Chapter 11
Management Suggestions for Process Control of Semiconductor Manufacturing: An Operations Research and Data Science Perspective

Marzieh Khakifirooz, Mahdi Fathi, Chen Fu Chien and Panos M. Pardalos

Abstract With advances in information and telecommunication technologies and data-enabled decision-making, smart manufacturing can be an essential component of sustainable development. In the era of the smart world, semiconductor industry is one of the few global industries that are in a growth mode to smartness, due to worldwide demand. The promising significant opportunities to reduce cost, boost productivity, and improve quality in wafer manufacturing is based on the integration or combination of simulated replicas of actual equipment, Cyber-Physical Systems (CPS) and regionalized or decentralized decision-making into a smart factory. However, this integration also presents the industry with novel unique challenges. The stream of the data from sensors, robots, and CPS can aid to make the manufacturing smart. Therefore, it would be an increased need for modeling, optimization, and simulation to the value delivery from manufacturing data. This paper aims to review the success story of smart manufacturing in semiconductor industry with the focus on data-enabled decision-making and optimization applications based on “Operations Research” (OR) and “Data Science” (DS) perspective. In addition, we will discuss future research directions and new challenges to this industry.

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11.1 Introduction

11.1.1 Industrial Revolution and “Industry 4.0”

The importance of national manufacturing strategies such as “Advanced Manufacturing Partnership” (AMP) of USA since 2011 [1], “Industry 4.0” of Germany since 2011 [2], “La Nouvelle France Industrielle” since 2013 [3], “Future of Manufacturing” of UK since 2013 [4], “Made in Sweden 2030” since 2013 [5], “Factories of the Future” of European Commission since 2014 [6], “Korea Manufacturing Innovation 3.0” since 2014 [7], “Industria Conectada 4.0” of Spain since 2014 [8], “Smart Industry” of Netherlands since 2014 [9], “Industry 4.1F” of Japan since 2015 [10], “Made in China 2025” since 2015 [11], “Fabbrica Intelligente” of Italy since 2015 [12], and “Innovation and Enterprise 2020 Plan” of Singapore since 2016 [13] have reemphasized the shifting standard of manufacturing and production system which led to the Fourth Industrial Revolution generation.

The industrial revolution stream drives the deployment of novel concepts for factories, new generation of monitoring and collaborating systems, or in general words the smart manufacturing system which it is built upon the CPS [14], “Internet of Things” (IoT) [15], and cloud and cognitive computing [16, 17]. The first step toward the smart manufacturing is the connectivity [18]. All the components in the industry must be connected to a single network, which is being allowed by the CPS and IoT which further confesses information interchange and alliance to attain a flexible and self-adaptive system of production. Moreover, by the integration of information and technologies, cloud and cognitive computing can facilitate the internet-based optimum interface and diagnostics, and can comprehend self-control system (self-learning, self-optimization, and self-awareness).

The fundamental concepts for designing smart manufacturing concerning the discipline and the precise distinction in their respective meaning and utilization are as follows [19]:

- Adaptation to human needs,
- Advance development of products and services,
- CPS,
- Corporate social responsibility,
- New systems in distribution and procurement,
- Self-organization,
- Smart factory.

The concepts mentioned above might experience several kinds of challenges and complications for smart manufacturing that may include technological, economical, social, political, and scientifical issues [20]. This paper aims to review the area of science and technology challenges and point out the industry which is one of the most capital-intensive and complex that is semiconductor manufacturing industry.
11.1.2 Semiconductor Industry and “Industry 4.0”

In this era as a part of the technology roadmap for semiconductors driven by Moore’s law [21] system scaling, there is more and more challenges by the poverty of resources and emergence of information technology. While the goal of semiconductor industry possesses the ability to continue technology migration to maintain overall performance, it is practically challenging to secure this objective due to the demand for appropriate action, together with all the steps required for the design to marketing. Therefore, the seamless interaction of smart manufacturing components such as big data, instant data, information technology (cloud, and multinode sensors), high-performance computing, mobile computing, and autonomous sensing and computing is necessary for driving “More Moore” (MM) technologies [22].

The “International Technology Roadmap for Semiconductors” (ITRS) [23] identified several critical limitations faced by semiconductor industry in the near future, will involve most, if not all, system integration, heterogeneous integration, heterogeneous components, external system connectivity, and factory integration.

ITRS determined a 35–40% less die cost [24], as one of the technical and reliability requirements to sustain MM technology. To achieve this goal, ITRS identified process integration, as one of the essential functional elements and critical challenges to stimulate the need for research and development and to meet a sustainable level of MM technology. The ITRS metrology chapter has underlined that the primary drivers in dealing with process integration are smart automotive, green energy, mobile communication systems, big data, and medical and health technologies [25].

