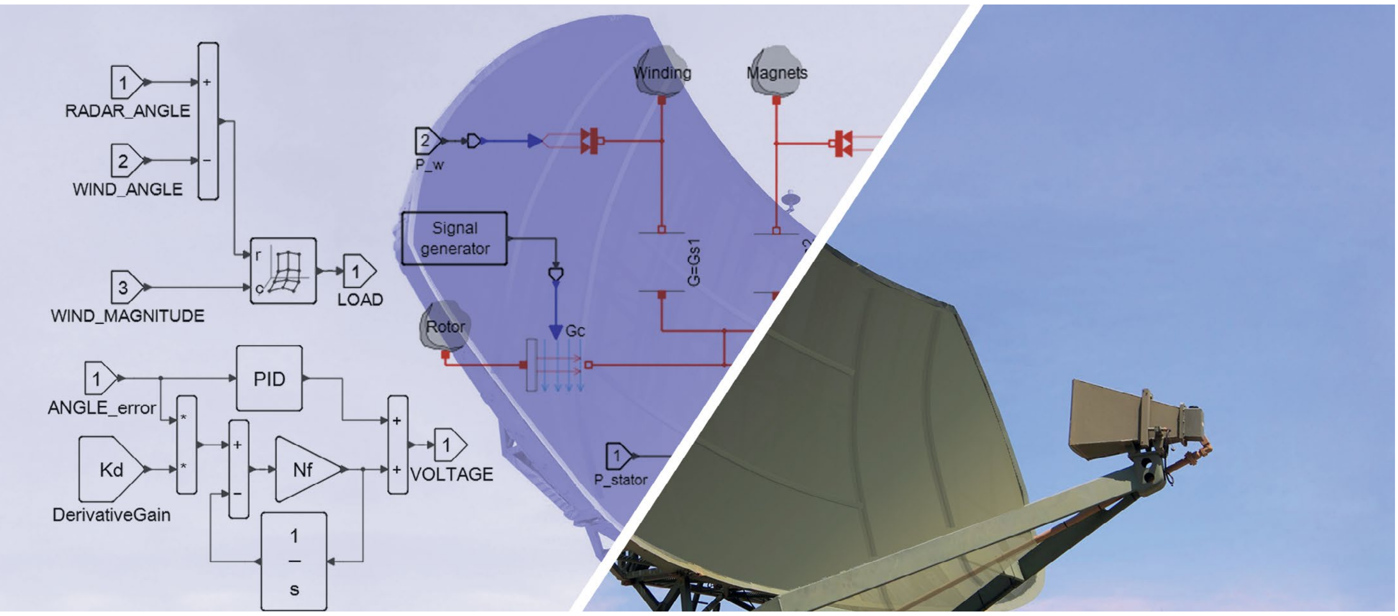
LEVERAGING DIGITAL TWINS TO INCREASE THE EFFECTIVENESS OF THE MBD APPROACH

As of today, the “classical” V diagram is very well known among more and more engineers. Nonetheless its usage – even partly – is far away from the potential that it offers. One reason might be, that its benefits are not really obvious for the end-users. With this presentation, we will bring a new view by “closing the old V” and transferring it to a “closed ∇ (Nabla) cycle”. The focus of this contribution is on the opportunities to significantly increase the effectiveness of the approach of model-based development (MBD) by re-using engineering efforts in multiple ways.



To illustrate this, we will use the application of a radar system as one exemplary use case for the combination of multiple physical domains. Because of this, there is usually a demand for the integration of different disciplines of virtual engineering. We will show how the interaction of these disciplines can be realized in an efficient way to close existing gaps in the design phase on the left side of the V. Furthermore, we will explain how to take advantage from the system design phase by re-using its models as starting point to move quickly over to the realization of what is often called a “Digital Twin”. Based on this, we will discuss different usage scenarios for Digital Twins of the same product.

Finally, the overall goal of this paper is to help you to focus on the real important questions, like:
- Is there a need for efficiency increase in your engineering work?
- Are there any gaps between the different stages of your development cycle, i.e. is there a lack of re-using existing know-how?
- What are the most important use cases of today and tomorrow – and how can specific methods of virtual engineering help to realize them in the most beneficial way?

We will address these questions and provide appropriate answers to emphasize that:
- Openness is essential – e.g., support of independent modeling languages or standardized model-exchange interfaces. This is one of the most important requirements to enhance existing processes and tool chains with new best-in-class methods.
- Altair is extending its heritage of 3D modeling to the forefront of enabling system modeling and system simulation as a central point of the development process.
- Feedback loops from existing products into the different design phases and their corresponding tools are key to constantly improve on your processes and finally your products.

