Michelle Bryner

# Smart Manufacturing: The Next Revolution

Moving to the next generation of production can help the U.S. keep its competitive edge.

Welcome to the chemical plant of the future, where self-aware heat exchangers, distillation columns, chemical reactors, motors, and pumps work in concert, wirelessly communicating their status with each other to produce the highest-quality product, in the least amount of time, with near-zero incidents, emissions, and waste. The plant is intimately connected with upstream and downstream processes, such that it can respond in real time to market shifts, customer demand, global economics, and political and socioeconomic activities. Constantly changing and adapting, the process learns and adjusts.

Glimpses of this vision exist. For example, two years ago, Tata Motors made headlines when it introduced the Nano — the world's cheapest sedan, with a sticker price in the Indian market of $2,500. This ridiculously low price was not the result of cheap labor and shoddy workmanship, but instead could be attributed to the company's "smart" factory in Gujarat and its out-of-the-box innovation.

Tata's Gujarat factory employs the latest automation technologies — sensors, microprocessors, and motor control devices — giving it the brains to predict bottlenecks and breakdowns before they occur, and the ability to get parts from suppliers in real time to meet orders. The factory also houses smart technology that traces and tracks each component of a customer's Nano back to its source. The traceability program minimizes the number of car recalls when a faulty product is identified.

The Nano is just one example of what can be accomplished with next-generation manufacturing, also called smart manufacturing (Figure 1).

"As smart manufacturing technology develops further, we will see an explosion in the amount of information available to our manufacturing plants and extended supply chains," says Theresa Kotanchek, Vice President, Sustainable Technologies and Innovation Sourcing at Dow Chemical. "This information will allow our product designers, developers, purchasing, manufacturing, and supply chain teams to respond quicker to customer needs and disruptions in the market place," Kotanchek says. "Part of our challenge in the future will be to design our manufacturing assets with the right capabilities and flexibility to take full advantage of these emerging benefits," she says.

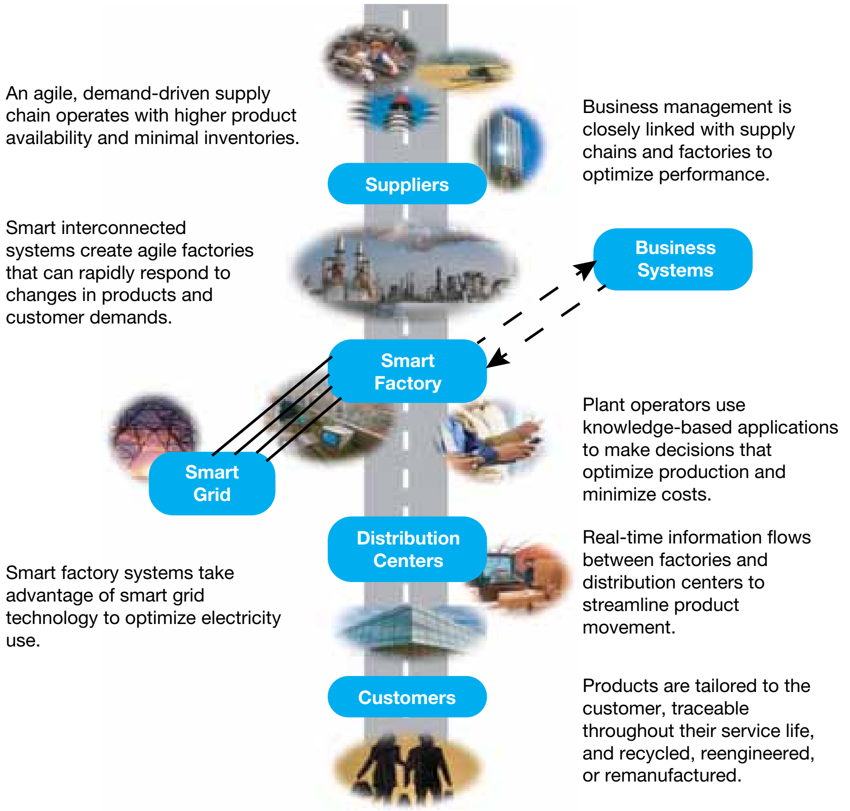
The goal of the smart manufacturing movement is to create knowledge-embedded manufacturing operations. Today's operations will be transformed from reactive to proactive, response to prevention, compli-

