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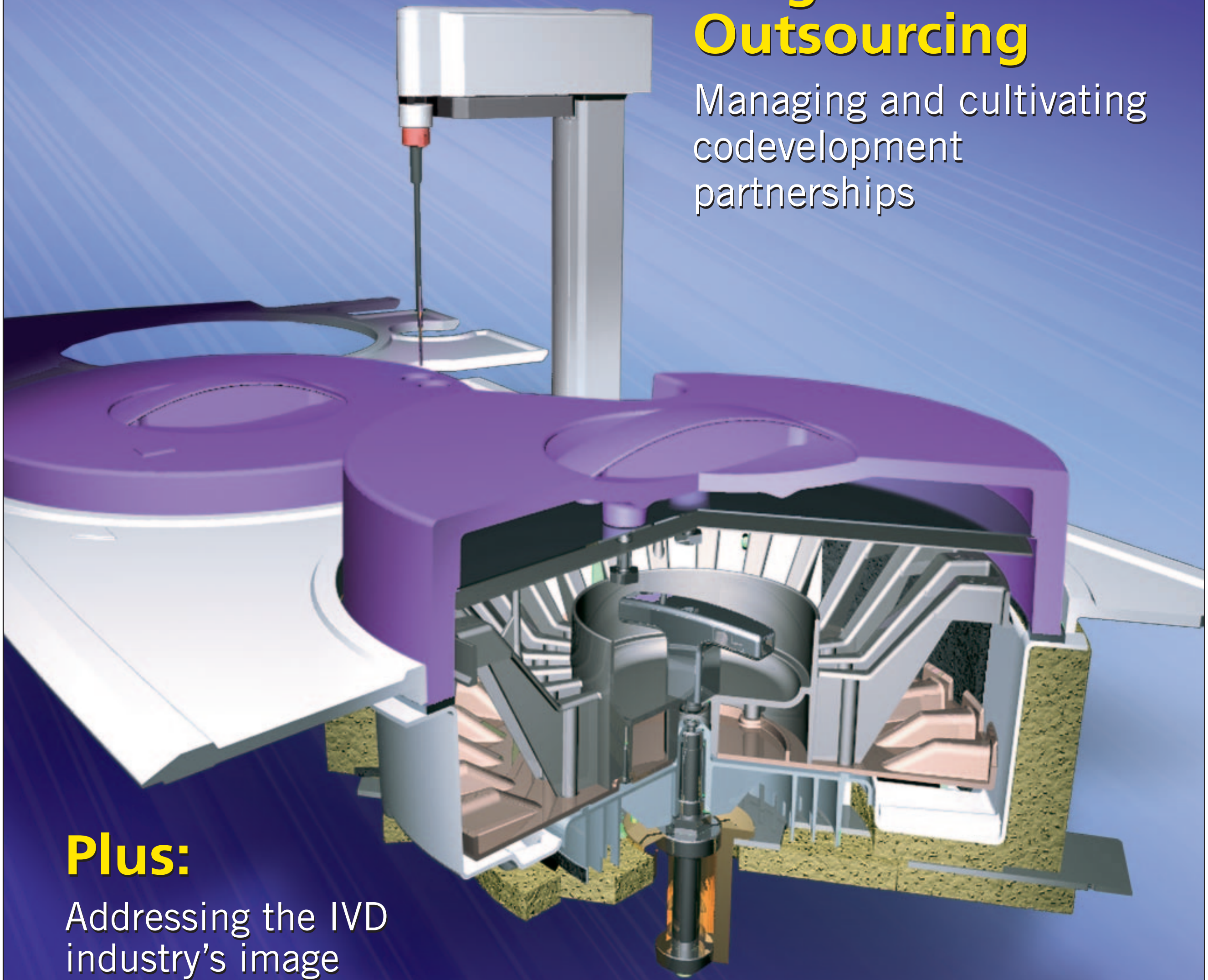

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Applying simulation for better diagnostic instrument design

Ian Macfarlane, David Fry, and Peter Leigh-Jones

Effective use of simulation tools offers numerous benefits, including decreased development time and costs.

