Research Areas and Suggestions for Sustainable Manufacturing Systems

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Abstract. Nowadays, sustainable manufacturing systems gain further awareness and importance because of considering economic, environmental, and social factors. This study presents a comprehensive evaluation to gain knowledge about sustainable manufacturing systems and related basic concepts such as circular economy, industrial symbiosis, eco-industrial parks, and life cycle assessment. Moreover, some suggestions for future research areas are presented to help to fill gaps in this field after many studies from the related literature are evaluated in detail.

Keywords: Sustainability · Sustainable manufacturing systems · Complex adaptive systems

1 Introduction

In the digital age, where market conditions are more dynamic, and customers are more active in the design, firms have started to move towards sustainable manufacturing systems. The firms must have sensitive, smart, and sustainable characteristics to be favored in the market. Being sensitive means that the firms can know the global context and detect interconnected environments that allow them to predict future situations. Being smart is to be an internet-based and a knowledge-based, and hence, a business responds to opportunities and is agile in using information. Being sustainable means that firm activities have positive economic, social, and environmental impacts. These properties are referred to as complex adaptive systems since they have many active elements that are non-linear and non-specific relationships (Chavarria-Barrientos et al. 2018).

The term sustainability was first introduced in 1987. It is expressed as the development that enables today's needs to be met without sacrificing the needs of future generations. Sustainability is explained with three dimensions as environmental, social, and economical (Garetti and Taisch 2012).

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The expected results of processes in sustainable manufacturing systems can be expressed as follows (Kishawy et al. 2018): Energy use reduction, waste reduction/disposal, product strength increase, elimination of health hazards and toxic distribution, higher production quality, recycling, reuse and remanufacturing activities, development of renewable energy sources.

The following changes can be listed to ensure sustainable manufacturing systems (Despeisse et al. 2012):

- Using resources less by significantly increasing the efficiency of natural resources,
- Transition to more biological and natural manufacturing models such as recycling, cleaner manufacturing, and industrial symbiosis,
- Moving to solution-based models such as product service systems and supply chain framework,
- Reinvesting in natural capital using a modification of inputs: the use of renewable and non-toxic materials for non-renewable and toxic.

The circular economy is a system based on reducing, reusing, recycling, and recovering materials in the manufacturing, distribution, and consumption processes (Kirchherr et al. 2017). For the transition to a circular economy, some changes in value chains of many areas such as product/production designs and related models and methods of converting waste to sources are needed. One of the key advantages of circular economy systems is that it keeps the benefit of the products as long as possible and eliminates waste. Even when a product reaches its end of life, it is kept in the economy so that its resources can be used efficiently, and it can create more value (Smol et al. 2015).

Industrial ecology aims to achieve development between industry and the environment. Industrial symbiosis is expressed as a subfield of industrial ecology (Cui et al. 2018). Sharing of by-products' resources and services among firms to add value to processes, improve costs, and environment can be expressed as industrial symbiosis (Gu et al. 2013). In an industrial symbiosis environment, one company's waste can become the raw material of another company (Albino et al. 2016). The industrial symbiosis success is based on companies that work together and have a common goal, including economic and environmental sustainability (Raabe et al. 2017).

The creation of eco-industrial parks has a positive effect on the development of industrial symbiosis, where different institutions can share common services and/or resources, thus reducing waste production and minimizing environmental impacts (Leong et al. 2017). Eco-industrial parks consist of a series of industrial symbiosis that allows the exchange of energy/materials between different industrial enterprises (Kuznetsova et al. 2016).

Life cycle assessment can be used to assess the environmental effects of a product during its overall life cycle (Shuaib et al. 2014). The object of methodologies used in life cycle analysis is to assess sustainability performance through the total product life cycle (Bilge et al. 2014).

In addition to economic and environmental sustainability, Industry 4.0 technologies can be used in creating sustainable value in social dimensions. Although the developments in the manufacturing sector have increased continuously to ensure a better standard of living for people, the recent developments in manufacturing have not been sufficiently sustainable. The developments in the manufacturing environment should also consist of preventive efforts to reduce climate change and energy resources. With intelligent devices and an intelligent manufacturing system, Industry 4.0 has technologies having the potential to reduce production waste, overproduction, and energy consumption. Manufacturing companies are connected through intelligent resources. However, the intelligent manufacturing systems, which are based on intelligent equipment such as large data centers and sensor devices, may have high energy and resource requirements that would negatively affect the environment to operate the system (Kamble et al. 2018).

In this paper, various studies and methods related to some research areas addressed in sustainable manufacturing systems are evaluated in detail. Also, the suggestions for future research areas are presented.