▲ **Figure 1.** Advanced automation and control is at the heart of smart manufacturing. This multipurpose system synchronizes and monitors processes in a bottling plant. Image courtesy of Rockwell Automation.

ance to performance oriented, tactical to strategic, and local to global. The pervasive application of networked information and knowledge through analytics, modeling, and simulation dynamically integrates the demands of the customer throughout the entire supply chain — enabling real-time response to changes in raw material costs, fluctuations in volume demand, and custom orders, while minimizing energy and material usage and maximizing environmental sustainability, health and safety, and economic competitiveness (Figure 2).

"We are interested in the capability, tools, and infrastructure that ensure that processes are seeking, at every instant in time, the optimum delivery of the best possible product without interruption, incident, or cause for alarm," says Jim Davis, Vice Provost for Information Technology and CTO at the Univ. of California, Los Angeles (UCLA) and a professor of chemical and biomoleculer engineering at UCLA. "We are further interested in a high level of responsiveness to market shifts, customer demand, global economics, and political and socio-economic factors."

Over the past few years, several initiatives aimed at modernizing manufacturing in the U.S. have materialized. Industry, academia, and government entities have formed the Smart Manufacturing Leadership Coalition (SMLC), for instance, to identify objectives, secure funding, and develop the IT platform that will support smart manufacturing. The coalition consists of 25 global companies, eight manufacturing consortia, six universities, one government lab,



▲ **Figure 2.** The future manufacturing plant will be interconnected with suppliers, distributors, customers, and business systems via information technology. Source: SMLC.

and four high-performance computing centers. It comprises companies across a broad spectrum of industry, including: batch, discrete, and continuous process manufacturers; chemical, pharmaceutical, and materials producers; automation providers; and power generators, among others.

"We sat down with a good cross-section of companies, and we identified common objectives that were driving manufacturing in very new directions," says Davis, leader of the SMLC steering committee. "We then took a look at the roles of information technology and the rapidly expanding capabilities of cyber infrastructure; that's where smart manufacturing, the terminology, emerged," he explains.

"If you're going to address all of these in a comprehensive manner, you need to address something that we call manufacturing intelligence, which means having the right information wherever you need it, whenever you need it, and in the form that is useful and actionable," Davis continues. The SMLC has identified actions needed to achieve this vision (Figure 3).

SMLC is one of several U.S. initiatives working on next-generation manufacturing. Government-funded entities, including the National Institute of Standards and Technology (NIST) and the National Science Foundation (NSF), are actively involved in smart (or advanced) manufacturing. The President's Council of Advisors on Science and Technology (PCAST) prepared a report entitled "Ensuring American Leadership in Advanced Manufacturing," which provided an overarching strategy along with specific recommendations to revitalize U.S. leadership in advanced manufacturing. The Advanced Manufacturing Partnership (AMP) was formed to work with the National Economic Council and the Office of Science and Technology Policy to implement the recommendations in the PCAST report.

Simply put, smart manufacturing can be dissected into four main elements: automation and control, models and simulation, a skilled workforce, and key performance indicators. The automation and control piece involves sensors and microprocessors on each piece of equipment, computing hardware and software to record and analyze data, and technology to connect sensors to one another as well as to connect one plant floor to other plant floors within a supply chain, all in real-time. Modeling and simulation refers to operating models that interpret and make sense of the collected data, and provide useful and actionable information for design, planning, production, etc. The human element (*i.e.*, skilled workforce) refers to an operational workforce (those running the processes) with advanced training and skills. And the key performance indicators (KPIs) are measurements that describe such parameters as sustainability, economic competitive-

**Industrial Community Modeling and Simulation Platforms for Smart Manufacturing**

1. Create community platforms (networks, software) for the virtual plant enterprise
2. Develop next-generation toolbox of software and computing architectures for manufacturing decision-making
3. Integrate human factors and decisions into plant optimization software and user interfaces
4. Expand availability of energy-management decision tools (energy dashboards, automated data feedback systems, energy apps for mobile devices) for multiple industries and diverse skill levels

**Affordable Industrial Data-Collection and Data-Management Systems**

5. Establish consistent, efficient data methods for all industries (data protocols and interfaces, communication standards)
6. Develop robust data-collection frameworks (sensors/data fusion, machine and user interfaces, data recording and retrieval tools)