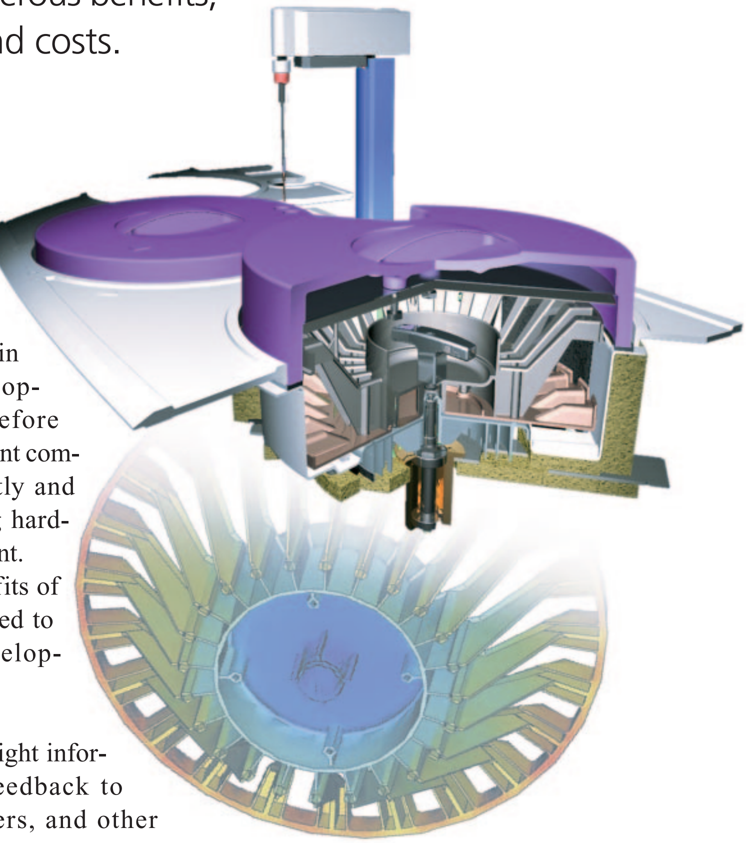

Figure 1. CAD simulation of an instrument work surface and Moldflow output of its carousel component.

A previous article entitled "Instrument development in parallel with product definition and core technology refinement" (*IVD Technology,* January/February 2004) offered six key strategies for addressing the challenges of parallel technology and product development. The first of these strategies, "ensure adequate core technology performance," is often on the critical path in any development assignment. A number of suggestions for achieving this goal, centering on the definition of objective measures to assess core technology performance, were reviewed. Expanding on this theme, this article will focus on the use of simulation, and how it can sharpen the ability to implement the first key strategy while reducing development time and cost.

Simulation Benefits

Computerized aircraft simulators for pilot training are, today, a commonplace instructional tool. Aircraft simulators provide realistic, software-generated representations of the visual world, and the physical response of an aircraft to external conditions and the control inputs of the simulator pilot. The value aircraft simulators provide is the safe, fast, and cost-effective acquisition of flying skills in a realistic virtual world.

In the world of IVD product design, simulation is the representation of system processes and physical behaviors using computer-based mathematical models. Product simulation delivers value by enabling designers to rapidly test and refine core technologies and design concepts on virtual prototypes in the early development stages, before making significant commitment to costly and time-consuming hardware development.

The key benefits of simulation applied to instrument development are:

- Valuable test flight information and feedback to users, designers, and other stakeholders.
- Detailed analysis of system behaviors that would be impossible, prohibitively expensive, or time-consuming to perform on physical systems.
- Reduced development-cycle time through on-screen testing and optimization of designs, often surpassing the traditional iterative design-build-test-fix/refine cycle.
- Rapid evaluation of tolerance-level variations in product designs to determine the performance sensitivity to real-world variability.