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1. Introduction

The conflicting goals of ever-growing complexity of all kinds of products along with their continuous diversification and the constant shortening of the corresponding development cycles are omnipresent for years, already. But, with new disruptive technological and economical approaches this has accelerated dramatically.

According to Karl-Heinz Land "In the course of Industry 4.0, the Internet of Everything brings together people, processes, data and things in a previously unknown dimension and leads to a quantum leap in the ... industry"[3].

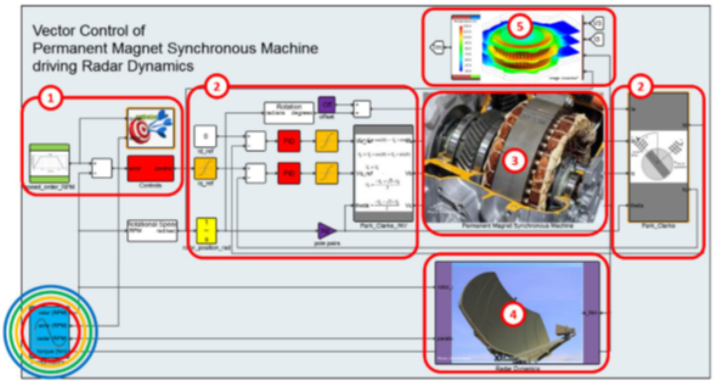
Along with terms like "Industry 4.0" or the often in its connection used "Digital Twin", people are seeking for answers to these challenges. Nevertheless – or maybe even because of this – there is still a lack of substance and a lot of misunderstanding regarding this topic.

With the aim to help to clarify these misunderstandings, we will explain an approach of model-based development with strong focus on continuity. To significantly increase the effectiveness of engineering efforts, re-use is essential for different stages – the design, the test and validation as well as the life cycle of complex products.

2. Radar Antenna – Modeling and Simulation of a Multi-physics System

Modern radar systems are a good example of a complex product – comprising electrical, mechanical and structural components. The overall radar performance, as measured by the electromagnetic (EM) radiation profile, is influenced by each subsystem – both individually and collectively – under a range of hostile, environmental conditions.

To evaluate such a system and especially its cross-domain interdependencies, a system simulation model – as shown in figure 1 – forms a valid basis.



Key: 1) Rotor speed control; 2) Electric command; 3) Electric actuation; 4) Mechanical plant; 5) Thermal loss

Fig. 1: System simulation model of a radar antenna

Thereby, three different techniques are used to enable multi-physics simulation of increasing complexity:

Chaining: « provider » solver compiles independent variables, such as time or Design of Experiment (DoE) parameters into Look-up Tables (LuT) of either time-based or surface responses that « client » solver uses during its own simulation.

Coupling: « provider » solver produces linear equations (LSE: Linear State Equations) – e.g. import of a structure into a mechanism model – or non-linear equations (GSE: General State Equations) – e.g. import of actuator dynamics into a mechanism model – to « master » solver that integrates all states.

Co-simulation (Co-Sim): « first » and « second » solvers are synchronized to exchange inputs/outputs at regular time intervals whilst both integrating separately their own states.

The usage of these techniques – often defined as virtual engineering – as well as its effects are described exemplarily for two components of the radar system.

2.1 Setting the System into Motion with Electric Motor Integration

Identified as "Permanent magnet synchronous machine", the simulation of this electric motor is divided into two levels.

The chaining solution is applied very early in the design cycle. Extracted from either FluxMotor™ or Flux™ 2D/3D, the lookup table offers a magneto-static representation with flux and torque generated by the motor in relation to the controller DC current and rotor position. These outputs can be directly incorporated into the radar model to be coupled with an appropriate description of the electric power supply. In that case, an acausal approach in use of the tool-independent modeling language Modelica® is feasible. Such coupling enables for the evaluation of the performance of the machine, choice of one type or another from an existing range, or even design of a specifically-optimized motor dedicated to the application.

The more accurate capability to co-simulate with Flux™ is applied during the integration and verification steps to replace the magneto-static look-up table used previously. Co-simulation offers a more accurate analysis of losses by taking into account saturation and Eddy currents, for instance.

