Engineering 3 (2017) 161–165

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Smart Process Manufacturing—Perspective

A Perspective on Smart Process Manufacturing Research Challenges for Process Systems Engineers

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ARTICLE INFO

Article history:
Received 24 November 2016
Revised 16 January 2017
Accepted 17 January 2017
Available online 16 March 2017

Keywords:
Smart manufacturing
Process systems engineering
Uncertainty
Flexibility
Optimization
Model-based control

ABSTRACT

The challenges posed by smart manufacturing for the process industries and for process systems engineering (PSE) researchers are discussed in this article. Much progress has been made in achieving plant- and site-wide optimization, but benchmarking would give greater confidence. Technical challenges confronting process systems engineers in developing enabling tools and techniques are discussed regarding flexibility and uncertainty, responsiveness and agility, robustness and security, the prediction of mixture properties and function, and new modeling and mathematics paradigms. Exploiting intelligence from big data to drive agility will require tackling new challenges, such as how to ensure the consistency and confidentiality of data through long and complex supply chains. Modeling challenges also exist, and involve ensuring that all key aspects are properly modeled, particularly where health, safety, and environmental concerns require accurate predictions of small but critical amounts at specific locations. Environmental concerns will require us to keep a closer track on all molecular species so that they are optimally used to create sustainable solutions. Disruptive business models may result, particularly from new personalized products, but that is difficult to predict.

1. Introduction

Smart manufacturing is a stated priority of most major economies, including those of the United States, China, and the European Union. It is mostly framed in terms of better use of big data—that is, measurements and market data—and intra-machine connectivity, particularly using the Internet of things. While comprehensive and timely data and massive connectivity are necessary conditions for this revolution, they are not sufficient. It is also important to have smart algorithms for intelligent and timely use of the data. This is the domain of process systems engineering (PSE). Process manufacturing, in which products are mostly continuous fluids or solid streams with fluid-like properties and molecular differentiation, presents different challenges than those of mechanical manufacturing. This paper reviews perspectives on smart process manufacturing and the potential contribution of and challenges for PSE, its research, and its practice community, in making the most of this revolution. This is a short perspective, so references are very selective and are not meant to be comprehensive.

The smart manufacturing revolution is said to have three phases:

- Factory and enterprise integration and plant-wide optimization,
- Exploiting manufacturing intelligence, and
- Creating disruptive business models.

All three phases have resonance in the process industries. The first phase is already underway, and the PSE community has been in the vanguard of providing tools and techniques for facilitating integrated design and operation. Ideas and research results for the second phase suggest that whole supply chains can be integrated more seamlessly in order to provide products more quickly, efficiently, and sustainably; however, such integration certainly remains a major challenge for the industry. Although we have seen little change in business models in the process industry over the past decades, smart manufacturing promises to enable us to develop new business models—for example, to deliver personalized medicine—in an

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http://dx.doi.org/10.1016/J.ENG.2017.02.003

efficient and sustainable way in the future. The current model of long-term contracts for the supply of large amounts between each part of the supply chain, which is common in chemicals, would not be appropriate. We need a model that allows the supply of bespoke products in small amounts, which will likely be of much higher added value and which will require the direct influence of the cost of product development, cost of manufacture, and strength of demand. This remains a major challenge.

A set of challenges for smart process manufacturing in the United States was discussed at a workshop in April 2008, resulting in a comprehensive report [1]. A specific test bed was proposed—the steam reforming of methane—in order to demonstrate and benchmark progress [2]. More recently, Li [3] addressed the challenges for the petrochemical industry from an industrial perspective. These challenges are common internationally for countries with a well-developed process industry base. It is clear from both these contributions that PSE lies at the heart of the smart process manufacturing challenge.

Over the past 50 years, PSE researchers have been developing methodologies—mostly computational, but not all—to be able to optimize whole systems, whether at the unit, plant, or enterprise level. A recent issue of the *American Institute of Chemical Engineers* (*AIChE*) *Journal* [4] celebrated the work of a pioneer in this field, Professor Roger Sargent, who has been working since the 1950s. Sargent has taught many people around the world and has inspired many more, as reflected in the 38 papers in this issue, most of which are relevant to this topic.

