一直以来，仿真都被认为是高速数字设计设计人员才需要的额外步骤，但对于差不多所有PCB设计人员来说，仿真现在已成为一个必需的步骤。可是，建模和仿真工具仍然相当落后。随着MEMS、SiP和纳米技术的使用增加，大部份建模和仿真工具都显得很旧。本文探讨仿真未来的趋势。

Modeling and Simulation at SYSTEM LEVEL

Technology goes forward, but modeling and simulation – from design through manufacture – face many bottlenecks.

by ROBERT C. PFAHL

As products become more complex and fast-paced market conditions shorten product development lead times, design engineers are increasingly turning to modeling and simulation to reduce design cycle time, provide insight into complex problems, reduce costs and shorten both time-to-market and time-to-volume. Modeling and simulation can also help reduce the amount of testing that must be done during product development, reduce or replace the need for prototypes, and help achieve first-pass success.

Modeling and simulation have been common in the semiconductor field for years. At the system level, however, the tasks are more complex, the needs are more diverse, and commercial tools continue to lag far behind industry needs. Traditional modeling and simulation have been implemented in a limited manner for some time. However, infrastructure costs – such as simulation tools and simulation experts – have restricted their use primarily to larger companies and government laboratories.

Rapidly shrinking cycle times, increased cost pressures and increased product complexity are making it almost impossible to rely solely on testing for development of a new product or process. Mastering the various types of simulation is, therefore, becoming a business imperative. Developing a model and then partially or fully verifying it can be used to study "what if" scenarios or to gain insight into complex phenomena much quicker that the different parameters can be tested. Problem diagnostics can be provided if products fail in qualification or problems occur in manufacturing lines. Design optimization can be performed to evaluate cost vs. performance trade-offs.

TABLE 1 summarizes some of the key challenges that modeling and simulation can help address.

Looking ahead, modeling must shift from the component level to the system level. The focus must be broadened from traditional product design to include manufacturing processes and even the complete supply chain, including dissemination of simulation knowledge through the distributed global supply chain.

This article looks at some of the areas where further development of modeling and simulation is needed. It includes information from the Modeling, Simulation and Design Tools chapter of the 2004 iNEMI (International Electronics Manufacturing Initiative) Roadmap, released earlier this year.

Mastering The Basics

Modeling and simulation must continue to address several issues in conventional design. For example, simulation of mechanical reliability remains a key focus for all product sectors, along with thermal and electrical simulation. Tools must also address new and emerging technologies, such as microelectromechanical systems (MEMS), system-in-package (SiP) technology and nanotechnology.

Deployment of new materials and lead-free assemblies is driving new demands for simulation techniques that will demonstrate reliability of these materials and of interconnects. At the same time, rapidly growing product sectors, such as medical electronics, demand ever higher levels of reliability, and "getting it right" is more important than ever.

TABLE 2 (online) lists some of the emerging simulation demands being driven by various product sectors.

Mechanical reliability analyses of packages are now routine, particularly thermo-mechanical and mechanical analyses of assembly and manufacturing steps, but there are still some areas that require attention. These include interfacial delamination, moisture diffusion modeling, solder joint reliability

TABLE 1. Benefits of simulation and modeling

Reduced cycle time and time to market	Study impact of variability and stochastic elements, identifying opportunities to reduce time requirements in system-level and intrasystem processes simulations in order to gain more insight, faster simulations
Increasing product complexity	Study impact of part-process interactions, supply chain characteristics, supplier base management, responsiveness of supply chain
Do it right the first time	Make strategic decisions in the design phase to reduce/eliminate trial-and-error methods
Rapid volume ramp-ups	Study impact of production levels on resource constraints, resource allocation, logistics for different production levels
System-level considerations	Systems are more complex, and continuously growing, simulations can be used to study impact of additional nodes/processes
Increased cost pressures	Cycle time reduction, right the first time

modeling and process modeling.

Interfacial delamination. Deficiencies currently exist in the ability to predict the nucleation of cracks in packages and their subsequent propagation under static and cyclic loads. As deployment of wafer-level packaging increases, interfacial delamination knowledge becomes even more crucial.

Moisture modeling. The ability to mechanistically predict the moisture performance of a package, including the diffusion of moisture, could significantly reduce cycle time. Currently, such functions as transient thermal analyses, associated stress analyses, and prediction of interfacial stress due to moisture desorption during reflow and its effect on interfacial crack propagation are determined primarily by build and test.

Solder joint reliability modeling. Much effort has gone into predicting solder joint fatigue life for various package families, designs and application environments. However (as pointed out in each iNEMI roadmap since 2000), the current methodologies provide poor agreement with the results of temperature cycling. In particular, these methodologies need to be examined closely for lead-free solders. With trends toward finer pitch and smaller form factors, as seen in handheld and portable products, industry may be nearing joint limits for current-carrying capacity. This can cause high current densities and lead to the consideration of electro-migration effects in solder joints and under-bump metallurgies.