The Time and Place for Simulation

The application of simulation has grown in the last decade through the following contributing factors:

- Improved performance of tools to represent comprehensively and accurately the physical world.
- Inclusion of specialized tools such as finite element analysis (FEA) as standard modules within widely used CAD/CAM software.
- Increased useability of the tools.
- Availability of powerful and inexpensive computers that make previously impractical simulations feasible.
- Increased awareness and acceptance of the capabilities and value of simulation within the scientific and engineering communities.

Simulation has been applied to many areas of IVD instrument development, including the following:

- Graphical user interface (GUI) simulators to develop and rapidly refine screen look and feel, and to obtain user feedback.
- Electronic communication protocol simulators to test communication functions.
- Analysis of the efficacy, safety, and fault tolerance of scheduling and sequencing algorithms representing instrument process flows.
- Electronic circuit simulators to test core function performance.
- Thermal analysis and design optimization of sample-heating systems.
- Motion simulation of instrument mechanisms for clash detection and clearance analysis in multiple operating modes.
- Natural frequencies analysis of instrument chassis, thereby ensuring that structural vibration frequencies are widely separated from internal and external vibration source frequencies, which may interfere with correct instrument function.
- Mold flow analysis to optimize the manufacturability and quality of plastic components.

Figure 1 shows a digital CAD image of the work surface of an IVD instrument, with the cutaway section showing the reagent carousel and a Moldflow simulation output of the carousel component.

The use of simulation is driven by the technical capabilities of the tools available, the skill and experience of those performing the simulation, and the cost/benefit of the approach. Figure 2 describes potential applications of simulation during each development stage.

In a recent project to develop a new instrument platform, a core detection system required a high-performance impedance-measurement subsystem. Simulation was used to explore alternative circuit designs that delivered the performance required while maintaining tight cost targets, protecting existing intellectual property, and accommodating physical constraints on the system. This detailed simulation took one to two people three months to perform. The work has been proven through physical testing, with physical system performance matching expectations. It is estimated that a physical design-build-test-fix/refine cycle providing the same results may have taken 12 months, and increased costs significantly. In this instance, the use of simulation tools reduced the development time for the core technology, which was on the critical path. It enabled the interface to the detection subsystem to be defined before the initial simulation work was completed, and the remainder of the development program moved ahead in parallel.

In another project, a point-of-care instrument required very accurate temperature control to ensure that a diagnostic test was performed at the correct temperature. Numerous heat sources within the instrument could have influenced this. A complex FEA model of the internal physical and thermal environment could have determined the scale of any problem, and been used to test potential solutions before constructing the physical hardware. However, in this case, it was clear that the solution and performance requirements could be proven most cost-effectively on simple test beds. The eventual remedy of adding airflow baffles and a cooling fan were within the instrument's cost limits, and did not negatively affect the instrument's other attributes.

The decision to conduct a simulation requires due consideration of viable alternatives, and the technical and commercial constraints applicable to the system under development.

IVD technology–related simulation tools, their application areas, and examples of commercially or freely available products are presented in Table I. Information on alternative products or any of these tools can be found by conducting an Internet search for specific application areas or product names. There is also a great deal of available printed literature focusing on each of the specific application areas for simulation.