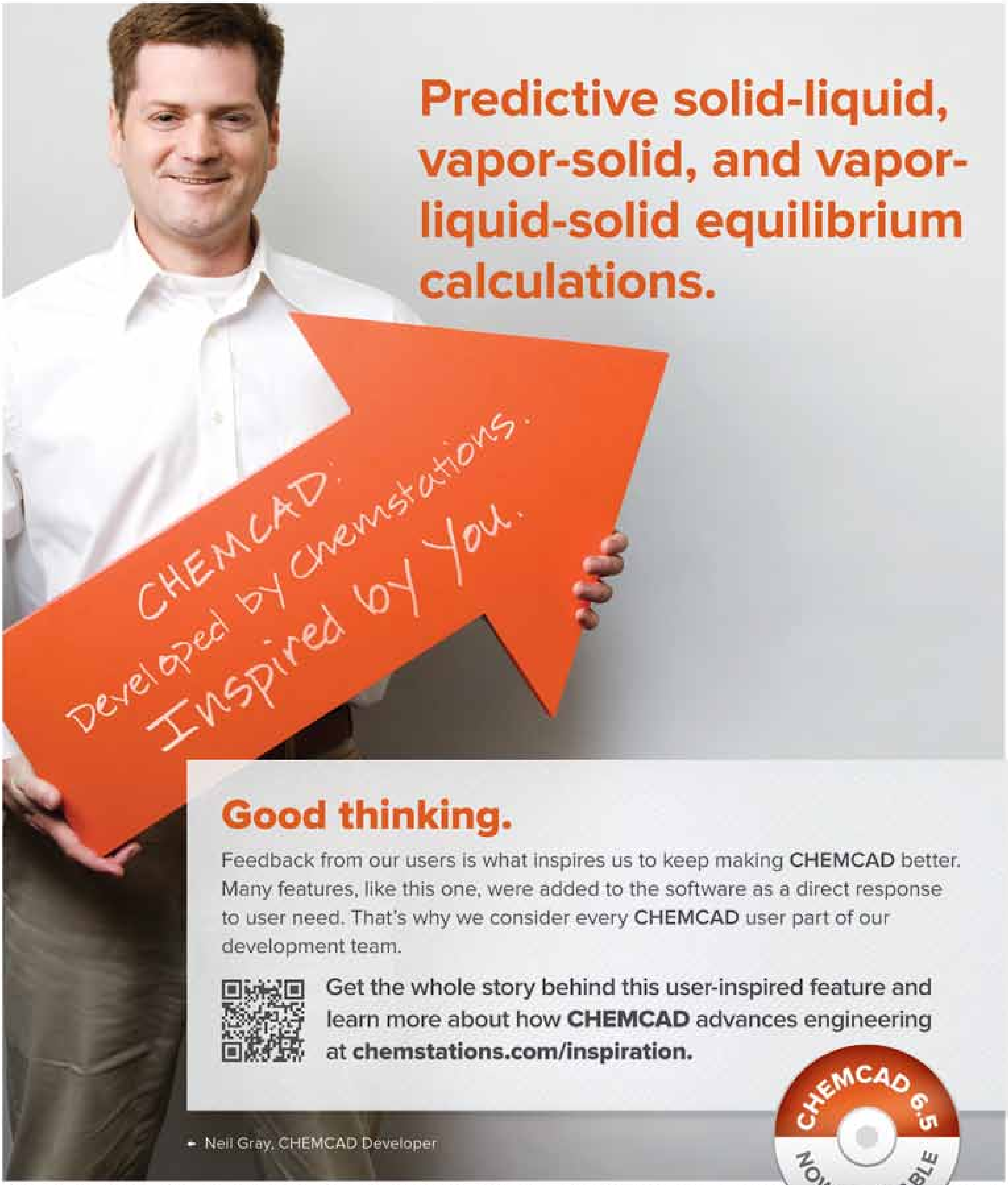
**Enterprise-Wide Integration: Business Systems, Manufacturing Plants, and Suppliers**

7. Optimize supply-chain performance through common reporting and rating methods (dashboard reports, metrics, common data architecture and language)
8. Develop open-platform software and hardware to integrate and transfer data between small and medium enterprises (SMEs) and original equipment manufacturers (OEMs) (data sharing systems and standards, common reference architectures)
9. Integrate product and manufacturing process models (software, networks, virtual and real-time simulations, data transfer systems)

**Education and Training in Smart Manufacturing**

10. Enhance education and training to build a workforce for smart manufacturing (training modules, curricula, design standards, learner interfaces)

▲ **Figure 3.** The SMLC has identified 10 priority actions required to move smart manufacturing into the mainstream industrial sector.



