Journal of Cleaner Production 161 (2017) 69–74

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Impact of advanced manufacturing on sustainability: An overview of the special volume on advanced manufacturing for sustainability and low fossil carbon emissions

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ARTICLE INFO

Article history:
Received 17 May 2017
Accepted 19 May 2017
Available online 19 May 2017

Handling Editor: Yutao Wang

Keywords:
Advanced manufacturing
Sustainability
Design theory and methodology
Energy efficiency
Parameter optimization
Process planning and production scheduling
Supply chain innovation
Product-service systems
Remanufacturing

ABSTRACT

Advanced manufacturing uses emerging technologies to critically enhance not only the economic competitiveness of individual manufacturers but also the sustainability of the whole industrial sector. New materials and technologies require new manufacturing processes and novel analytical models for process controls and parameter optimization regarding cost, reliability, quality, product flexibility, energy consumption, and fossil carbon emissions. The successful adoption of advanced manufacturing for sustainability can only be realized by following a systematic approach from concept development, product design and manufacturing to product delivery and service as well as in forward and reverse supply chain management. This special volume reports on progress of advanced manufacturing on sustainability improvements along the whole life cycle and covers the six themes: 1. Design theory and methodology for sustainability with advanced manufacturing; 2. Energy efficiency assessment and control of mechanical manufacturing systems; 3. Parameter optimization for advanced manufacturing and remanufacturing; 4. Low fossil-carbon process planning and production scheduling; 5. Integration of supply-chain innovations and advanced manufacturing; 6. Sustainable innovation for product-service systems. In addition, this SV introductory article, highlights future research directions, such as the need for energy consumption and emission data for advanced manufacturing processes, optimization models and control schemes, supply chain innovations, and product-service integration.

1. Introduction

The manufacturing industry is responsible for about 29% of the total direct CO_2 emissions from the industrial sector (IPCC, 2014; IEA, 2016). Reducing energy consumption and fossil-carbon emissions in manufacturing processes is crucial for societal sustainability. The IPCC report pointed out that the absence of acceptance of advanced manufacturing processes is a major obstacle for reducing energy consumption and emissions in the manufacturing industry. Advanced manufacturing focuses on the coordination of information, automation, computation, software, sensing, and networking in manufacturing (PCAST, 2011). Advanced manufacturing uses new materials and emerging technologies (e.g., additive manufacturing and digital manufacturing) and is expected to be essential, not only for the economic competitiveness of individual manufacturers at a global scope, but also for the sustainability of the overall industrial sector. New materials and technologies of advanced manufacturing require new manufacturing processes and novel analytical models for process controls and parameter optimization regarding cost, quality and reliability, product flexibility, remanufacturability, energy consumption, and fossil carbon emission reductions. It is expected that those new processes will profoundly transform manufacturing systems, including facility design, scheduling, process planning, material handling, workforce scheduling, quality control, and inventory management. Furthermore, the successful adoption of

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http://dx.doi.org/10.1016/j.jclepro.2017.05.101
0959-6526/

advanced manufacturing for sustainability can only be realized by following a systematic approach from concept development, product design and manufacturing to product delivery and service as well as in the management of the used products at the end of their useful lifetimes. This will also require innovations in forward and reverse supply chain management, which will catalyze changes from labor-intensive and capital-intensive traditional manufacturing to information-based advanced manufacturing.

To fully understand and to maximize the potential of advanced manufacturing to save energy and resources, systematic approaches are necessary to consider all stages of product life-cycles, integrate multiple functions within enterprises, and have effective supply-chain management across enterprises. This Special Volume (SV) of the Journal of Cleaner Production (JCLP) was designed to enhance and to promote societal sustainability and the low-fossil carbon economy, which can result from integration of advanced manufacturing at all stages along product life cycles, including design, process, planning, supply chain management, delivery, and service. This SV covers the following six themes:

Theme 1: Design theory and methodology for sustainability with advanced manufacturing;
Theme 2: Energy efficiency assessment and control of mechanical manufacturing systems;
Theme 3: Parameter optimization for advanced manufacturing and remanufacturing;
Theme 4: Low fossil-carbon process planning and production scheduling;
Theme 5: Integration of supply-chain innovations and advanced manufacturing;
Theme 6: Sustainable innovation for product-service systems.