Process modeling. Traditional areas of process modeling, such as solder joint formation during reflow (for leaded and lead-free systems) and underfill flow with finer pitches need to be revisited. One area that has been overlooked is the ability to model wet processes such as electro-deposition of copper and under-bump metallurgy. This involves combining simulation of fluid mechanics of the process and equipment with the associated electrochemistry. Electro-chemistry in particular will be quite challenging and will require close interaction between academia, national laboratories and industry. Correct implementation will reduce the number of trials in equipment and process selection for high-density substrates and finer pitch printed wiring boards.

Emerging Technologies

The increased use of MEMS, SiP and nanotechnology is creating demands for new and expanded simulation capabilities. TABLE 3 summarizes some of the key capabilities that must be addressed.

MEMS technology is increasingly used in the automotive sector, where reliability requirements are among the most stringent of any industry. MEMS generally have moving elements, so line widths are often several microns (a far cry from the sub-micron sizes of more conventional chips). This movement, along with other factors, makes relia-

TABLE 2. Emerging simulation demands are driven by various product sectors

TREND (BY PRODUCT SECTOR)	DRIVING THE NEED FOR
OFFICE/LARGE BUSINESS SYSTEMS PRODUCTS	
Increased complexity, including increased I/O, more layers on boards, etc.	System-level modeling; more sophisticated and powerful modeling tools are required
New material sets, proliferation of organic flip-chip BGAs, use of Pb-free solder	Simulation techniques for reliability of new materials, interconnects
Shrinking cycle times	Do it right the first time — reliability, thermal and electrical analyses at beginning of design cycle
Increased power densities at chip and component levels	Thermal and computational fluid dynamics simulations at system level
Thin films and optoelectronics at the backplane area (optical PWB waveguides)	Electrical performance
Nano-scale devices and materials	Higher density devices, better performance, and innovative design
Cost pressures	Factory systems/manufacturing or assembly and supply chain modeling
AEROSPACE/DEFENSE PRODUCTS	
Increased use of COTS – deployment of BGAs and plastic components	Reliability simulation under harsh environments
Large acceleration factors between lab and field conditions	Field reliability models are key
Use of high-density connector systems	Simulation in areas of contact and reliability
AUTOMOTIVE PRODUCTS	
Thermal management is a key factor	Higher reliability in a harsh environment
Deployment of new materials	Simulate reliability in laboratories, relate to field
Proliferation of MEMS devices and RF systems/devices	Transfer of simulation knowledge from other sectors to automotive
Cost pressure	Need to build understanding of failure mechanisms of MEMS device Reliability prediction is a challenge for MEMS scale devices due to the different failure mode and governing physics
	Factory systems/manufacturing and supply chain management simulations
CONSUMER/PORTABLE PRODUCTS	
Cycle time is key — short time to market	Modeling and simulation to shorten cycle times
Increased complexity — higher silicon integration, product complexity (e.g., 3D stacking)	Simulation to understand increased complexity
Design for postponement	Factory information systems or supply chain simulations to adjust design elements to customers' rapidly changing needs
Increased use of MEMS	*See discussion under Automotive Products*
Smaller and less protection from environment	Importance of predicting drop/impact resistance

bility prediction a real challenge. Although MEMS reliability has been studied in recent years, there is still no concerted effort to use modeling and simulation to predict reliability of MEMS under various environments.

MEMS reliability must be studied under various stimuli in order to build a comprehensive understanding of failure mechanisms. Experimental studies can be used to define models to simulate failures of thermo-mechanical and multi-physical origin. Such an activity may require infrastructure development to characterize materials and establish the relationship between the results of analyses (such as stresses and strains) and the failure criteria (such as the number of cycles to failure, interfacial delamination, stiction – static friction – and impact resistance).

Nanotechnology is also getting plenty of attention. Nano-scale, along with optoelectronic, simulations are emerging as industry moves toward smaller scales in the digital silicon technology and wafer-scale packaging. Also, the needs for signal integrity and propagation at higher frequencies, respectively, are driving simulation in these areas.

Taking a System-Level View

For several roadmap cycles, iNEMI has highlighted the need for system-level modeling and simulation. While decreasing product cycles and increasing cost pressures continue to fuel the need for this higher-level, broader view, implementation still lags behind.

The use of modeling and simulation in electronics manufacturing can be viewed in four broad categories: system-level design strategy, policy optimization, design for robustness, and simulation-based real-time control. These four categories require different levels of abstraction. The following paragraphs discuss three of these broad categories.

System-level design strategy. This level of modeling and simulation is inherently more complex than component-level modeling and requires a well-mastered modeling strategy. System-level simulation techniques require models of the highest form of abstraction and are typically used for making strategic decisions in the design phase. This type of modeling can be used to:

- Provide different levels of abstraction for problem definition.
- Provide problem diagnostics at the system level.
- Evaluate "what-if" scenarios to identify the best configuration of system components/processes/standards without having to learn by trial-and-error.
- Provide full-field, in-depth understanding of the system.
- Provide insight into extremely complex problems, phenomena and product-process sets.

