making in Critical Urban Systems (5 years, 35 M€, more than 250 years of cumulated research).