In total, this SV includes twenty-three papers, which cover all six themes (see Table 1). Since this SV is a virtual SV, the papers were published mainly in volumes 135 and 137 in 2016 and volume 140 in 2017 except that Wu et al. (2016) was included in volume 131 and Watson and Taminger (2017) is still pending. The remainder of this overview is organized following the six themes.

2. Design theory and methodology for sustainability with advanced manufacturing

To enhance the sustainability of our society, unconventional advanced manufacturing processes have been considered for reducing energy consumption and emissions. Whether additive manufacturing (AM) or subtractive manufacturing is more energy efficient for production of a given metallic part has been investigated by Watson and Taminger (2017) with a decision-support model from the aspect of product life cycle. They highlighted the need to develop improved knowledge of the energy embodied in each phase of the additive manufacturing process based on energy-per-unit-volume of production for each material of interest. Energy consumed during machine idle time and energy required to generate feedstock material should be collected and incorporated in any comparison between AM and subtractive manufacturing. Ford and Despeisse (2016) explored the impacts of AM on environmental, social, and economic (business) sustainability based on the cases across four stages of the product life cycle: product and process redesign; material input processing; make-to-order component and product manufacturing; and closing the loop, and summarized the documented sustainability advantages and challenges of AM adoption in each stage. The authors reported that although AM could play a role in the transition towards a more sustainable industrial system, there were risks that unintended consequences with negative sustainability impacts may arise from its adoption and application. Possible negative impacts include uncertain performance of products and parts during the usage phase and over extended lifespan because of low maturity of technology. Therefore, more research is necessary to understand the sustainability aspects of various AM processes and sustainability should be a concern during AM process development, which is evolving rapidly. Existing LCA models for conventional manufacturing processes usually do not consider the design freedom, which is one feature of AM. Therefore, a methodology based on LCA framework was proposed by Tang et al. (2016) for assessing the environmental impacts of AM to cover the design optimization opportunities. The framework covers three stages: design optimization for sustainability, energy and material consumption modeling, and LCA. The framework has the functional descriptions of a designed product as inputs. The proposed framework primarily focused on the binder-jetting AM process and it was evaluated to be helpful for designers to select the most suitable AM process for minimum environmental impacts. The study found that binder-jetting consumes significantly less energy and emits less CO2 than Computer Numerical Control (CNC) milling for the same product. The environmental benefits were mainly realized through design optimization, supporting the argument that design optimization plays a key role in the proposed framework evaluating AM's sustainability. Taking the design of some components in the U.S. aircraft fleet as examples, Huang et al. (2016a,b) considered AM technologies for selected steel, aluminum, nickel, and titanium alloy components and compared their cradle-to-gate energy and GHG emission footprints with the case of conventional manufacturing (CM) technologies for those same components in an analytically consistent manner. The life-cycle inventory analysis of cradle-to-gate energy use showed that producing AM components might use 33%–50% less energy than producing them via CM. Total fleet-wide life-cycle primary energy savings potentials were estimated at 1.2–2.8 billing GJ and the associated cumulative emission reduction potentials of CO2e is 93–217 million tons for the aerospace industry through 2050.

Beyond AM, other alternative manufacturing processes can

Table 1
Summary of papers in this special volume.

Themes	Papers Included in this SV
1: Design theory and methodology	Ford and Despeisse (2016), Huang et al. (2016), Salonitis et al. (2016),Tang et al. (2016), Watson and Taminger (2017), Zhang et al. (2016), Zhou et al. (2016)
2: Assessment and control of manufacturing systems	Jeon et al. (2016), Li et al. (2017), Lu et al. (2016), Palasciano et al. (2016), Shao and Wang (2016), Yan et al. (2016), Yan et al. (2017), Zhou et al. (2016)
3. Parameter optimization	Costa et al. (2016), Huang et al. (2016), Jiang et al. (2016), Li et al. (2017), Vijayaraghavan et al. (2016), Lu et al. (2016), Yan et al. (2017), Yang et al. (2017), Zhong et al. (2017),
4. Process planning and production scheduling	Palasciano et al. (2016), Yan et al. (2016), Yang et al. (2016), Zhang et al. (2016)
5. Integration of supply chain innovations	Ford and Despeisse (2016), Huang et al. (2016a,b), Tang et al. (2016), Watson and Taminger (2017), Wu et al. (2016)
6: Product-service systems	Wu et al. (2016), Yang et al. (2017)