Guest Editorial Knowledge-Based Automation for Smart Manufacturing Systems

Smart manufacturing is targeted as the next generation of manufacturing by many national and international strategic development. The increasingly rich production data, the integration and extensive application of information technology, and the intelligent data processing and system modeling methods have collectively enabled smart manufacturing. Building upon them, manufacturing system modeling, knowledge acquisition, design, and real-time control are the key components [item 1) in the Appendix], [item 2) in the Appendix]. It is still one of the really huge challenges to gather data, transform them into information, and derive knowledge out of this information, especially given the requirement of knowledge that can be trusted as manufacturing systems may harm humans and the environment if they come to the wrong conclusion. Despite the learning and derivation of knowledge, it could be modeled beforehand and taken, for example, as an environmental model for online decisions like in deliberative agent-based systems. Nevertheless, for decisions during operation, real-time requirements, dependability, and security issues are to be guaranteed. Finally, for acceptance and trust, humans need to "understand" the reasons behind automated decisions; therefore, explainability or at least a white box description is an issue of such knowledge-based systems.

Emerging opportunities and future directions in enabling knowledge-based smart manufacturing systems are focused. Consequently, methods and principles for manufacturing knowledge acquisition during runtime of manufacturing systems are included as well as advanced human-machine interaction for manufacturing automation.

This Special Issue focuses on how the promise of smart manufacturing could be fulfilled by providing knowledge either from models before operations and/or from data during operations of manufacturing systems. The goals of this Special Issue are: 1) to present the state-of-the-art research in science, engineering, and methodologies for knowledge-based automated manufacturing systems and 2) to provide a forum for experts to disseminate their recent advances and views on future perspectives in the field. We received 35 submissions until March 2019, spanning a range of topics, and after careful reviews, 15 were accepted (three being short papers). The work began at CASE 2017, discussing the main topics and shaping it. The papers are grouped into four sections:

1) machine learning;
2) scheduling of complex manufacturing systems;
3) performance analysis;
4) Industry 4.0.

In the first group of the paper, machine learning [item 3) in the Appendix] approaches are addressed to build knowledge-based systems. Xiao *et al.* explore commonalities of optimization models and use the knowledge to respond quickly to new machining tasks integrating meta-reinforcement learning (MRL) of machining parameters. Specifically, the optimization problem is first formulated as a finite Markov decision process (MDP). Then, the continuous parametric optimization is approached with actor-critic (AC) framework. On the basis of the framework, meta-policy training is performed to improve the generalization capacity of the optimizer. The significance of the proposed method is exemplified and elucidated by a case study with a comparative analysis.

Gao *et al.* develop a novel in situ nondestructive quality evaluation for friction stir blind riveting in joining lightweight materials. This method can solve the small sample size problem that commonly occurs in manufacturing experiments. The proposed method achieves an optimal integration of the tensor decomposition and ensemble learning by utilizing the mutual benefits. Numerical studies and case studies have demonstrated the effectiveness of the proposed method and its superiority over the existing methods.

Yue *et al.* propose two new active learning algorithms for the Gaussian process with uncertainties, which are variance-based weighted active learning algorithm and D-optimal weighted active learning algorithm. Through numerical study, they show that the proposed approach can incorporate the impact from uncertainties and realize better prediction performance. The approach has been applied to improving the predictive modeling for automatic shape control of composite fuselage.

Zhang *et al.* focus on the reduction of energy waste in idle machines. A Gaussian mixture model integrated neural network is proposed to predict the duration of the idle periods for the idle machines. A numerical case study for a five-machine-and-four-buffer manufacturing system is conducted to validate the effectiveness of the proposed prediction model in terms of the energy waste reduction for the idle machines.

Scheduling: Scheduling in complex manufacturing systems is a complicated problem. Cao *et al.* investigate an extended version of a flexible job shop problem that allows the precedence between the operations to be given by an arbitrary directed acyclic graph and develop a knowledge-based cuckoo search algorithm (KCSA). Especially, the proposed algorithm combines offline learning using reinforcement learning and hybrid heuristics with an online search using feedback infor-

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mation. Simulation experiments are performed to validate its effectiveness and superiority over existing methods. The novel paradigm of collaborative automation, with machines and industrial robots that synergically share the same workspace with human workers, requires to rethink how activities are prioritized in order to account for possible variabilities. Casalino *et al.* propose a scheduling method for collaborative assembly tasks that allow to optimally plan assembly activities based on the knowledge acquired during runtime. The scheduler is based on time Petri nets, and the output plan is optimized by minimizing the idle time of each agent. A realistic industrial use-case consisting of a small assembly line with two robots and a human operator confirms the effectiveness of the approach.