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ness, energy consumption, and level of health and safety (unlike traditional performance metrics, which are based on output/input productivity).

## Automation and control

Automation and control technologies are not new to manufacturing industries. Sensors, computer hardware and software, and actuator technologies have been used on individual pieces of equipment and isolated portions of processes for decades. To reach the smart manufacturing vision, however, information technology (*e.g.*, data management and modeling) must be pervasive and integrated throughout the multiple layers of operation and decision-making (*e.g.*, sensors and actuators, operators running the process, supply chain, etc.), and be extended across multiple process units within a factory, as well as across an entire factory and supply chain.

Achieving the smart manufacturing vision will be a significant undertaking and will require the build-out of a new IT infrastructure, Davis says. Consensus is building around the need for a standard, pre-competitive infrastructure for deploying multiple, smart manufacturing systems. Providing this infrastructure as a shared platform will lower the barriers (*e.g.*, cost, complexity, ease of use) for implementing sensor-measurement-driven modeling and simulation, which in turn makes these technologies accessible to small- and medium-sized companies.

In the past, different control systems were used for different applications. For instance, discrete processes such as those used in the automotive industry relied on programmable logic controllers (PLCs). PLCs work well for discrete processes but do not have the capability to handle continuous processes. Instead, distributed control systems (DCSs) are typically used for continuous processes. The development of the programmable automation controller (PAC) changes this.

"Today, we have programmable automation controllers, which are able to do both — you can use the same general-purpose computer system for applications in the process world that you can for an assembly line," says John Bernaden, corporate director at Rockwell Automation and vice chair of the SMLC.

In addition to the controllers themselves, the automation and control system will require a common networking technology to enable sensors to talk with one another across a plant floor and for one plant floor to communicate with others in the supply chain. While wireless networks are extensively used for consumer electronics, they were not designed for the manufacturing environment.

"The factory floor is a pretty demanding environment, both in terms of the noise — mechanical and electrical noise that interferes with the measurements that these sensors are making — and the need for real-time deterministic operation," says Fred Proctor, leader of the control systems group at NIST. "For example, unlike video streaming for your laptop, where an occasional glitch is fine, control operations on a factory floor require dead-on timing," Proctor says. "In the factory, if that timing is delayed a little bit, or if on average it's okay but there are periods where information comes in really fast or really slow, that wreaks havoc on controls."

In support of a standardized IT infrastructure, the SMLC is creating a smart manufacturing platform (SMP) — a standardized toolkit of hardware, software, and network technologies that are accessible and adaptable across industries and processes. The SMP can be thought of as a common operating system, allowing users to download and use the same apps, compare and share data, and communicate easily with one another.

## Modeling and simulation

Just as automation and control technologies are not new to manufacturing, modeling and simulation are

## A Call to Action

The Society of Manufacturing Engineers (SME) released a white paper last month, "Workforce Imperative: A Manufacturing Education Strategy," that provides recommendations to increase the number of skilled manufacturing workers in the U.S.

"With an estimated 600,000 unfilled manufacturing positions across the country, the shortage of advanced manufacturing engineers, technologists, and technicians is already impacting most industries," SME says. "With the retirement of much of the core workforce over the next 10 years, and new generations not prepared to — or even interested in — taking their place, the manufacturing industry is facing a crisis."

The plan calls for academia and industry to work together to:

- attract more students into manufacturing
- articulate a standard core of manufacturing knowledge
- improve the consistency and quality of manufacturing education
- integrate manufacturing topics into science, technology, engineering, and mathematics (STEM) education
- strategically deploy resources to accomplish these goals.

"It is imperative that manufacturing is working hand-in-hand with education to properly train and educate both our current and future workforce," says Mark Tomlinson, SME executive director and CEO. "Importantly, we must communicate to our young people the tremendous opportunities that exist in manufacturing and then provide them with the educational foundation necessary to succeed," he says.


