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# Model-based system testing

Efficiently combining test and simulation for model-based development

## Executive summary

New products must accommodate a growing number of product variants, provide increased energy efficiency and exceed previous performance and reliability. To meet these expectations while minimizing development costs and cycles, the role of simulation continues to grow. The development methodology has evolved from test-centric to a model-based development (MBD) approach, but its practical realization relies on the quality of the models. Model-based system testing (MBST) is a framework of engineering solutions that optimally balances the combined use of test and simulation. It enhances productivity of the MBD approach and provides better engineering insights across industries. MBST solutions help test and simulation engineers enhance product performance, including vehicle dynamics, acoustics and comfort for their complex mechatronic and smart systems.

# Abstract

The combined use of test and simulation has a long tradition in the domain of model parameter identification and validation. However, the interaction between simulation and test is a constantly evolving paradigm. For example, today's systems are more mechatronic due to the main market drivers (energy efficiency, growing number of system variants and performance). They have electronic controllers to improve their performance and define their character. Due to the added programmable capabilities, the development of these systems is more complex. As complexity increases, repeatedly creating and testing physical prototypes is not an effective way of solving system design problems. That is why product development processes are increasingly being driven by simulation. With the complex, innovative and personalized nature of product designs, engineers must deal with more product variants and explore innovative designs while paying more attention to quality issues.

New technological advancements continuously redefine what is achievable by combining test and simulation. In

recent years, the fidelity of simulation solutions has drastically improved due to the increase in the computational power of computers. For example, the number of elements in finite element (FE) models has grown from hundreds of thousands to several million elements. Modern multibody simulation software can simulate realistic scenarios for systems composed of hundreds of flexible bodies within an hour. State-of-the-art system simulation solutions can accurately simulate the multi-physical nature of systems by embedding all relevant physical phenomena (mechanics, electrics, hydraulic, pneumatics, etc.) in one solver.

Simulation solutions have matured to the extent they have transformed the development process of complex systems to become a process cornerstone. The highly accurate simulation models are called digital twins and are used throughout the lifecycle of the product to predict real-life performance, understand the manufacturing process or to detect operational failures.

# Unlocking the potential of digital development

To master today's system engineering complexity in a productive way, it is crucial that simulation and test engineers collaborate closely to optimize product development efficiency. In these development processes, digital twins are ubiquitous. They are used throughout the development cycle, from the early design stages (concept models, system simulation) to the detailed modeling stages (finite element modeling, multibody modeling). For a product development approach to be successful, the use of test and simulation solutions must be optimally balanced. This requires testing solutions that can bridge the gap between test and simulation.

Model-based system testing is a framework of engineering solutions that enable and optimally balance the combined use of test and simulation. MBST encompasses a broad and varied set of solutions to validate functional performance using proven analytics and perform attribute engineering on virtual models, virtual-physical systems and physical prototypes. Based on these solutions, three main categories (see figure 1) of combined use of test and simulation can be established: (1) test for simulation, (2) test with simulation and (3) simulation for test.

**Test for simulation** is the closest to the model validation process and covers a wide range of approaches in which test data is essentially used to build, validate, improve and drive simulation models. The use of virtual models for systems engineering is the goal.

**In test with simulation**, the physical and virtual worlds interact to complement each other in multiple scenarios. This approach is of interest for testing and experimentally optimizing subsystem behavior in a virtual system integration context, which may even include the human user. All these applications require the modeling approach as well as the testing procedures to fulfill new requirements compared to the pure simulation or the testing scenario for isolated design engineering tasks.

**In simulation for test**, the objective is to mirror the test for simulation approach. Simulation models are used to define, improve and compare test data, opening the way to extended data exploitation and using models in product lifecycle testing.