Process integration, in particular, is dealing with technology and requirements associated with several phenomena such as:

- Cross leveraging factory integration technologies, across boundaries to achieve economies of scale.
- Attaining financial development goals while margins are decreasing.
- Increasing global restrictions on environmental issues.
- Dealing with the growing complexity.
- Achieving factory requirements such as capability, cost, equipment reliability, and productivity.
- Meeting adaptability, scalability and extensibility requirements of a profitable pioneering factory.
- Post-conventional Semiconductor manufacturing uncertainty (i.e., manufacturing requirements for new devices, timing uncertainty to identify new devices).
- Constantly responding to ever fluctuating, intricate business demands.

This paper is an extended version of [26] and aims to provide a systematic literature review on the scientific progress of the fourth industrial revolution (“Industry 4.0”—the most pointed national smart manufacturing strategy) with the perspective of OR&DS for semiconductor manufacturing. Most precisely, three research questions are given below.
1. What would be the main challenges in the OR&DS point of view, enabling the industrial revolution in semiconductor manufacturing?
2. How are the OR&DS addressed the science and technology challenges in smart manufacturing?
3. What are the managerial suggestions from the integrated information of reviewed papers to prevail the unseen and future challenges in the path forward to the implementation of smart semiconductor manufacturing?

In Section 11.2, we identify the core challenges of wafer fabrication processes addressed in literature and the reviewing criteria are used for categorizing the findings and studies. In Section 11.3, we detail how these studies are considered the OR&DS fields into the intelligence semiconductor manufacturing, and how particular methods are distributed. Thereafter, from the gap in the literature, we propose some managerial suggestions in Section 11.4, for who are interested in walking into the field of semiconductor intelligence from the OR&DS perspective and in the domain of the “Industry 4.0”. We conclude the paper in Section 11.5, by providing recommendations for further research and align our mindset for the next step.

11.2 Semiconductor Manufacturing Engineering

In semiconductor fabrication facilities (fabs), in order to fulfill the volatile demands of the high-mixed product, the related processes and electronic equipment are employed to produce Integrated Circuits (IC) with the help of a vast number of processing steps, batch processing models, sequence-dependent tool structures, the auxiliary resources [27] and recirculating flows. Therefore, this industry remains the most capital-intensive, for fully automated manufacturing systems [28]. The operations control of manufacturing facilities of semiconductor is known as tough task and is envisaged as one of the most composite manufacturing environments. One solution to deal with these difficulties is to choose the manufacturing and process data to analyze and modeling processes to empower factories in order to intensify an enhanced knowledge of the challenges associated with the production process and to grow visions which can develop prevailing procedures. Hereupon, this is very important to have enough understanding of the prevailing position of research about decision-making-based data engineering technologies in semiconductor industry and recognize fields for future research to maintain the further technologies for IC manufacturing. Therefore, this study aims to detect gaps in the existing works, develop significant research ideas, categorize existing research struggles and form a layout that will deliver different ideas related to the OR&DS area in smart IC manufacturing.
11.2.1 Challenges in Control of Semiconductor Manufacturing Process

Despite the sophisticated production process of wafer fabrication, the OR&DS techniques are using basically for the purpose of throughput enhancement and quality assurance. Regards the general application and intention of using OR&DS techniques, the main challenges in semiconductor manufacturing are categorized as follows:

- Photolithography process as the cutting-edge process and being bottleneck in the production process of semiconductor devices. The main challenge in the photolithography process is a misalignment between laser beam, wafer surface, and patterning mask, the error caused by this misalignment is called overlay error. Overlay error basically has a nonlinear relationship with overlay parameters and overlay parameters are not independent of each other.

- Large number of processing steps, batch tools, random equipment failures, re-entrant flows, sequence-dependent tool setups, and auxiliary resources for some process (i.e., photolithography process) are another source of challenges in semiconductor manufacturing process. Besides these facts, the semiconductor manufacturing equipment is extremely costly and to save the cost and time, the production schedule is mixed, or required to be patched. Dispatching the mixed schedule from equipment with auxiliary resources to cluster tools is one of the interesting topics which is required the state of the art of OR&DS techniques.

- Beside the dispatching, dynamic scheduling in semiconductor itself is a challenging topic. Scheduling system should design in a way such that consider the bottlenecks, reduce the length of production time or in another word the cycle time, maximize the throughput capacity and wafer capacity, and make a balance between the raw material inventory, wafer in process inventory, and finish product inventory.