2 Literature Related to Research Areas

In this section, various studies in some research areas related to sustainable manufacturing systems such as industrial symbiosis, eco-industrial parks, and sustainable cellular manufacturing systems are presented chronologically.

2.1 Industrial Symbiosis

Cecelja et al. (2015) present a semantic algorithm built on ontology modeling of information in the field of industrial symbiosis to construct industrial symbiosis networks. The creation of an innovative industrial symbiosis network is achieved by separating features that characterize the relevant resources, solutions, and process optimized for the set of environmental criteria.

Albino et al. (2016) examine the formation of self-organizing industrial symbiosis networks in environments with different levels of uncertainty. In the study, industrial symbiosis networks are introduced as complex adaptive systems, and an agent-based simulation model is presented.

Yazan et al. (2016) present a guide study for the future evolution of industrial areas operating based on industrial symbiosis principles. The proposed model provides the decision maker with appropriate plans to identify and deal with the wastes.

Fan et al. (2017) propose an emergy analysis evaluating the performance of industrial symbiosis to assess economic and technological development. This study examines the industrial symbiosis applications in detail and describes the importance of these industrial symbiosis applications for the overall performance of the industrial park.

Song et al. (2018) use social network analysis for one mining industry park to analyze the amount, structure, and characteristics of the industrial symbiosis network. The authors of the study mention that many studies have dealt with optimizing the flow of materials and energy in industrial parks; however, there are fewer studies that also handled social aspects. Therefore, the study focuses on the social aspect of industrial symbiosis by using social network analysis.

Domenech et al. (2019) present an overview of industrial symbiosis developments in terms of the various factors such as a map of basic networks, size of networks, and geographic distributions.

2.2 Eco-Industrial Parks

Rubio-Castro et al. (2011) present a mathematical programming formulation including various factors such as wastewater containing many pollutants and optimization of a network for minimum total annual cost consisting of fresh water, piping and regeneration costs.

Tan et al. (2011) develop a fuzzy bi-level programming approach for designing water consolidation networks in eco-industrial park centers. With the further expansion of the model, it is possible to take into account the changes in the quality levels of flow rates and process water flows, as well as the introduction of new facilities into the eco-industrial park network.

Rubio-Castro et al. (2012) offer a mixed integer non-linear programming model to develop an eco-industrial park. The optimization method is proposed for the strengthening of multi-plant water networks and the integration of eco-industrial park into a common infrastructure.

Zhang et al. (2016) propose a generalized network optimization method for evaluating waste heat recovery opportunities in eco-industrial parks. Moreover, the method considers various factors such as energy efficiency, CO_2 emission reduction, energy balance, and investment limit.

Tiu and Cruz (2017) propose a model for eco-industrial parks using goal programming to minimize economic and environmental factors simultaneously. The economic costs mentioned in the study combine the piping and operating costs with freshwater, wastewater, and treatment costs. Moreover, the volume and quality of the water used by the eco-industrial park are taken into account as the environmental impact.

Zhou et al. (2017) develop a simulator system called J-Park Simulator for designing and operating of eco-industrial parks. The simulator can be defined as an ontology technology-based decision support system.

Ramos et al. (2018) introduce an approach for designing a utility network in an eco-industrial park. In the proposed approach, the flowchart simulation of each enterprise involved in the eco-industrial park is taken into account. Moreover, the approach considers the total annual cost and the equivalent CO_2 consumption related to the utility consumption in the eco-industrial park.

2.3 Sustainable Cellular Manufacturing Systems

Industry 4.0 forces firms to become more flexible and agile. Dynamic cellular manufacturing systems are considered to meet the requirements encountered in the transition to Industry 4.0. Also, manufacturers and managers have begun to consider environmental and social issues when designing manufacturing systems because of the growing importance of the concept of sustainability (Niakan et al. 2016).

Ghodsi et al. (2015) provide a multi-objective mathematical model to create a stable cellular manufacturing system considering the environmental impacts and costs related to the system. The model proposed in their study considers two objectives: The first objective includes various manufacturing cost elements such as part manufacturing time costs and costs of moving parts. The second objective deals with sustainability criteria.

Aljuneidi and Bulgak (2016) present a mixed integer linear programming model that deals with the reconfiguration issues for cellular manufacturing systems with different periods. In their study, an integrated approach is presented for design issues in sustainable manufacturing systems. In their model, three main cost items that are machine costs, manufacturing and remanufacturing costs, and returned products costs for remanufacturing are minimized.