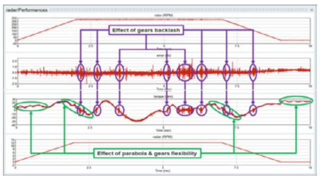


Fig. 2: Radar Dynamics: Comparison between results obtained by Modelica® and MotionSolve®

2.2 Applying Radar Dynamics (Mechanical – Drive-chain Loads)

The first level, applied early in the design cycle, uses Modelica® equations for idealized implementation of the three planetary gear sets (necessary for speed reduction) and a rigid antenna structure. A computational fluid dynamics solver (e.g., AcuSolve®) produces a look-up table of results for aerodynamic loads, arising from high wind speeds, with respect tothe antenna position.

Another level, applied later during the integration and verification, uses the capability to co-simulate with MotionSolve® – a Multi-body Dynamics Simulation tool – for roller bearings, details of gears and a flexible antenna (from OptiStruct component mode synthesis equations) coupled with the aerodynamic loads. In this case, the antenna is rotated at a constant speed of 12 rpm under the influence of hurricane wind speeds (120 km/h) leading to pressure maps, on both front and back faces of the antenna, from results of the CFD calculation. To consider the effects of vibrations on the antenna assembly, a structural model from OptiStruct is used to determine the antenna deformation when the pressure map is applied. To simulate the radar drive-chain – i.e., planetary gears and roller bearings – the multi-body dynamics solver determines the wind load on the bearing assembly as the antenna rotates.

Comparing the results obtained at the different stages of simulation in figure 2, the electric motor torque (3rd trace) comprises a blue line obtained by Modelica® with a superimposed red line from MotionSolve. Differences between the red and blue traces result from the flexing of the antenna. In the motor speed error curve (2nd trace), the short-duration fluctuations are associated with a null point in motor torque and attributed to backlash in the gears.

Both of these findings illustrate the importance of a multi-physics, integrated simulation approach to see factors that would be missed using the simpler, chaining solution.

Modelica® library functions are also used to calculate conduction, radiation and convection between the components and therewith predict the magnet temperature profiles which affect the electric motor performance.

As the overall goal of the multi-physics simulation design approach is to predict in a reliable, robust manner the electromagnetic performance of the radar and the deformation of the antenna for each position during 360° rotation caused by the combined contributions of the torque arising from components in the drive-chain, along with the aerodynamic loads is fed into FEKO® – a high frequency-domain solver.

3. From Virtual Engineering to Digital Twin and Beyond

For the realization of an overall system model, as described in chapter 2, a significant amount of work has to be done, not only for the structural creation and implementation of the model but also for the collection of all the data that is necessary to parameterize it sufficiently. It is more than obvious that the re-use of these efforts of virtual engineering offers huge potential for a tremendous efficiency increase in different manner.

For the first method we stick to the left side of the V-cycle model. The idea is to create a so-called concept 2 model on the same level of detail as the concept 1 model, i.e., the same level within the V as the first system simulation model (see figure 3).

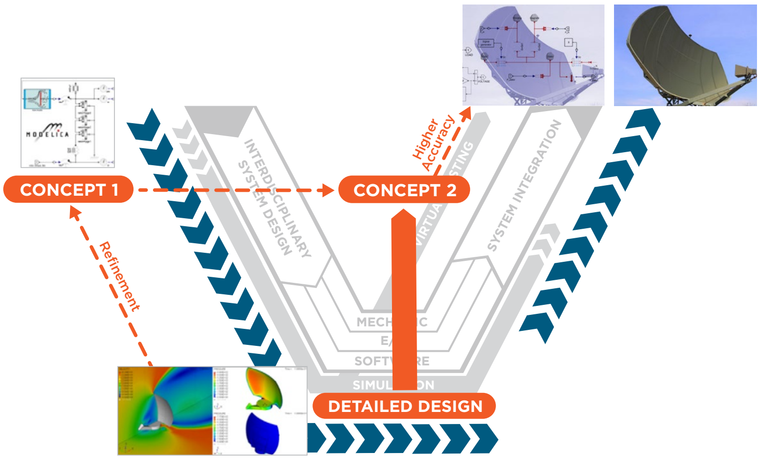


Fig. 3: Concept models with different levels of detail in the development cycle

The difference between both concepts is the accuracy of its results. This is due to a refinement of the concept 1 model, taking into account the findings from more detailed simulations done in later stages of the design process. Feeding-back these findings and results into models from the earlier stages – e.g. by chaining, coupling or other reducedorder model approaches – is beneficial for two reasons:

1. The higher accuracy of models used in early stages helps to increase the trust in such kind of models and therewith to make them a commonly accepted design tool of future projects.
2. Furthermore, these adjusted concept 2 models form a very valid basis for the creation of digital twins.