- Run-to-run (R2R) control of semiconductor fabrication because of re-entrant flow of production process, required a flexible, accurate, stable, and fast optimization process. The main challenge is how to design the R2R control such that can deal with high-mixed dynamic scheduling plan of wafer fabrication. In addition, ITRS projected a roadmap for yield enhancement and error reduction which demanded a highly reliable control system.

- Delay for characteristics measurement from Metrology tools is unavoidable in semiconductor industry. This is a source of measurable and predictable uncertainties, however, make a challenge for process engineers to design a quality control system to deal with this source of uncertainty. Yet, there are several sources of unmeasurable uncertainties which in brief call noise. Dealing with noise is another challenge in semiconductor manufacturing environment.

- The final product in wafer fabrication is integrated circuit packaging for protecting the semiconductor device. The main challenge in this step is designing a packaging system which can protect the integrated circuit from
environmental changes like thermal effect and particle effect, or in general disturbance effect.

- Semiconductor manufacturing process is engaged with chemical processing. Most of the chemical processes are the source of uncertainties, they reduce the lifetime of fabrication equipment, are the source of particle, and change the balance in environmental factors. If the chemical process, doesn’t react well for any reason, this will be affected on the quality of the wafer. One of the challenging processes which deal with chemical reaction is the etching process. The lifetime of etching tools is less than three days, and any uncertainty caused by quality reduction of etching tools affect on edge, depth, and length of the wafer, called critical dimension error.

- The automated material handling in semiconductor fabrication although brings a huge source of benefits to this industry, however, the dynamic scheduling system of wafer fabrication required a dynamic allocation system for material handling as well.

### 11.2.2 Review Method

The methodological review used in this study is the systematic review with the objective of history review, and status quo review [29]. In the first place, the duration of review is narrowed by the milestone of national manufacturing strategies since 2011. We abstracted how with development the national manufacturing strategies semiconductor industry is adapted to vision and evolution of the smart industry. From studies conducted after 2011, especially recent trends since 2017, most prevalent terms selected out of index terms of papers in the field of “smart semiconductor” or “semiconductor intelligence”. The candidate search terms considered to be the most linked items to the scope of this paper are summarized in Table 11.1.

In this paper, the systematic review conducted based on several classification methods to categorize the review papers as follows:

- Organize the type of research methods by Wieringa et al. [30] (including: validation, evaluation, solution, philosophical, opinion, experience).
- classify the areas of manufacturing by Meziane et al. [31] (including: quality management, design, process and planning, control, environment, health and safety, maintenance and diagnosis, scheduling, and virtual manufacturing).
- categorize the form of contribution by keywording method [32] (including: architecture, framework, theory, methodology, model, platform, process, tool).
- classify the type of analytic by Delen et al. [33] (including: descriptive, predictive, and prescriptive).
11.3 OR&DS Problems in Semiconductor

As mentioned previously in Section 11.1, the main challenges and threats engaged in semiconductor manufacturing and smart industry can be answered by OR&DS perspective solutions. Following this section, we provide OR&DS role in smart semiconductor industry by answering some additional research questions in this direction.

11.3.1 By Growing the “Industry 4.0”, How OR&DS Related Research Found Their Way into Semiconductor Manufacturing Intelligence?

The milestone of smart manufacturing by national perspective plans started with AMP by the US government in 2011, which indicates the timeline of our roadmap design horizon based on OR&DS. The following is the historical review of the infrastructure of smart semiconductor manufacturing aligns with the Fourth Industrial Revolution.

- before 2011
  Methods such as

  - data mining [34–42], artificial intelligence [43], heuristic algorithm [44–46], machine learning [47, 48], data development management [49, 50], Fuzzy logic [51], neural network [52–54], linear programming [55], statistical analysis [56, 57], optimization method [58–62], and decision analysis [63–67]

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<tr>
<th>Table 11.1 Main and candidate search terms</th>
<th>Minor terms</th>
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<tr>
<td>Major terms</td>
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<tr>
<td>Semiconductor manufacturing</td>
<td>High-tech industry, integrated circuit, wafer fabrication</td>
</tr>
<tr>
<td>Smart manufacturing</td>
<td>Advanced manufacturing, advanced robotics, agent-based system, augmented reality, CPS, Industry 4.0, integrated manufacturing, open manufacturing, smart manufacturing, virtual factory</td>
</tr>
<tr>
<td>Data science</td>
<td>Artificial intelligence, big data, classification, cloud computing, clustering, data architect, data-driven technology, data management, data mining, data visualization, deep learning, IoT, machine learning, predictive modeling, statistics</td>
</tr>
<tr>
<td>Operation research</td>
<td>Convex optimization, decision theory, dynamic programming, forecasting, game theory, graph theory, linear programming, mathematical programming, nonlinear programming, optimization, queueing theory, soft computing</td>
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and concepts such as