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also not new. While much progress has been made in this area, modeling and simulation are still not ubiquitous throughout manufacturing, and they are not often used for business and technical decision-making. In addition, modeling is rarely used during plant operation. The smart manufacturing vision incorporates modeling and simulation into the actual operation of the manufacturing process.

"Model-based techniques, simulation, and smart tools to manage information and process knowledge are key elements in smart manufacturing," says Yiannis Dimitratos, Technology Manager of the Process Dynamics and Control organization at DuPont Engineering Research and Technology.

A plant that made Pringles potato chips (which at the time was owned by Procter & Gamble) realized the benefits of modeling and simulation during manufacturing when it built an additional process line to manufacture chips in a new flavor. Typically, this endeavor would take about three months and about $250,000, says Rockwell Automation's Bernaden. Because the company's Pringles plants were equipped with state-of-the-art automation and control technology, a lot of data on the existing Pringles lines was available. The research and development team at P&G ran the data through aerodynamics models and simulations using a high-performance computer system.

"They obtained aerodynamic models because these Pringles are literally flying down the assembly line," Bernaden says. (P&G made about a half-billion chips per hour.) "Using the big computer model, they discovered that a 47-degree angle [between the chip and the conveyor] allows the assembly line to go as fast as possible and has the aerodynamics to keep the chip hugging the assembly line," Bernaden says. Then they used these same aerodynamic models to determine the best method to apply the flavor dust to the chip while it was moving at such high speeds. "With $36,000 of computer time over about two weeks, they created a virtual next-generation assembly line," Bernaden says.

Instead of one-off models, in which a model is developed and used for only one isolated project or process, the smart manufacturing vision calls for models to be accessible across supply chains and industries, in the form of open-source software. The application of models to every aspect of manufacturing, from planning, design, and development through operation, will be pervasive, coordinated, consistent, and managed. The objective of the models is to optimize a set of predetermined performance metrics.

## Skilled workforce

In his book, *Make It In America — The Case for Re-Inventing the Economy*, Dow Chemical CEO Andrew Liveris discusses the need for a skilled workforce to revitalize the U.S. manufacturing sector. "A properly educated workforce is an issue of deep concern to business, especially to manufacturers," Liveris writes. "Our worry isn't just that our children are being educated poorly; it's that they're being educated poorly in the subjects most relevant to our economic well-being. There isn't enough focus on science, technology, engineering, or math in our schools."

## Key performance indicators

Key performance indicators will allow companies to compare, share, and understand one another's performance metrics. Examples include elements of cost, productivity, quality, energy, environment, sustainability, and other factors. While there are thousands of such indicators, their meaning varies across companies and industries.

"Performance is difficult to quantify," NIST's Proctor says. "We have a good handle on measurements like length and time; those are the fundamental units that we have tools to measure. The harder thing is how to measure performance."