3.1 The Birth of a Digital Twin

As mentioned earlier, the "Digital Twin" is both – one of the most often used terms of today and at the same time still not really clear to everyone. To help avoiding misunderstandings, finding answers to the following questions might be useful.

What differentiates a Digital Twin from a "simple" simulation model? Using the V-cycle approach again, we can illustrate, that a Digital Twin is part of the upper right side whereas most simulation models are used in stages of the mid and lower left side. In other words, Digital Twins are somehow connected to a real physical system, while numerical models work stand-alone and are not necessarily connected to varying boundary conditions of the real world.

Beside these differences, there is also a significant overlap between both with regard to the description of the functional behavior of the real system. For that reason, simulation models – and, especially system simulation models – can form a valid basis for the creation of a Digital Twin, taking into account certain requirements.

What are the requirements for a Digital Twin? To re-use a simulation model on an external platform in the sense of a Digital Twin, the most important requirement is accessibility. That means that the model's functionality has to work also in other environments as the one it was created in. Therefore, code export – either for specific target platforms or in use of generic interfaces like Functional Mock-up Interface (FMI) – is a widely used option.

Depending on the use-case of the model, i.e. the way of interaction with real components such as control devices, different levels of real-time capability are another prerequisite. In this case, real-time means, that the computation of each single simulation step has to be realized in the same time (or even less) then the communication interval with its environment. Thereby, we differentiate between soft – e.g. for interaction with other simulation models – and hard real-time – for interaction with real hardware devices.

If we want to use our Digital Twin within different use cases, a certain level of adjustment capability is necessary. This can be realized by enabling the model for variation of specific parameters or even by switching the model's entire level of complexity.

Last, but not least, specific visual analytics, combined with some intelligent data analytics algorithms in the background, are very valuable for getting the most out of the huge amount of data that is created by both – the Real and the Digital Twin.

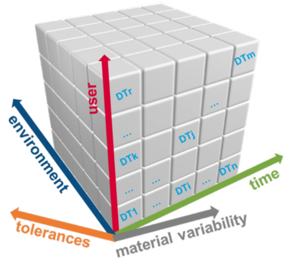


Fig. 4: Illustration of different dimensions of a Digital Twin's adjustment capability

Twins, Triplets or even more - How many Digital Twins are really needed? Although the Digital Twin is commonly used in as a singular term, the different usage scenarios, boundary conditions and resulting real-time requirements lead to the thesis, that more than one Digital Twin might be necessary for a specific application.

In our radar example different parameters have significant influence on the behavior of the realworld system. Because of that, every Digital Twin should adjust itself, taking into account these parameters, like individual users, different aging factors (e.g. wear or leakage) or environmental conditions (e.g. temperature, wind or ice). In consequence the number of Digital Twins needed is a result of dimensions of varying parameters and can be illustrated as a n-dimensional space (fig. 4).

3.2 From V-Curve to ∇-Cycle

The focus of this paper is on efficiency increase in engineering work by closing gaps between different stages of its process from design to usage, different disciplines and also different users or departments within a company. The V-curve is already a good metaphor of this process but still with missing feedback from product use to design. To close this loop, we want to enhance that V-curve and close the loop. Therefore, we introduce the ∇ (Nabla) symbol as an illustration of this closed loop, also, with regard to the definition of the Nabla–Operator according to Wikipedia: "The nabla is used in vector calculus as part of the names of three distinct differential operators: the gradient (∇), the divergence (∇), and the curl ($\nabla\times$)... The symbol is also used in differential geometry to denote a connection."[2]

The idea of this is not, to start a general discussion about the usefulness of the V-approach. We simply share the opinion, that the shape of the Greek letter fits better to our view of the development process – as it should be.

4. Use Case Scenarios

Referring to chapter 3.1, the idea of different digital representations of one specific product was discussed. To elaborate on this idea, we will use the influence of different boundary conditions on the radar antenna's performance to explain two different usage scenarios. In this specific case we take into account the environment (e.g. temperature, dust, wind), wear, etc. to explain the general methodology.

4.1 Single Product

In this first scenario, we focus on the mechanical dynamics of the radar antenna. Along the time, due to different boundary conditions – external (environment) as well as internal ones (wear) – the friction behavior of the real system changes. The continuous collection of this real-world data and its comparison against the "ideal" model is essential to recognize a drift and react in use of two different options.