- advanced manufacturing [68], intelligence manufacturing [69], Enterprise Resource Planning (ERP) [70], Overall Equipment Efficiency (OEE) [71, 72], Decision Support System (DSS) [43, 73–77], risk management [78], virtual manufacturing [79, 80], e-manufacturing [81], electronics manufacturing service [82], research and development management [83, 84], digital management [85], and “industry as a whole” [86]

have been appearing in literature to discover the challenges in semiconductor industry and moving forward to the smart manufacturing.

- **2011**
  The birth of AMP.
  Morse [87] reviewed the reputation and future of nanomanufacturing under the AMP plan.

- **2012**
  The birth of “Industry 4.0”.
  The first “International Symposium on Semiconductor Manufacturing Intelligence” (ISMI) launched in Hsinchu, Taiwan [88].

- **2013**
  The first US patent [89] cited the “Industry 4.0” into semiconductor industry.
  The earliest field in order of “Industry 4.0” was in the area of soft computing for scheduling dilemma in semiconductor manufacturing [90].

- **2014**
  Digitalization of “Industry 4.0” has been discussed at AKL congress.
  “Industry 4.0” is introduced as the Fourth Industrial Revolution [91].

- **2015**
  The “Industry 4.0” points of view appeared for the first time in the theoretical and analytical researched. This trend was published in the area of the discrete event [92] and scheduling.

  SEMICON Europa 2015 hold in Germany [93] with the primary context of “Industry 4.0” of semiconductor industry, and among all the highlighted trend in semiconductor intelligence discussed in the area of:

  - “Organization and Goals of the “Industry 4.0” Platform”
    Five frameworks are considered to undertake the organization and structure of the “Industry 4.0”: (1) reference architecture, standardization, (2) innovation and research study, (3) safety of networked systems, (4) legitimate context, and (5) labor training.

  - “Cyber-Physical-Production-Systems at the BTU Model Factory”
    Address the need for fast and adaptive reconfigurable approaches in production planning, logistics and “Manufacturing Execution Control” (MES) for the “Industry 4.0” platform.

  - “The Right Security for the IoT”
    Data security, system integrity, Intellectual Property (IP) and product and service
quality were sanctioned as the requirement for fruitful application of “Industry 4.0”.

- “Technical Visions of “Industry 4.0””
  Explained in what ways semiconductor industry can sustain its role as the innovation driver in the area of manufacturing technologies and how it can grow from “Industry 4.0” initiative.

- “Connecting things and services. How Industry 4.0 increases the benefit of automation at the Bosch 200mm-Waferfab”
  Showed how modularity guarantees a modest role of high-tech automation in a current environment.

- “Interface A: Candidate for “Industry 4.0”? Adoption and Challenges in Semiconductor Industry”
  Introduced InterfaceA as an on-proprietary web technology-based interface which is equipped with data acquisition deliver a flexible interface among manufacturing tools and other IT resolutions and advances the limitation on data collection of the generic model for control of manufacturing equipment interface.

**2016**

Following that, most industrial countries have their road map for Fourth Industrial Revolution and digitized industry, researches focused more intensely on challenges and adversities emerged with semiconductor industry and smart manufacturing. Among all, some important researches are listed as follows:

- Dequant et al. [94]: a comprehensive review on variability in semiconductor manufacturing to meet the “Industry 4.0” obligations.
- Waschneck et al. [95]: a comprehensive review of job-shop scheduling. A discussion on the complexity issue with regards to the delegation of authority of decisions, tractability and adaptableness, incorporation and interacting, human aspects, and other “Industry 4.0” frustrations.
- Moyne et al. [96]: a discussion on the requirements of data analytics, merging, quality, rates, and volumes for digitalis semiconductor industry in control process.
- Tang et al. [97]: a discussion on the application of big data and IoT for reliability assessment in semiconductor industry.
- Weber [98]: an introduction to the e-manufacturing on semiconductor device modeling.
- Herding and Mönch [99]: an introduction to agent-based planning control system for semiconductor.

**2017**

Researches have exponential growth with 100% improvement compared to 2016. Out of over 400 academic papers, the highest percentage of researches were in the field of OR (~50%), following by DS (~25%), roadmap and management field (~12.5%) and image processing (~12.5%) solutions.