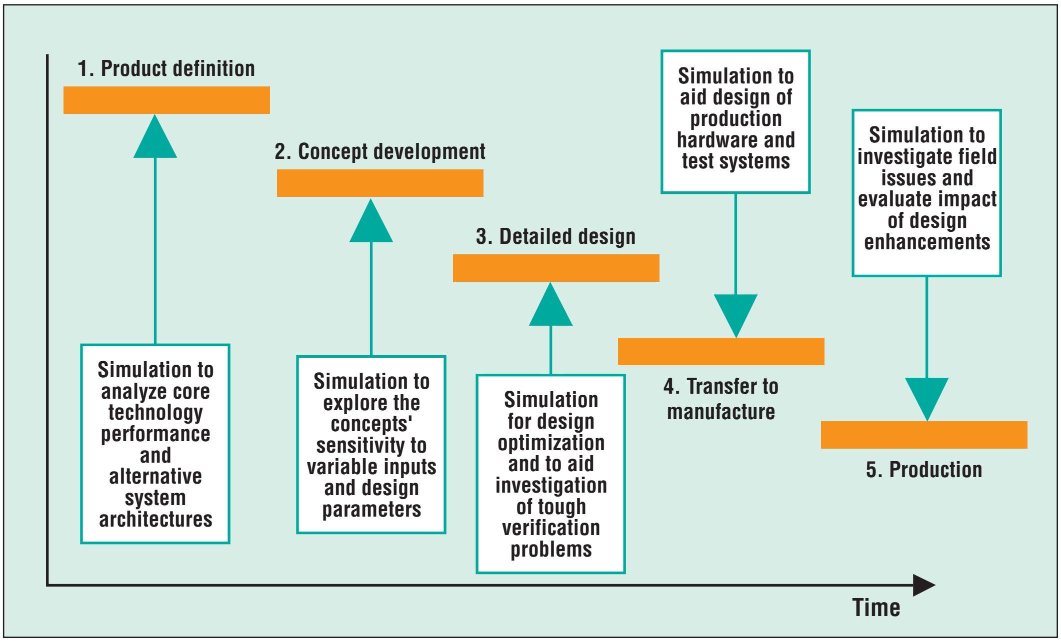

Figure 2. Typical development stages and simulation benefits.

The Commercial Justification for Simulation

Any organization considering enhancing its simulation capabilities should undertake a thorough cost-benefit analysis.

Simulation tools can range from inexpensive and commonplace spreadsheet software to complex, specialized, and expensive FEA software. When developing the commercial justification for acquiring the more expensive simulation tools, organizations should consider the following key costs:

- Initial tool acquisition cost, plus any additional IT and infrastructure costs.
- Ongoing software maintenance and support costs.
- Recruitment and employment costs for specialists required to operate and support the tools.
- Initial and ongoing user training costs.

On the benefits side, value should be attached to the following:

- Reduced risk exposure associated with the implementation of better-understood and better-developed core technologies, and more highly engineered systems.
- Revenue increases from faster time to market.
- Reduced labor costs of faster projects.
- Reduced prototype materials, construction, and testing costs.
- Reduced development- and production-stage redesign and rework costs through higher-quality designs.
- Reduced warranty costs through higher-quality designs.

An illustration of the potential time- and cost-saving benefits of using FEA to develop and verify an instrument chassis is presented (see Figure 3).

If the evaluation of the purchase of an advanced simulation tool does not show a clear benefit, this does not necessarily preclude its use. Many organizations offer simulation services on a consulting basis, providing a pay-per-use option when the establishment of advanced in-house simulation capabilities cannot be clearly justified. Even when a clear commercial benefit for in-house capabilities can be shown, outsourcing simulation trials before committing to an in-house investment can provide firmer data on the actual capability and value of the tools, when applied to the particular needs of the organization.

Performing the Simulation

This section describes the key simulation process steps, illustrating each step with an example where simulation is used to develop a complex electronic impedance-measurement subsystem for a life sciences instrument.

Define the problem to be solved, including the design targets and acceptance criteria of the simulation outputs. Establishing clear simulation goals is the critical first step. Many simulations have easy-to-evaluate pass-fail criteria, such as whether two moving parts clash during an instrument operation, or whether a particular process-flow produces an acceptable fault condition response. However, in many cases, the simulation goals must be derived from a higher-level system requirement. For example, a requirement that an instrument remain safe or functional under a defined loading condition must be interpreted to describe an allowable structural response. This could be defined as maximum allowable stress and/or deformation levels. In such instances, care must be taken to ensure that the derived goal does not overstate or understate the actual requirement to be met.

