Editorial

Fazleena Badurdeen* and Julius Schoop

Department of Mechanical Engineering,
Institute for Sustainable Manufacturing,
University of Kentucky,
Lexington, Kentucky, 40506, USA
Email: badurdeen@uky.edu
Email: julius.schoop@uky.edu
*Corresponding author

Biographical notes: Fazleena Badurdeen is a Professor in the Department of Mechanical Engineering at University of Kentucky and serves as the Director of Graduate Studies for the Online Manufacturing Systems Engineering MS Program. Her research interests are in sustainable product design, modelling and analysis of manufacturing systems and sustainable supply chains including the development of tools and visualisation techniques to support decision making in these areas. She has published over 150 peer reviewed papers and her research has been funded by federal agencies as well as by industry.

Julius Schoop is an Assistant Professor in the Department of Mechanical Engineering at University of Kentucky and serves as the Director of the Integrated Computational and Experimental Manufacturing Engineering (ICEME) research program and laboratory. He has an industrial background in process optimisation, and continues to maintain close ties to industry. His research interests are in sustainable process modelling and optimisation, including model-based development of advanced materials. His work has been funded by federal agencies, as well as by industry.

Evaluating and improving sustainability performance in manufacturing requires a multi-disciplinary and convergent approach. First and foremost, sustainable manufacturing must consider the economic, environmental, and societal impacts, usually referred to as the triple bottom line (TBL). The lifecycle of a manufactured product can broadly be divided into four different stages: pre-manufacturing, manufacturing, use and post-use. The processes used to manufacture the product, together with the broad system that enables the procurement and conversion of materials into finished products, as well as those used to deliver products to end users, also affect product sustainability. Therefore, sustainable manufacturing requires the consideration of the entire lifecycle of manufactured products. Manufactured products contain significant amounts of valuable resources including materials and embodied energy. For more sustainable manufacturing, it is imperative that these resources (materials and embodied energy) are recovered at the product's end-of-life (i.e., post-use stage). Such value recovery mandates an emphasis on all four lifecycle stages for closed-loop material flow. Maximising value recovery also requires considering potential multiple lifecycles, where the remaining value in products at the end of one life can be recovered and channelled back into the subsequent lifecycles of the same, similar, or even different products. To enable this closed-loop approach to multi-lifecycle material flow, a holistic framework such as that put forward through the

6R methodology (Jawahir et al., 2006) must be followed. The innovation-based 6R (*reduce*, *reuse*, *recycle*, *recover*, *redesign* and *remanufacture*) approach allows for a transformation from the cradle-to-grave concept to a closed-loop multiple lifecycle consideration; it enables a circular economy to concurrently pursue sustained economic growth, environmental protection and societal wellbeing.

Building on prior definitions to incorporate the 6R approach, as well as total and multiple lifecycle considerations, Jawahir et al. (2013) defined sustainable manufacturing to indicate practices that "at the product, process and systems levels must demonstrate reduced negative environmental impact, offer improved energy and resource efficiency, generate minimum quantity of wastes, provide operational safety and offer improved personnel health, while maintaining and/or improving the product and process quality with overall lifecycle cost benefits." Sustainable manufacturing, therefore, is a complex systems problem that requires simultaneous consideration of three integral and interacting aspects: products, processes and systems (Jayal et al., 2010). This means a holistic product-process-system approach that engages all stakeholders is essential to achieve the common objectives for advancing sustainable manufacturing. It also requires optimally designing products, processes and systems by considering the interactions and trade-offs among them.

Thus, circular and total lifecycle-based, practices in manufacturing will enable minimising virgin resource use and maximising secondary feedstock usage to promote economic growth while minimising adverse impacts on the environment or society. Sustainable value creation for a circular economy through sustainable manufacturing, however, will require significant advances in technological capabilities (Badurdeen and Jawahir, 2016). This special issue presents a total of 19 papers that cover various techniques and decision support tools, as well as educational approaches, for advancing sustainable manufacturing at the product, process and system levels for a circular economy.

To enable the manufacture of more sustainable products through die casting processes, Pagone et al. present a multi-criteria decision making approach to assess cost, quality and sustainability performance when they are made with different materials. Kinoshita et al. employ linear physical programming to design disassembly-to-order systems for component reuse and material recycling. Remanufacturing is one the most beneficial strategies to maximise value recovery from end-of-life products. Evaluating parts for suitability to remanufacture is a challenge as the quality of used products can be highly variable. Lehr et al. present an application developed for fast, onsite visual identification of parts using images taken with mobile devices. Numerous risks are also encountered when designing new products. The sustainability benefits of new product designs can be compromised by such unforeseen risk events. Enyoghasi et al. present an approach to identify potential risks that may occur throughout a product's lifecycle and evaluate the influence of interdependent risks using Bayesian belief networks during the early design stage.