The Simcenter™ software family of solutions offer a unique opportunity to accelerate the attribute engineering of today's complex mechatronic and smart systems. The close integration of test and simulation tools on

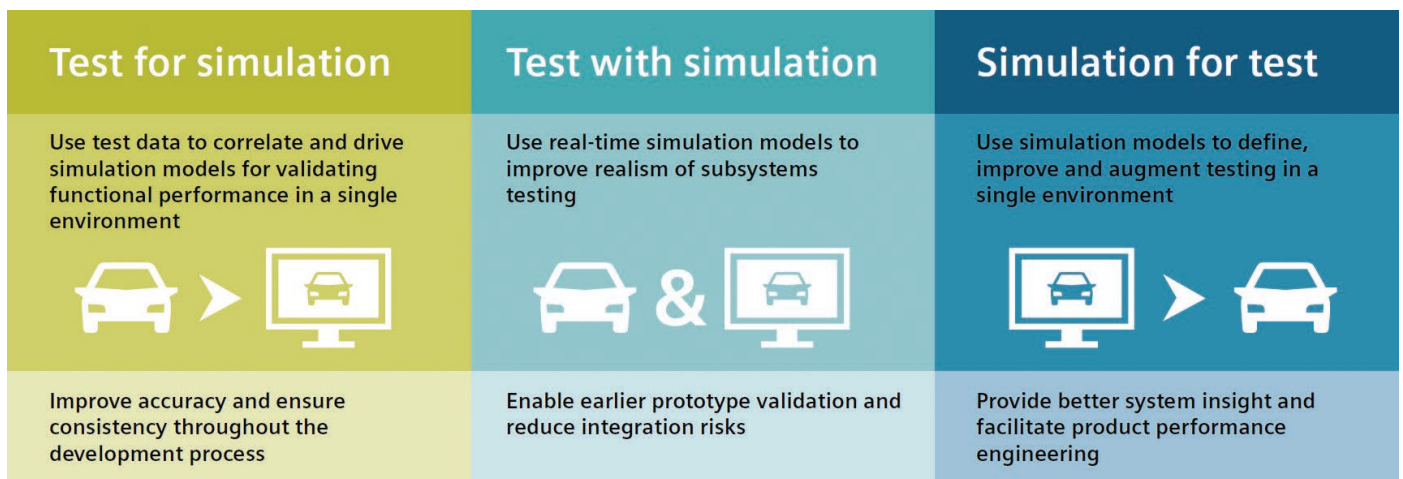


Figure 1. The three main categories of model-based system testing.

the one hand, and the creation of new model-based real-time testing solutions on the other, supports model-based development and testing of systems. Model-based real-time testing allows development teams to frontload the testing of physical prototypes while maintaining the added value of testing under real-life conditions. These new elements bring consistency to the tools and methods used along the system development cycle. This consistency translates into more agile mechatronic system development.

**Test for simulation**

Although simulation has become a centerpiece of any modern computer-aided engineering (CAE) approach, the need for test data has not diminished. The first reason is the level of accuracy and completeness provided by simulation models is still inadequate for many applications. Further, test data is essential to identify model parameters, provide realistic model inputs and validate numerical models. This is true for all engineering fields and industries in which simulation is used. How do you identify all model parameters? What metric should you use to validate a model against? How can you efficiently process terabytes of test and simulation data?

For example, in structural testing, damping parameters must be identified together with clamping or

connection stiffness values. For multibody systems, joint and connection parameters are often uncertain and, therefore, need to be experimentally obtained. For multi-physical systems, many system parameters are hard, if not impossible to derive from a priori information (see figure 2). Consequently, dedicated test benches are often needed to estimate values for missing or undetermined model parameters.