The assumptions and limitations of the simulation must be considered when

	Days Duration	Cost
Design & Verify Instrument Chassis—Using Simulation	49	46
Design	20	20
Simulate & refine design iteration 1	2	3
Simulate & refine design iteration 2	1	2
Simulate & refine design iteration 3	1	1
Build & test prototype	20	15
Refine design, modify prototype, retest	5	5
Design verified		
Design & Verify Instrument Chassis—Without Simulation	63	46
Design	20	20
Build & test prototype	20	15
Refine design, modify prototype, retest iteration 1	10	10
Refine design, modify prototype, retest iteration 2	8	8
Refine design, modify prototype, retest iteration 3	5	5
Design verified		

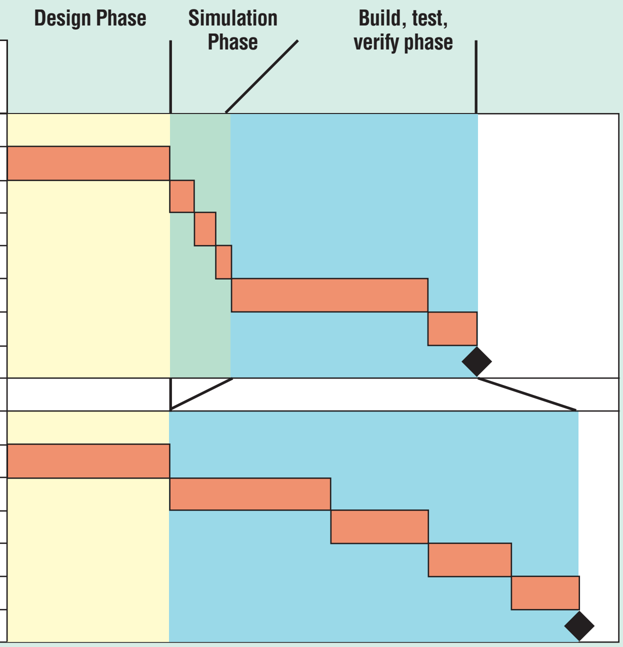

Figure 3. Illustration of cost and time savings when applying simulation to the development of an instrument chassis subsystem.

Simulation Tools and Products	IVD Technology–Related Applications
Spreadsheet software MS Excel Lotus 1-2-3	Problems that can be represented by mathematical formulas and logic. Often used to model simpler and common physics, chemistry, and engineering problems not requiring the more sophisticated tools. Examples include instrument cycle-time analysis, structural analysis, thermal analysis and dimensional tolerance analysis.
Specialized mathematical analysis software MathCAD	Any problem that can be represented by mathematical formulas. Software typically includes a library of basic to very complex mathematical functions including statistical methods to develop customized models of system behavior.
Control systems and embedded system design MatLAB/Simulink IBM/Rational Rose IBM Rational Rose Real Time	Control system process modeling and automatic code generation. Embedded systems simulation, development and automatic code generation.
Scheduling software MS Project	Instrument cycle-time analysis and subprocesses scheduling development. MS Project was not written for short time-span events (i.e., seconds or milliseconds). It can be adapted for fast processes.
Graphical user interface simulators Macromedia Flash Macromedia Director MS Powerpoint	Hardware-independent simulation of an instrument user interface. Extremely useful for gathering early feedback on usability of the interface including screen layout, design, colors, icons and work flows.
CAD/CAM software—mechanical design Unigraphics (UG) Catia Pro-Engineer (Pro-E) SolidWorks Solid Edge	Three-dimensional mechanical component and assembly design. Multiple-components mechanical motion and interactions simulation, tolerance, clash and clearance analysis. Machining process simulation and cutting-tool path development.
Finite Element Analysis (FEA) software ANSYS Multiphysics MSC Nastran SRAC Cosmos	Structural deflection, strain, vibration and fatigue, mechanical motion, thermal, fluid-flow, electrical, magnetic, electromagnetic, acoustics problems. Linear steady-state to fully nonlinear dynamic problems.
Plastic injection molding analysis Moldflow Part Adviser (within UG CAD)	Simulates how plastic flows into the mold tool. Used to determine presence or extent of molding-related problems to develop remedial part, tool, and process design measures if required.
CAD/CAM software — electronics design Protel	PCB layout, design-for-manufacture checking, automatic router tool path generation, circuit signal processing and logic analysis.
Electronic circuit simulators PSpice LTSpice	Electronic circuit logic design, signal processing, noise and thermal analysis.
Digital circuit design Altera Max+Plus	Digital circuit simulation and design tool for programmable logic gate arrays.
Electronic communication protocol simulators Custom developed	Partial or complete simulation of the host and peripheral device ends in a communications link, for validation and troubleshooting of the protocols. For example, a laboratory information management system host computer linked to multiple diagnostic instruments.
Software: general programming languages C++ Pearl Python	Customized instrument scheduling programs. Interfacing software simulation when the actual host system is unavailable. Emulators for low-level sensor inputs when the electronics are unavailable.