Design for robustness. At this stage, the simulation models are used to study the impact of stochastic (random) elements in the performance of the system. More specifically, these models are used to study methods of risk minimization and the effects of variation associated with the factors identified in the earlier stages. The main impacts for this phase of simulation modeling are:

- Identify through experimentation the impact of stochastic elements for a chosen system and its operational policies.
- Provide methods to quantify risks associated with random events in any system-level or component-level interactions.
- Provide methods to analyze the impact of variations in system processes.

Simulation-based control. The most data-intensive use of simulation in the context of system modeling for discrete systems is to control the transactions in a system. In this scenario, the system needs to keep track of even the "smallest" event – such as loading a part in a machine, in order to effectively control an entire system. As can be expected, the simulation models used for this purpose are the most detailed models compared to those used in the previously mentioned stages. The advantages of simulation-based control include:

- Availability of higher fidelity models for analysis purposes. Since the simulation models used as real-time controllers include minute details of the system being modeled, they bear very high fidelity to those systems. As a result of which, any simulation analysis using such models will provide more reliable results.
- Increased modularity in system modeling and design.
- Enhanced usability of simulation models by providing them with the ability to be used as control execution systems as well as analytical tools.

Gaps and Showstoppers

Some of the apparent bottlenecks that are inhibiting the widespread use of simulation in manufacturing include:

- The time and effort required to develop accurate simulation models.

TABLE 3. Projected development and research needs for simulation in emerging areas

EMERGING SIMULATION AREA	NEEDS BY 2005 TO 2011	COMMENTS
MEMS	■ Multi-phase flows simulations, bioMEMS ■ Multi-physics simulations: (e.g., Joule heating in sub 50 nm interconnects, electro-chemical phenomena in bio-MEMS devices) ■ Multi-scale simulations from sub 50 nm to mm (similar issue to nano-scale methodology) ■ Methodology to predict failure of MEMS devices – e.g. delamination, cracking – surface & material science ■ Analog and digital design	■ High volume production is a challenge – many custom processes different from usual Si foundry ■ Lack of standards ■ New experimental techniques may also be needed to verify the modeling algorithms. Very accurate displacement measurements will be required. ■ New failure modes and mechanisms will need to be identified. ■ Limited commercial software packages available, criticality in 2005
Nano-scale modeling and simulation	■ Thermo-mechanical models for nano-scale ■ Experimental tools capable of measuring electrical and thermal and mechanics phenomena/material properties at smaller scales ■ Scale dependent algorithms will be needed – ability to shift scales	Drivers: ■ Wafer-package convergence ■ Device/package circuitry moving to smaller scales: < 65 nm in 2007 ■ Advanced materials, e.g., TIM (thermal interface materials) ■ Issue: How is the property and behavior different from bulk behavior/macro-scale? ■ Critical in 2007
SiP	■ More I/Os, more layers in the boards, and rapidly increasing power densities, occurring at both chip/component and system levels	■ Need for thermal and computational fluid dynamics (CFD) simulation, as well as electronic and mechanical simulation. ■ Mixed signal simulation challenges need to be addressed.

- The inadequate use of available data within the appropriate time span. Today, large quantities of data are collected on the facility floors of most EMS providers. There is, however, an absence of mechanisms to effectively use the data collected.
- The need for effective data collection. Often, large quantities of data are being collected, but data that is needed is often absent or not collected. This situation must be rectified.
- The use of advanced inference methods such as neural networks and genetic algorithms in simulation and modeling. While the use of simulation in electronics manufacturing is in its nascent stage, the use of advanced optimization techniques within the simulation model is nearly absent in actual use. It is now considered more of an academic exercise.
- A reduction in the time needed for software development. This is perhaps the single most important bottleneck after model development; however, the use of object-oriented techniques is reducing the effort required for software deployment. Software development that is based on visual icons and macro-level programming will help reduce the effort associated with the implementation of a simulation model.
- There is a widespread lack of knowledge among practitioners about the use of simulation in electronics manufacturing. This is a hurdle that needs to be overcome through effective education and training. In addition, while some practitioners are comfortable with the use of software, they are not as comfortable with statistics. The use of simulation as an effective tool requires the appropriate level of statistical knowledge.
- There is still no true plug-and-play environment. Simulation models that require real-time access to other computers and data sources are still challenging to implement, especially if computing systems that use multiple platforms and/or operating systems are part of the overall manufacturing environment.
- There is a need for customizable simulation modeling tools specific to the electronics manufacturing arena. Such tools will significantly reduce the time required to build and test models. Existing tools are geared toward either discrete systems or primarily continuous systems. The electronics manufacturing domain can exhibit both characteristics in system behavior and process behavior. This will impose additional requirements on any simulation tool developed for this domain. PCD&M

ROBERT C. PFAHL, PH.D., is vice president of iNEMI and co-chairs the consortium's Technical Committee. He can be reached at bob.pfahl@inemi.org.

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