Ou *et al.* introduce a method of integrating Q-learning with approximate dynamic programming for gantry work cell scheduling. This gantry scheduling is a sequential decision-making problem and can be presented by MDP.

Qin *et al.* investigate a hybrid flow shop scheduling problem which consists of a batch processor in the upstream and a discrete processor in the downstream. They introduce a genetic programming-based scheduling approach for a hybrid flow shop with a batch processor and waiting time constraint.

Ye *et al.* focus on a joint scheduling problem that considers corrective maintenance due to unexpected breakdowns and scheduled preventive maintenance in a generic M-machine flow shop. To find the optimal job sequence and predictive maintenance schedule with minimal cost, dynamic updates of the predictive maintenance interval based on real-time machine age are proposed.

Performance Analysis: There has been a long-standing problem of the low accuracy for the aggregation based approach for production system performance evaluation, especially systems with multiple bottlenecks, such as "inverted bowl" lines and "oscillatory" lines. Yan *et al.* explore the root causes of low accuracy and develop an improved aggregation method (IAM). Numerical studies indicate that IAM can effectively improve the estimation accuracy of the aggregation method while maintaining a reasonable computational efficiency.

Wang and Ju introduce a novel modeling approach for a multistage geometric serial production line with residence time limits and propose a method that dramatically reduces the complexity of the system. Such a method provides a quantitative tool to effectively evaluate the performance of multistage geometric lines with residence time limits.

Although significant progress has been reached to studying flexible manufacturing systems, most of the research contributes to a steady-state analysis. However, the transient performance is of critical importance for control and improvement of such systems, particularly when the system's setup times cannot be ignored. An analytical method using approximation and aggregation procedures is introduced by Wang *et al.* to evaluate the performance of flexible serial lines with Bernoulli machines and setups.

Yan optimizes the energy consumption in the two-machine Bernoulli line with general bounds on machine efficiencies. The results obtained are extended to the problem of minimizing the energy consumption per job to improve the energy efficiency of the two-machine Bernoulli line.

Industry 4.0: Modern production systems are becoming more and more complex to comply with diversified market needs, flexible production, and competitiveness [item 4) in the Appendix]. Such complexity also implies an increased complexity of human-machine interfaces (HMIs), which are the main point of contact between the operator and the machine. Villani *et al.* propose a general framework for the design of HMIs that adapt to the skills and capabilities of the operator, with the ultimate aim of enabling a smooth and efficient interaction and improving user's situation awareness. Several examples and implementations have been presented to demonstrate the effectiveness of the proposed adaptation patterns in real-world scenarios. Meanwhile, biopharmaceutical manufacturing is an evolving industry with great potential to improve public health, but laden with technical and operational challenges. Lin-Gibson and Srinivasan explore the recent industrial roadmaps and explicitly identify "fully automated facilities" and "knowledge management" as two of the critical enabling capabilities that will drive the biopharmaceutical industry in the next decade. The study also serves as a "call for action" for collaboration among key stakeholders, including the robotics and automation community.

Wei *et al.* develop a decision-level data fusion approach that transforms low-dimensional decisions (i.e., predictions) made based on individual sensor data such as temperature and vibration to high-dimensional decisions. The integration of these high-dimensional decisions is formulated as a convex optimization problem rather than a traditional multivariate linear regression problem. The prediction accuracy in quality control in additive manufacturing and predictive maintenance in aircraft engines was improved.

Wang *et al.* introduce a needs-based product configurator design for mass customization using a hierarchical attention network. Customer needs are expressed in natural language as input to generate satisfactory product variants as output.

Cao *et al.* propose an ontology-based holonic event-driven architecture for implementing loosely coupled, holonic, autonomous distributed systems. Therefore, an ontology model and the corresponding autonomous configuration mechanism are introduced. A demonstration case is furthermore presented to elaborate the effectiveness, efficiency, scalability, and reliability of the proposed approach.

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APPENDIX
RELATED WORK

1) B. Vogel-Heuser and D. Hess, "Guest editorial: Industry 4.0-prerequisites and visions," *IEEE Trans. Autom. Sci. Eng.*, vol. 14, no. 2, pp. 411–413, 2016.
2) *World Economic Forum Annual Meeting, The World Economic Forum*. Accessed: Dec. 2020. [Online]. Available: https://www.weforum.org/events/world-economic-forum-annual-meeting-2016
3) Wikipedia. *Machine Learning*. Accessed: Dec. 2020. [Online]. Available: https://en.wikipedia.org/wiki/Machine_learning
4) Wikipedia. *Fourth Industrial Revolution*. Accessed: Dec. 2020. [Online]. Available: https://en.wikipedia.org/wiki/Fourth_Industrial_Revolution