1. The first one is commonly known as predictive maintenance. In that sense we use the Digital Twin in a smart way to recognize the requirement for maintaining actions, e.g. cleaning or lubrication, as early as possible.
2. The second one needs the Digital Twin's capability to adjust its parameters in correspondence to the varying behavior of the real system. With the help of signal processing algorithms, e.g. using Altair Compose, or additional models for optimization, e.g. using Altair Activate, to adjust the friction parameters within the Digital Twin to have a good correlation between both – the digital and the real radar antenna.

The benefits of this use case are clear. On the one-hand side, a smart Digital Twin helps to avoid error-prone results due to drifting data that may lead to wrong maintenance predictions and that will significantly reduce operational costs.

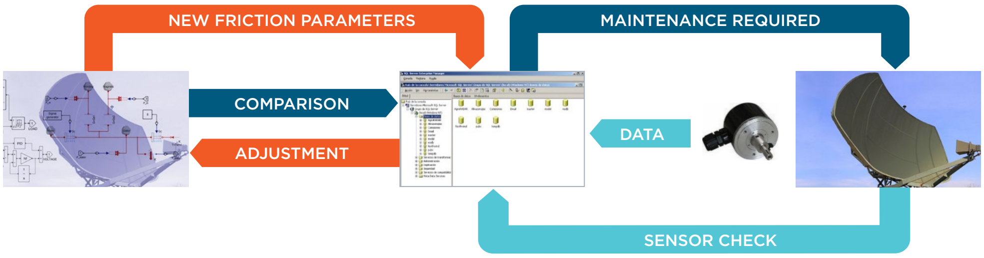


Fig. 5: Interaction of a "Single product" with its Digital Twin and a shared data base

On the other-hand side, continuous validation is a significant benefit compared to "usual" simulation models, that are validated only once, i.e. for one specific set of boundary conditions. That leads to more accuracy and subsequently to more trust and acceptance with regard to virtual engineering methods as an inevitable development tool.

4.2 Product Family

In contrary to the scenario of chapter 4.1, Digital Twins may differ from each other, even if they refer to the same product and require more than one digital copy, up to a whole "family". One reason can be the varying environmental boundary conditions (compare figure 4), as it is the case when the radar antenna is operated in different locations all over the world.

4.2.1 Re-Calibration of the Digital Twin

For the first use case of this scenario we stick to the right side of the V-cycle, i.e. we adjust the controller parameters "offline" – without the need of being connected to any real hardware.

One specific example is, that the magnitude of the wind raises sharply in a dedicated location. As a consequence, the radar doesn't properly follow its reference, not because the voltage command reaches the saturation but because its dynamics is too low. To increase the dynamics of the controller, we have to decrease derivative gain. Therefore, we run an optimization in Altair Activate combining the Digital Twins offline with the historical data of the anemometer's measurements. The optimized derivative gain can then be distributed to all radar antennas – real and digital ones – in all locations. This step can be automated in use of a dedicated IoT platform.

4.2.2 Refinement of the Products – Closing the "V"

For the second use case we come back to the title of this paper, i.e. we're about to close the gap between operation and design of products.

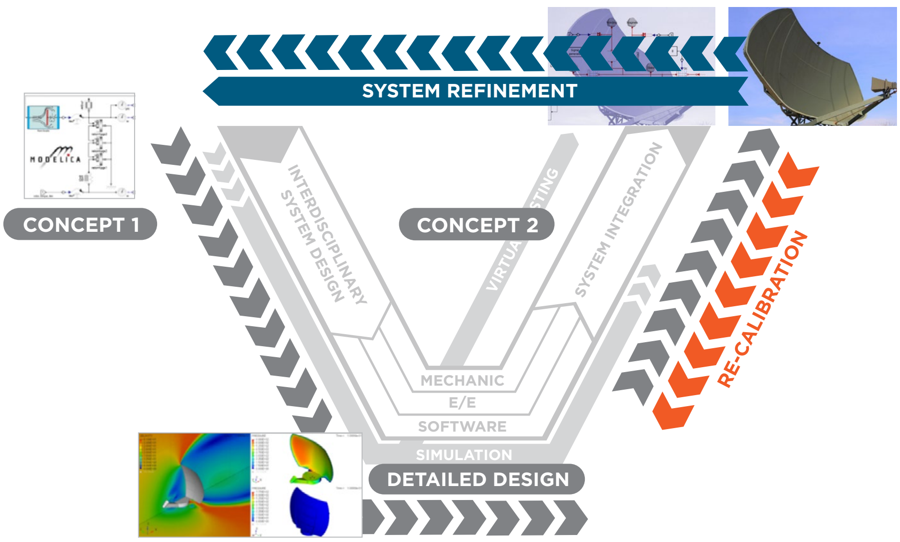


Fig. 6: Comparison of the use cases "re-calibration" and "refinement" of the scenario "Product Family"