Simcenter Testlab™ Neo software has integrated interoperability to simulation data and models to support engineers in creating and validating their models

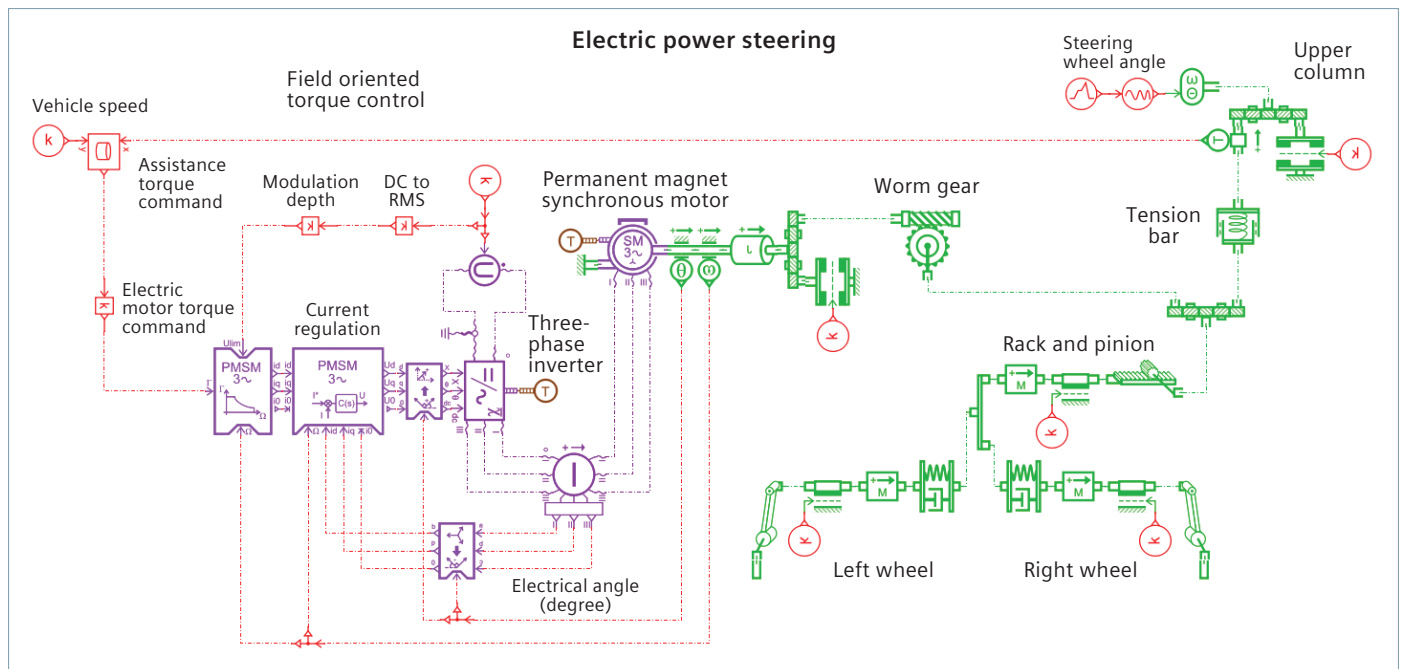
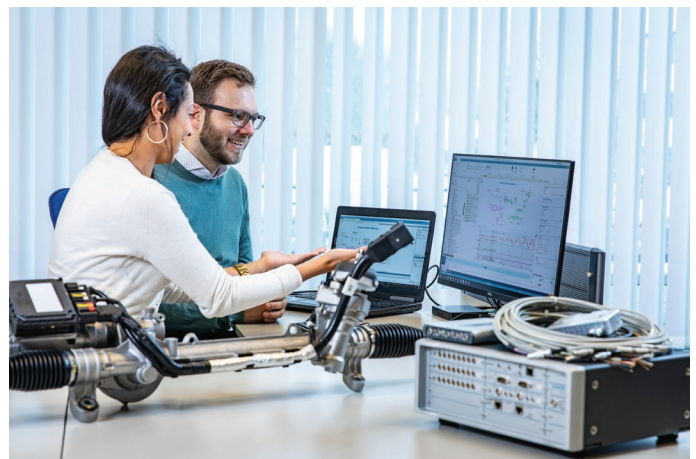


Figure 2. Efficient validation of electric steering system models with field test data.