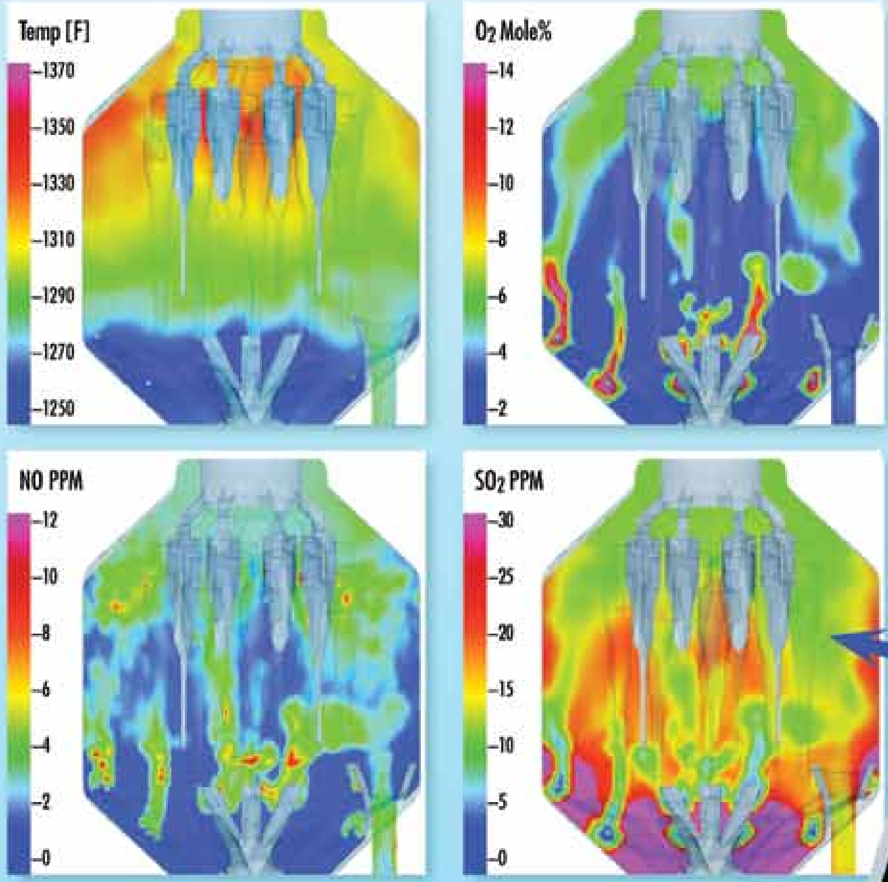
NIST has initiated the Factory Equipment Network Testing Framework project to address this need. The aim of the project is to develop a unified testing framework that will enable the development of new performance measurement methodologies — better ways to define and measure key performance indicators — and apply them to factory equipment.

## The smart ecosystem

Many of the smart manufacturing technologies and concepts are being applied at the plant level and/or on isolated production lines. Most chemical plants are equipped with automation and control technologies that alert operators when the process is operating outside of preset limits.

Dow Chemical, for example, uses a proprietary process control system that it developed 30 years ago. Chemical engineers at Dow developed the Manufacturing Operating Discipline (MOD) because the commercial products available at the time did not meet the company's needs. In the 1980s, Dow implemented the MOD-5 system (the latest version) globally, which allowed every plant and facility running on the MOD-5 hardware and software to communicate with one another.

"Today, our manufacturing assets are highly automated, including automatic startups, shutdowns, deviation responses, and formulation changes, and many of our plants utilize online dynamic models for process optimization," Kotanchek says. "The value to this process automation is clear in terms of process safety, cost, yield,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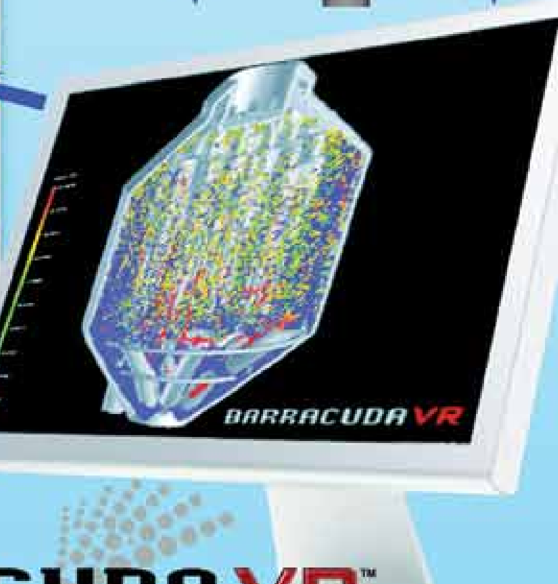
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efficiency, quality, and reliability. But we realize there is still a lot of value to be mined."

In the smart manufacturing ecosystem, this intelligence will be extended beyond the automation and control systems. "When the smart manufacturing vision is achieved, intelligence will be not only in the automation system, but it will be in every computing system that we are using at the plant. It will be in field instrumentation. It will be in our safety systems. And it will even be in our unit operations," Dimitratos of DuPont says. "Think of an intelligent reactor or intelligent distillation column … It will have the self-awareness of what it's supposed to do and its current state; it will have the capability of learning and adapting; and when it's running at the risk of, *e.g.,* violating some constraint, it will be able to take some corrective action," he says.