Within the framework of the innovation-based 6R approach, sustainable products can be created, using sustainable processes. Thus, the manufacturing process level requires optimised improvements to ensure more efficient resource (material, energy, water, etc.) use, reduced emissions (solid, liquid and gaseous), as well as improved safety and health being assured. When attempting to create sustainable manufacturing processes, there are several possible approaches for characterisation and improvement of 'process sustainability'. Kumar and Melkote present a fracture mechanics approach for reducing subsurface damage in silicon wafers produced by diamond wire sawing. Following the same paradigm, Morczinek et al. compare abrasive water jet technologies for cutting of ceramics, and contrast this non-traditional machining technology with more conventional hard machining strategies. Manoharan et al. characterise the process sustainability of cyclic manufacturing, using hybrid (additive/subtractive) manufacturing as a case study. The results of their model indicate that a hybrid manufacturing process has better environmental performance than a conventional milling process for the four polylactide (PLA) parts evaluated. Focusing on conventional machining, Khatri and Jahan investigate the process performance of conventional flood-cooled, as well more sustainable dry and near-dry minimum quantity lubrication (MQL) machining of Ti-6Al-4V alloy. By avoiding the rapid cooling induced by water-based flood coolant, the MQL-based near-dry cooling strategy resulted in less microstructural stage transformation, indicating reduced negative impacts on the mechanical properties of the machined components.

Uhlmann et al. leverage online process monitoring to adapt cutting parameters in turning of gear steel to achieve constant surface roughness despite progressive tool-wear. They show that more sustainable manufacturing processes can be achieved by integrating expertise/capabilities in physical processes within cyber-physical systems, such as computer numerical controllers (CNC). Building on the increasing interest in additive, subtractive and hybrid manufacturing, Ingarao et al. present a study in which they develop guidelines to compare additive and subtractive manufacturing processes from an energy demand perspective. Uysal et al. provide a novel approach towards minimising the carbon emissions and adverse human health effects from machining of austenitic stainless steel. Their multi-objective optimisation considers various process-level factors, such as tool and coolant consumption, waste generation and energy consumption. Through this comprehensive analysis, an optimised processing strategy based on environmentally benign cryogenic machining is proposed. Nyemba et al. present a study for modelling and simulation of circuit boards to improve throughput, efficiency and productivity during the mineral recovery process.

Another important aspect to ensure product and process sustainability is the manufacturing system at different levels (i.e., the plant, enterprise and the entire supply chain). The system integrates numerous individual processes to transform raw materials into finished products, convey products to end users and also for the reverse flow of products during post-use. Optimising sustainable product or process designs independently could lead to sub-optimal performance at the systems level. Therefore, a more holistic approach that comprehensively considers the sustainability impacts of products and processes on the systems level is essential for sustainable manufacturing.

Shen et al. present a comprehensive review of sustainable supply chain management literature. Their work shows three key opportunities for future advances in sustainable supply chains: holistic integration, cross-system collaboration, and adaptive evolution via continuous innovation. Guidat et al. examine the potential and demand-oriented barriers for remanufacturing products, from the perspective of developing countries, through a case study in Vietnam. They point out the challenges to increasing the use of remanufactured parts particularly when low-cost counterfeit products are widely available in the market. The use of operations research models to design process chains, or production lines, for manufacturing fibre-reinforced plastics to increase sustainability performance and reduce costs is presented by Brillowski et al. In their paper, Götze et al. present a methodology to evaluate human-robot collaboration to assess contributions to improving sustainability and demonstrate by applying the approach to an industrial case study. They emphasise the need to better integrate such evaluation techniques early during the design stage to ensure improved benefits to all stakeholders. Lifecycle assessment (LCA) is widely applied to evaluate environmental performance of products and systems. Kamalakkannan et al. present the findings from a study integrating LCA and social LCA techniques to study the tea manufacturing industry in Southeast Asia. A common thread throughout these contributions is the clear need for more quantitative evaluation of system-level sustainability.

Novel and more advanced practices for educating and training the next generation of manufacturing workforce are essential to implement advanced technologies for sustainable manufacturing. In their paper, Menn et al. investigate a different approach in which augmented reality (AR) could be used to enhance learning in manufacturing operations, such as for product assembly and 3D printing. Gladysz et al. present their findings on developing and teaching a sustainable engineering masters module using a project-oriented teaching and learning framework. They report on the benefits of both face-to-face (physical) and virtual collaborations and using environments that simulate real-life on-the-job conditions for teaching the module.

Overall, the adoption of a sustainability-focused approach towards manufacturing continues to show tremendous potential for improving TBL outcomes across the product, process and systems levels. This special issue documents a collection of recent work that present novel methods and techniques to advance capabilities for sustainable manufacturing.

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