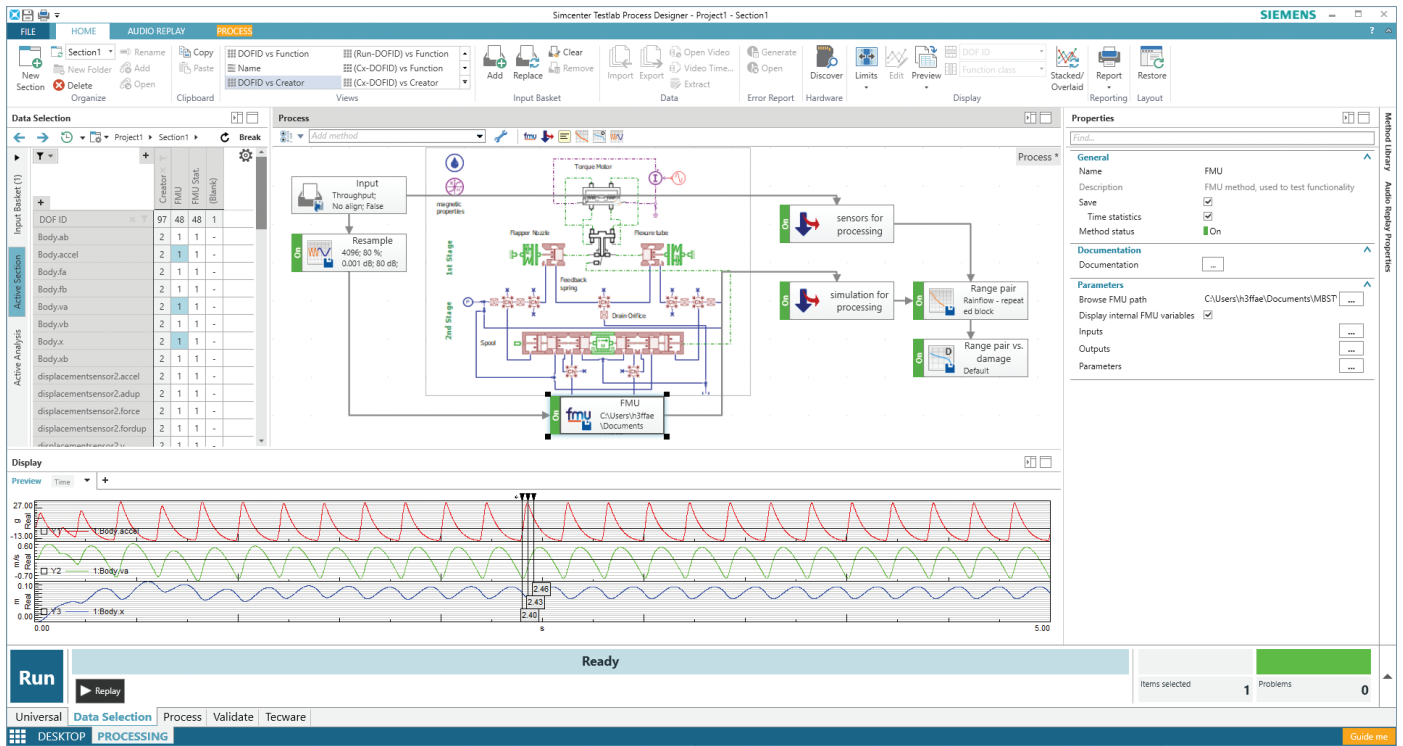


Figure 3. Model-driven comparison of multiple design variants of a servo valve using the Simcenter Amesim sketch viewer in Simcenter Testlab Neo.

efficiently. The Simcenter Amesim™ software sketch viewer in Simcenter Testlab Neo (see figure 3) gives engineers direct model-driven access to system simulation data for comparing design variants, updating model parameters and validating the system simulation models. Simcenter Testlab Process Designer provides powerful postprocessing capabilities for test and simulation models. The integration (import and execution) of Functional Mockup Interface (FMI) 2.0 models for co-simulation facilitates model correlation against test data (see figure 7). It allows strong interaction between test data and simulation models, which is especially

well suited for situations when big test datasets must be fed into FMI models and the corresponding set of results must be postprocessed. Test for simulation also

requires data acquisition solutions to acquire multi-physical data from a wide variety of sensors (for example, flow sensors, anemometers, accelerometers, inertial motion units, microphones, thermocouples). Not all data acquisition systems have the capability to acquire multi-physical data, but the Simcenter SCADAS hardware acquisition solution has it.