The combination of an IoT platform with dedicated data analytics tools is a valid basis for a long-term analysis of variance (ANOVA) of the relevant data. This will lead to the recognition of main influencing factors on the operation the radar system for each location. Whereas in Africa the sand periodically obstructs the system because of the proximity with the desert, in Alaska the downgrade of the lubricant properties below -20°C is essential. Specific solution approaches could be the adoption of a sand-proof cover over the rotational system for all the next radars that may face sand or dust issues in regions like Africa or the change of the lubricant type for all radars that may experience temperatures below -20°C, like in Alaska.

The stringent usage of this feedback loop will substantially change the way products are designed as purposedriven, referring to knowledge that is gained over the years of individual product usage under varying conditions. As the most beneficial result, this will lead to better products as we understand the "why" of their behavior.

5. Summary

Finally, let's come back to the questions from the beginning and summarize the previous chapters by collecting appropriate answers:
Is there a need for efficiency increase in our engineering work? The need for more efficient approaches is undeniable, the reasons are manifold – shortening of development cycles, increase of variants up to batch of one, new usage models, general cost restrictions. Frontloading by means of commonly accepted use of simulation models is a first step on the way to simulation driven design. The consequent implementation of a Model Based Development approach is the only way to fully exploit the potential of virtual engineering methods.

Are there any gaps between the different stages of your development cycle, i.e. is there a lack of re-using existing know-how? As of today, there are gaps between the different stages in nearly all companies. The good news is, that these gaps can be overcome with the help of re-use of models, corresponding data and therewith existing knowhow. The given use case explains how Altair is extending its heritage of 3D modeling to the forefront of enabling system modeling and system simulation as central point of the development process.

The Model Based Development approach with Activate™ ensures the consistent progressive deployment of multiphysic simulation models throughout the design cycle. Thereby, openness – e.g. support of tool independent modeling languages, like Modelica® or standardized model exchange interfaces, like FMI – is one of the most important requirements to enhance existing processes and tool chains with new best-in-class methods. Based on these technologies purpose-driven model fidelity, according to the principle "as simple as possible, as accurate as necessary", is the way to continuous engineering.

What are the most important use cases of today and tomorrow – and how can specific methods of virtual engineering help to realize them in the most beneficial way? Although terms like V-curve, Nabla-cycle or Digital Twin are used several times, the aim of this paper is not to provide perfect definitions. The focus is on a generic approach that one can adjust to his specific needs and use cases – even partly – instead of getting lost in philosophic discussions about phrases being in the flavor of the month. As by now, more and more products are able to connect with its end-users, with each other or with its operators, the collection of data under real world conditions is invaluable for its developers.

To benefit from this, feedback loops from existing products into the different design phases and their corresponding tools are key to constantly improve one's models, processes, methods and finally the products.

6. Outlook

With respect to the wider range of Model Based Systems Engineering, an enlargement of the presented approach seems obvious for both sides of the V. On the left-hand side, this means a connection of the system simulation model to earlier phases of the development, like functional concept and architecture or requirements management. Taking into account the multitude of tools for both stages, the use of standardized interfaces like FMI is the most promising option to continue the approach of an open tool chain.

On the right-hand side the constantly growing number of IoT platforms and connected tools for data analysis come into play. Altair's Digital Twin gateway named SmartWorks is one of these solutions for the collection and exchange of both types of data – those from the real world and ideal ones, created in use of simulation models and Digital Twins.

Working with Altair

Altair Activate provides a single platform to integrate different disciplines, fostering multidisciplinary team work for efficient virtual engineering. Used as the core of Altair's open flexible Digital Twin Platform, it easily combines high-fidelity models with reduced-order models built using 3D + 1D + 0D techniques for efficient and accurate computations. Finally, it enables engineers to cover all the different stages of the development cycle, easily connecting their simulations with real physical system, to refine and optimize the performance their complete equipment according to its real world working conditions.

Altair is a global technology company that provides software and cloud solutions in the areas of product development, high-performance computing (HPC) and data analytics. Altair enables organizations across broad industry segments to compete more effectively in a connected world while creating a more sustainable future.

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