Extending the technologies and concepts currently being applied at the plant level to the entire supply chain and multiple industries will require a standardized infrastructure. In such an ecosystem, small, medium, and large companies will use hardware and software that are interoperable. They will all rely on compatible computers and operating systems. The modeling and simulation software will be accessible to all companies, which can then customize it accordingly. In essence, companies will have access to the equivalent of Apple's App Store for the iPhone and iPad. And cloud technology will allow for the management and sharing of data across the supply chain.

### AIChE Takes On Manufacturing

AIChE will launch a Manufacturing Initiative by the end of this year, to provide a home for manufacturing organizations and professionals to share challenges faced by the industry and work together to develop solutions.

**Stay tuned for more information.**

## ENERGY

### New Battery Takes Charge of its Power

Conventional wisdom says that electricity is generated in one unit (*e.g.*, wind turbine, photovoltaic cells) and stored in another (*e.g.*, battery, supercapacitor). This paradigm could be changing.

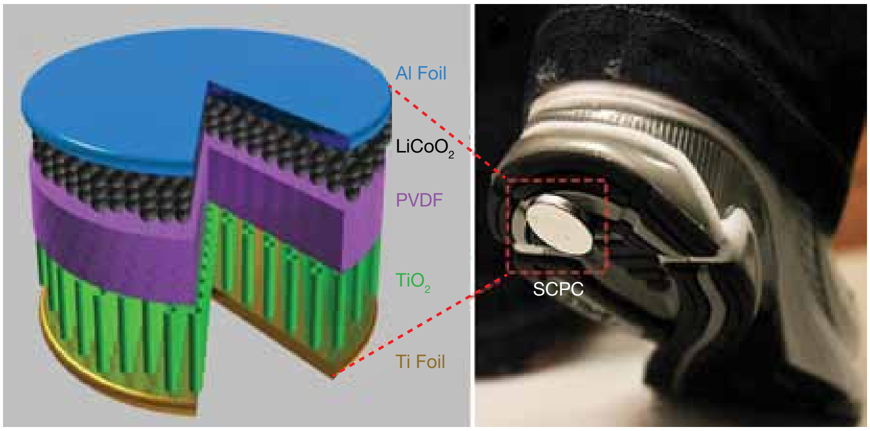
Researchers at the Georgia Institute of Technology have figured out a way to combine energy generation and storage into a single unit — eliminating intermediate steps and saving energy in the process.

"People are accustomed to considering electrical generation and storage as two separate operations done in two separate units," says Zhong Lin Wang, a professor of materials science and engineering at Georgia Tech. "We have put them together in a single hybrid unit to create a self-charging power cell, demonstrating a new technique for charge conversion and storage in one integrated unit."

The new self-charging power cell (SCPC) resembles a typical lithium-ion battery and consists of two electrodes, an electrolyte, and a separator film. The main difference: The SCPC uses a piezoelectric polyvinylidene fluoride (PVDF) film instead of polyethylene as the separator.

The power cell consists of a lithium-cobalt oxide ($LiCoO_2$) cathode and a titanium dioxide anode ($TiO_2$ nanotubes) separated by a PVDF film. Initially, the lithium hexafluorophosphate ($LiPF_6$) electrolyte is evenly distributed across the uncharged cell. When stress is applied to the cell, the PVDF generates voltage (positive potential at the cathode and negative potential at the anode), causing lithium ions in the electrolyte to migrate from the cathode to the anode — thereby charging the "battery." The ions continue to migrate across the cell until a chemical equilibrium between the two electrodes is reached. Once the applied mechanical pressure is released, the cell can supply power; the voltage disappears and the ions can move back to the anode, establishing a new equilibrium.

So far, Wang and his colleagues have built 500 power cells. By attaching the cells to the bottom of a shoe, the team confirmed that their technology can be used to convert mechanical energy directly into chemical energy and that walking provides enough compressive stress to drive this conversion.



▲ Georgia Tech researchers have constructed a self-charging power cell (SCPC) that is a hybrid of a piezoelectric nanogenerator and a lithium-ion battery. The anode consists of $TiO_2$ nanotubes grown on titanium (Ti) foil; a layer of polarized PVDF film acts as a separator; and the cathode is a $LiCoO_2$ mixture on aluminum (Al) foil. This structure is sealed in stainless-steel 2016-coin-type cells, as shown in the inset. When stuck to the bottom of a shoe, the SCPC converts the compressive energy generated by walking into chemical energy, which it stores. Image courtesy of Georgia Tech.