### Testing with simulation

To keep development times as short as possible and development costs as low as possible, access to full-system prototypes has been reduced during the product development cycle. The integration of physical components as part of a full system, such as a steering system, only happens in the late phases of the development cycle, thus increasing the risk of late discovery of flaws. How can you mitigate the risks of late component integration in the full system? How can you identify system integration issues as early as possible?

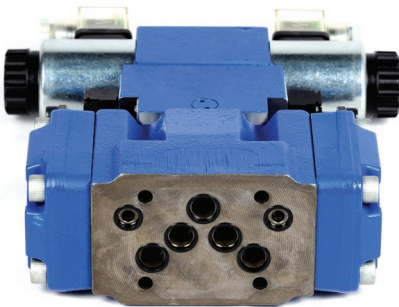


Figure 4. Image of the real servo valve.

The answer is front-loading component testing in the development cycle. It maximally reduces costs, development time and risk in systems engineering. For that, test and simulation can be tightly coupled in a model-based, real-time testing approach. This approach is suitable for the following types of testing: hardware-in-the-loop (HiL), system-in-the-loop (SiTL), human-in-the-loop (HuiL), hybrid testing, real-time substructure testing, etc. All these applications require the simulation models to fulfill several new criteria when compared to pure simulation-for-design engineering tasks. Advanced models are needed to enable highly accurate correlation with the physical behavior. Reducing computing time for real-time execution is obtained with reduced sized models and model order reduction techniques.

#### HiL, SiTL, hybrid and HuiL testing

HiL, SiTL, hybrid and substructuring testing allows early testing of components or subsystems as if they are part of the full system and are being subjected to operational loading (or near real-life) conditions. They enable advanced early evaluation of the full system integration (such as a steering actuation system in the complete vehicle steering mechanism). HuiL allows early evaluation of user perception (for example, comfort of a new vehicle shock absorber) based on real-time simulation models of the full system. This is a whole new domain for most modeling, validation and verification engineers.

#### Hardware-in-the-loop testing

In hardware-in-the-loop testing, the electronic controllers (engine control units, transmission control units, flight control units) are physically present on the test bench and are connected to a real-time platform simulating the rest of the mechatronic system. Control algorithms, controller settings and even control hardware can be tested and calibrated in near real-life scenarios (vehicle driving scenarios, flight scenarios) without the need for system realization.

#### System-in-the-loop testing

In system-in-the-loop testing, a few components or even a subsystem (steering actuator, flap actuation mechanism, vehicle driveline) are physically present on the test bench and are connected to a real-time platform simulating the rest of the mechatronic system (aircraft, vehicle, motorcycle). Component/subsystem attributes such as energy consumption, dynamic performance or acoustic intensity can be tested and improved in near real-life scenarios (vehicle driving scenarios, flight scenarios) without the need for system realization (see figure 5).

#### Hybrid testing and real-time substructuring

Hybrid testing and real-time substructuring extends the concept of partitioned structural analysis to SiTL testing. This method is used for advanced structural testing, such as a scaled aircraft wing, using a real-time aircraft structural model.



Figure 5. Front-loading of motorcycle gearbox testing. From proving ground to bench testing in near real-life conditions via the system-in-the-loop approach.

### Human-in-the-loop testing

In human-in-the-loop testing, users (for example, car drivers, aircraft pilots) can physically interact with a simulation of their machine or vehicle in driving simulators, machine simulators or flight simulators. Therefore, calibration and optimization of perceived system performance in a HuIL context becomes feasible.