Table I. IVD technology-related simulation tools with examples of commercially available products.

defining the design targets. Appropriate design margins should be applied, particularly to functions and features critical to safety and performance.

In the impedance-measurement system example, it was imperative to determine the minimum target performance of the instrument. System parameters such as minimum and maximum amplitude and phase values, frequency range, number of steps, measurement precision, reproducibility, accuracy vs. frequency, and measurement time, were established. Defining this envelope suggested a demanding hardware implementation, and indicated that the tools and resources were available to test the implementation using simulation.

Define the system attributes that contribute to the response to be investigated. The relevant system attributes depend on the response under investigation. For example, in a thermal analysis involving the heating of a steel component, the key physical properties are the specific heat, thermal conductivity, and density of the steel. Other relevant attributes include the convection coefficients to be applied to the component's external surfaces. When simulating a real-time instrument process, attributes such as subprocess cycle times, and control-system processor and communications speeds, are important.

The uncertainty and variability of system attributes must be understood and evaluated in the simulation. For example, published materials data presents a range of values for physical properties. Manufacturing tolerances can result in significant response differences at the tolerance extremes. The potential effect of such variability should be assessed, and simulations performed as required.

For the impedance-measurement system example, the relevant system attributes were derived from an initial functional block-model of the system. This led to identification of a list of likely system components, such as analog-to-digital convertors, multiplexers, and signal generators. From this list, important attributes were defined, a range of commercially available components was searched, and actual data from the device manufacturers were obtained.

Define the system inputs that contribute to the response to be investigated. These inputs are such things as the environmental conditions and external stimuli that initiate and affect the system response. In a structural analysis seeking deformation and material stress responses, inputs might include the ambient temperature, and the forces or pressures applied to a component or assembly. In an instrument process simulation, the inputs might be control system inputs such as sensor states and values, user inputs, etc. Consideration must be given to how well defined or controlled these inputs might be. For example, if the force applied to a structure is not easily determined, a worst-case maximum should be estimated and applied to ensure acceptable performance. For the impedance-measurement system example, the key simulator inputs were voltage, current, and frequency ranges.

Construct and check the simulation model. The specifics of simulation model construction depend on the tool to be used. For a spreadsheet model, entering the data and mathematical formulas that represent system attributes and behavior is a key part of model construction. When building an FEA model of a physical system, defining geometry using CAD tools and entering the relevant material properties, as well as defining the boundary conditions, interface states, and properties are key tasks. For an instrument process model, generating the flowcharts that represent the system logic, developing the function algorithms, and generating the associated software code are the main construction tasks.

Before embarking on a complex simulation, progressively constructing the simulation model and testing it to confirm its soundness is normal practice, and highly recommended. This approach can help to remove bugs that might be difficult to find in a complex model. This modular construction and qualification methodology can be extended to most simulation models, and reflects a more reliable approach to building a complex system from simpler and prechecked components.

It is important that a qualified independent reviewer check and approve the simulation model. The organization should develop simulation checklists to facilitate thorough and consistent reviews.

For the impedance measurement system example, a freeware specialized electronic circuit simulator was used to model the critical circuit elements. A review of the results from initial runs indicated some oversimplifying assumptions and modeling errors. Further refinement of the simulation model was required to produce accurate results.

During the creation and refinement of the model, designers regularly reviewed and checked their work with experienced colleagues. It was verified that the simulation model was sound by simulating elements of the total system—such as the multiplexer transient response and speed—to confirm expected behavior. This building-block approach also allows for testing and optimizing the selection of components before a full simulation model is completed.