This paper considers each of the three phases in turn, and then examines some of the key technical challenges that arise. I will particularly consider research progress and challenges that confront the PSE research community in enabling smart process manufacturing to progress more rapidly. I will reflect not only on petrochemical and commodity chemical manufacturing, but also on specialties and medicines, as well as on contributions that consider wider environmental impacts that are part of the system of systems that we influence. While some challenges and opportunities are similar to those in other manufacturing sectors, there are distinctive differences.

2. Factory and enterprise integration and plant-wide optimization

A key tenet of smart manufacturing is plant-wide optimization, which is not new in process engineering. Process engineers have been considering systems of connected unit operations and looking for better—or even optimized—solutions for a long time, with these activities driving their education.

Plant-wide optimization is at the heart of PSE thinking. The routine use of simulation tools with embedded optimization capability has resulted in plants being optimized for profitability and, increasingly, for minimizing environmental impact while seeking sustainable production. Many tools for process integration have been developed (using a heuristic [5,6], optimization-based [7], or properties-based [8] approach), all of which are based on steady-state models. Process integration approaches have been used to design heat-integrated plants and, to some extent, whole sites [9]. Real-time optimization and model-based control have enabled solutions for optimizing the dynamic behavior of operations in short to medium timescales (see e.g., Ref. [10]). Their implementation is not universal, but it is common, particularly in petrochemical plants [3]. Enterprise integration has also been a goal through the use of whole supply chain models and business software systems.

Many tools are available, and some experience of deploying these tools is discussed in Section 5. Plant-wide optimization is an area that would benefit from more benchmarking and testing to give more confidence. Coordination of multiple enterprises and their customers, most of whom are other businesses within an extended supply chain, remains a challenge. Although this is a technical problem, it is also about relationships: ensuring that the valuable commercial and strategic relationships that have been developed are not disrupted by any proposed technical solutions.

3. Manufacturing intelligence

Smart manufacturing seeks to involve the customer more closely in order to have a more responsive and agile system. Many supply chains producing domestic products now produce on demand, with very short production and delivery timescales. The process industry typically produces intermediate products that are either processed further or used to produce specific products. For example, the plastics industry produces many polymers and many different grades for different end uses. The manufacture of a raw polymer is followed by various stages of treatment, forming, molding, and assembly before the polymer becomes a final product for the consumer. As a result, most process manufacturers have a remote relationship with the end users of the final products. Each stage has its own dynamics, inventory, uncertainty, and commercial drivers. In order to become more responsive and agile, the process industry will need to incorporate information technology (IT)-enabled manufacturing intelligence, with communication occurring between all parts of the supply chain.

Clearly, commercial and technical challenges are associated with this objective. It will require computational methods that can handle multiple stages within the supply chain that support different types of commercial relationships as well as different dynamics at each stage. It will need to be able to take into account technical constraints on flexible manufacturing at each stage, and incorporate the ability to handle uncertainty in demand and production.

The processes will be customer-driven and sensitive to markets, but will include various contractual constraints in dealings between different elements of the supply chain. End-user suppliers will have huge amounts of data on trends in customer demand in order to allow the prediction of expected demands, as they currently do for consumer-oriented product industries. This will shift to incorporating more immediate-demand data, which should rapidly influence manufacturing in all parts of the supply chain. Although immediate-demand data is now common for the fresh food industry and for the processed food industry [11], it would be quite a departure for the chemical, petrochemical, and pharmaceutical industries. Cao et al. [12] presented a data-driven refinery-scheduling model that can incorporate unexpected events from data over a one-day period; however, this approach is still a long way from the overall system responsiveness that is common in the food industry. The aim of smart process manufacturing is to support an agile, robust, and sustainable process industry that minimizes waste while maximizing profitability.

4. Disruptive business models

Perhaps the biggest change in chemical plants over the last few decades was the introduction of the coordinated control systems that are now in place. The basic structure of the set of connected unit operations has not changed much for a considerable period of time. Environmental performance has added significant pressure to the industry, resulting in more integrated design and operation, with less end-of-pipe treatment.

Smart manufacturing could provide more motivation for significant change through small-scale and microscale local production, for example, which would bring production closer to the consumer. This would be essential for the potential development of personalized medicine, and perhaps also for the manufacture of more individualized personal products and smart materials for specialized