### Main benefits

Model-based, real-time testing brings multiple benefits to engineers following a model-based development approach, such as:

- What-if testing allows engineers to easily change the simulation models exciting the system-under-test to evaluate the performance of different system variants, such as a shock absorber performance when used in different vehicles
- System integration de-risking is intrinsic to model-based real-time testing due to the virtual-physical integration. It reduces the risk of discovering flaws late and the associated re-engineering costs and delays
- High-fidelity testing becomes possible thanks to the near real-life excitation provided by the simulation models to the system-under-test
- Realistic test repeatability becomes possible when testing on automated model-based test benches. Test repetitions are useful for statistical data analysis
- Accelerated and automated testing when using models for real-time testing is possible as all tests are performed on test benches. Therefore, engineering productivity is guaranteed
- Substituting a simulation component for a physical one can be used to avoid modeling a component due to high cost. Instead, it can be replaced with the component being tested and connected to the rest of the simulation. For example, bushing testing or complex hydraulic component testing can be interfaced to a real-time simulation
- Support in regulation compliance allows engineers to evaluate if the impact of their new components on the full system complies with fuel emissions or energy consumption regulations

- Test scenarios enabled only by simulation express the fact that model-based, real-time testing enables the testing of scenarios that are unsafe or unrealistic in real life. An example is to study the vehicle behavior after imminent crash detection from the automatic emergency braking system

Siemens Digital Industries Software provides test and simulation solutions that enable the efficient realization of model-based, real-time testing.

### Simulation for test

Today, simulation models play a larger role in the testing process. They are used to improve or accelerate this process, helping test engineers master system engineering complexity during development.

Requirement validation procedures are ideally established via simulation during the product definition phase: What are the system parameters or responses to validate against test data? Where and how should the tests be performed to obtain this information? With the increasing complexity of both the systems-under-test and the related test procedures, the definition of the corresponding optimal tests becomes a key task in the design stage.

Efficient test procedures are already well adopted in domains such as automotive, aircraft and aerospace structural testing. For instance, optimal sensor placement and excitation using simulation enable you to maximize test quality and efficiency. More recently, models of the full system (for example, vehicles or aircraft) have been used directly in the test cell to accelerate component testing by assessing the influence of component dynamics on the full system. Validated simulation models can also be used to verify the test instrumentation is correct and sensors give meaningful measurements (correct calibration, wiring, configuration, etc.)

Virtual testing procedures are adopted to reduce the high cost of test execution for expensive, safety-critical or hard-to-access structures and systems, and to respect tight test schedules and/or test facility availability. Fully simulating tests allows checking, validating and optimizing the complete test process prior to performing the actual test. Aircraft ground vibration tests, aircraft engine tests, satellite qualification tests and acoustic

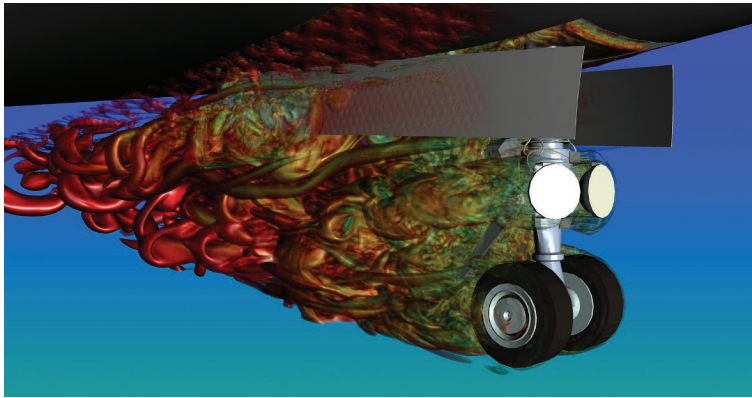


Figure 6. Virtually pretesting landing gears for improved field testing later in the development cycle.

wind tunnel tests are all examples in which the efficiency and effectiveness of the test process is optimized using virtual testing procedures (see figure 6).