Perform the simulation. The specifics of performing the simulation depend on the tool to be used. In a simple spreadsheet model, the simulation is performed when input data values are entered or changed in cells and the formulas processed. When using FEA software, performing the simulation can require elaborate setup—such as defining analysis types and options; applying forces, temperatures, vibrations, heat sources, etc.; and defining input and output file names and locations. In all cases, each simulation run should be clearly identified and described, with the input data, model configuration, simulation tool settings, and output results preserved for subsequent review and use.

For the impedance-measurement system example, each simulation run was performed by inputting, via the circuit simulator software GUI, a trial impedance value that represents the test object.

Review and confirm the validity of the simulation outputs. It is wise to regard simulation outputs as suspect until they are proven otherwise. It is easy to overlook erroneous input data, particularly with large and complex simulation models. One misplaced decimal point in a key property or system input value, or a wrongly applied boundary condition due to an incorrect screen-pick, can produce misleading results. A qualified and independent reviewer should always check the model and the results. Simulation output checklists are a very useful aid to thorough and consistent reviews. The degree of review should be proportional to the risk level associated with the subsequent usage of the simulation outputs. For example, a process simulation intended to demonstrate a safety-critical feature would be more rigorously checked than a simulation used to minimize the material content, and therefore cost, of a cosmetic instrument cover.

For the impedance-measurement system example, no reference data were available to assess the validity of the simulation outputs. The experience and judgment of the designers was relied upon, and the above-mentioned qualification work was done during model construction.

Alter the system attributes based on the simulation outputs and iterate the simulation steps as required to achieve the desired design targets and acceptance criteria. This is the step at which simulation delivers the greatest benefits and value. A well-constructed simulation model enables the designer to test and rapidly compare a range of different system configurations to determine which is most suitable.

It is important that the degree of design optimization required for a system be understood by the designers, particularly when iteration requires significant work. The cost of this work must be weighed against the benefits provided. It is, therefore, important that the stated design goals and acceptance criteria be regularly referenced during the optimization process, to prevent unnecessary refinement.

For the impedance-measurement system example, the model parameters, such as integrated circuits and peripheral component specifications, were systematically changed to obtain the desired performance characteristics within the specification and project constraints.

Verify and use simulation results. The degree and priority of verification required of any instrument subsystem or process developed using simulation should be proportional to the criticality and associated development risks inherent in the process or subsystem performance. For example, the core instrument subsystems design and layout developed using simulation—which define and control, for example, the critical sample throughput performance—should be constructed and physically tested early in the development to demonstrate that acceptable performance is achieved.

For the impedance-measurement system example, a prototype circuit board was constructed, and tests were performed using laboratory equipment that included a high-precision signal generator and network analyzer. The initial testing revealed noise problems that were not predicted by the simulator. The noise was investigated experimentally, and it was determined that the noise was due to the physical effects of circuit component placement, which were not represented in the simulation model. It was also concluded that the circuit was fundamentally sound. A re-layout of the PCB rectified this problem. The ultimate measured performance of the system closely matched the predicted performance of the simulator.

Conclusion

Through the rapid maturing of core technology, simulation facilitates parallel instrument definition, instrument development, and core technology refinement. To maximize the benefits and reduce overall development risk, simulation must be applied with due consideration of the following:

- Identify and use alternatives when more appropriate.
- Simplify the problem as much as possible to enable a faster, cheaper, and potentially more reliable solution.
- Use the simplest tools available for a faster and cheaper solution.
- Ensure that the data on which the simulation is based are available and valid.
- Assess the effects of variability in system attributes and inputs.
- Ensure that appropriately skilled personnel, either within or outside the organization, conduct the simulation and check and verify the simulation approach and model.
- Understand the limitations of the simulation and apply appropriate safety margins.
- Verify the simulation outputs.

Any organization considering developing enhanced in-house simulation capabilities should conduct a cost-benefit analysis and evaluate alternatives.

When employed correctly, simulation is a very powerful tool that can be successfully applied to all stages and areas of IVD instrument development. It can save many months, and significant costs, in the development of new and challenging IVD instruments.



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