Virtual sensing is an emerging field for the use of simulation models in testing. Models and a limited set of experimental data are fused to estimate system variables that are difficult (inaccessible location, inaccurate direct measurements, no existing sensor) or costly to measure. Virtual sensing enriches the measurement dataset, thus providing better insight into the system-under-test to engineers. Accurate models are required

as a starting point (often obtained with model updating test approaches). State estimators are then used to fuse test and simulation data and ensure optimal data quality.

Simcenter Testlab Neo has integrated support for data interoperability with several simulation software products. Simcenter Testlab Process Designer provides powerful postprocessing capabilities for test and simulation models. One of its outstanding features is the direct import and execution of one or more FMI 2.0 models in a test process. These models can be used for parameter updating, calculating model-based virtual sensors or checking sensor instrumentation (see figure 7).

Embedding FMI models in a test process enables strong interaction between test data and simulation models, which is especially well suited for situations when FMI models that are being used for virtual sensing must be fed by big test datasets and when the corresponding set of results must be postprocessed.

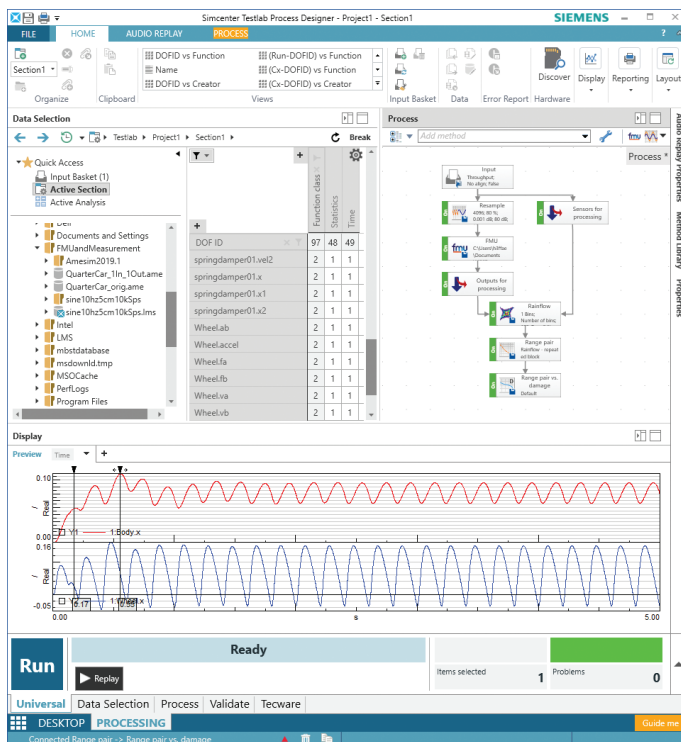


Figure 7. Feeding FMI models with test data in a user-defined process in Simcenter Testlab Process Designer.



# Conclusion

Siemens Digital Industries Software has created a portfolio of test and simulation products to support system development from concept design and system simulation to component and field testing. Our products help customers in the attribute engineering of their systems along the entire development cycle.

Model-based system testing is supported by the following products: Simcenter Testlab is the engineering testing solution for data acquisition, visualization, post-processing and reporting. The data it acquires comes from the Simcenter SCADAS hardware family. It is used for multi-physical data acquisition from an extensive range of sensors. Simcenter Testlab Neo Desktop includes Simcenter Amesim sketch viewer for direct

model-driven access to Simcenter Amesim data. It enables productively combining Simcenter Amesim data and Simcenter Testlab data. Simcenter Testlab Process Designer is the multidisciplinary postprocessing solution for time and frequency domain analysis. It can be used to postprocess test and simulation data for efficient model correlation and consistent data analysis throughout the development cycle. It also enables the direct import and execution of simulation models complying with the FMI 2.0 standard. Embedding FMI models in a test process enables strong interaction between test data and models, which is well suited for situations when big datasets must be processed.

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