Niakan et al. (2016) deal with dynamic cell formation problem and present a bi-objective mathematical model for this problem that takes into account worker assignment and environmental and social criteria. In the first objective function of the model, the production and labor costs are minimized while the second objective function minimizes the total production waste such as energy, chemicals, raw materials, and CO_2 emissions.

Aljuneidi and Bulgak (2017) offer an integrated approach that considers remanufacturing, recycling, disposing options needed for sustainable manufacturing system design. Moreover, the mixed integer linear programming model presented in their study includes reconfiguration issues for cellular manufacturing systems.

Iqbal and Al-Ghamdi (2018) aim to save energy consumed in a machine shop environment by optimizing production process assignments and grouping of machines in various cells.

3 Methods Applied in Related Research Areas

Some methods used in research areas related to sustainable manufacturing are presented in this section.

3.1 Eco-Efficiency Approach

The eco-efficiency approach aims to ensure continuous improvement. Moreover, this approach provides efficiently use of resources and energy. The environmental and economic aspects of activities are measured by using the eco-efficiency approach. Eco-efficiency can be defined as a ratio between value and environmental impact (Ferrera et al. 2017).

The method of evaluating resource efficiency considers the basic design elements in the value stream mapping. The activities of value added and non-value added in a processing system are determined. In this approach, efficiency analysis is ensured, and the system performance is measured by evaluating process parameters such as time, energy, and water (Ferrera et al. 2017).

3.2 Optimization Approaches

The optimization approach offers a variety of mathematical programming techniques to gain a best or optimum solution for a problem. In general, optimization problems can be divided into four groups, including constrained/unconstrained, single variable/multi-variable, one criterion/multi-criteria, and linear/non-linear problems (Hersh 2006).

Galal and Moneim (2015) aim to find the optimum product mix to maximize the sustainability of a manufacturing plant. To determine the product mix of the manufacturing plant and maximize the proposed sustainability index, including economic, environmental, and social impacts, they develop a mixed integer non-linear programming model.

The goal programming models can be used as optimization approaches like integer programming models. In a goal programming model, the aim is to ensure a solution that minimizes the deviations from the goals based on the priorities (Hersh 2006). As seen in the study of Kinoshita et al. (2016), for sustainable manufacturing systems, the goal programming can be used for different objective functions such as recycling rate and cost. Kinoshita et al. (2016) propose a selection of environmental and economic disassembly parts according to the goal programming with recycling rate and cost. Their model has two different objectives that are minimizing total recycling cost and maximizing total recycling rate.

3.3 Meta-heuristic Approaches

Some problems addressed in sustainable manufacturing can be expressed as non-polynomial hard that cannot be solved optimally in polynomial time. Therefore, heuristic or meta-heuristic algorithms can be used as solution methods (Ferrera et al. 2017). Meta-heuristic algorithms are generally conducted to calculate near-optimal results of problems that cannot be easily or in no way solved using other techniques that make up most of the problems (Bozorg-Haddad et al. 2017). Meta-heuristic algorithms consist of various algorithms such as tabu search, ant colony optimization, simulated annealing, particle swarm optimization, and genetic algorithm.

The genetic algorithm that is one of the algorithms inspired by natural process is one of the best-known evolutionary algorithm (Bozorg-Haddad et al. 2017). Al-Kindi and Atiya (2018) present a genetic algorithm approach including three different objectives, minimizing manufacturing cost, minimizing carbon dioxide emissions, and maximizing recycling rate, which aims to optimize high sustainability performance.

Non-dominated sorting genetic algorithm is an evolutionary algorithm generally used in multi-objective problems (Niakan et al. 2016). Niakan et al. (2016) propose a hybrid meta-heuristic approach that includes a non-dominated sorting genetic algorithm and multi-objective simulated annealing. In their study, sustainable multi-period cell formation problem with the economic, environmental, and social factors is considered.

The particle swarm optimization algorithm can be used as one of the most common approaches based on swarm intelligence (Bozorg-Haddad et al. 2017). Zhou and Shen (2018) deal with the optimization problem of material delivery tasks in mixed model assembly lines and present an energy efficient scheduling method. They develop a particle swarm optimization algorithm with taboo for solving the problem.

Energy efficient scheduling approaches are used for improving the energy efficiency of manufacturing companies (Gahm et al. 2016). Dai et al. (2013) propose an energy efficient scheduling methodology considering maximum completion time and total energy consumption in a flexible flow shop. They also present a genetic-simulated annealing algorithm.

3.4 Simulation Approaches

A simulation model that takes the decision variables as inputs can be expressed as the computational-related imitation of a real-world system over time (Bozorg-Haddad et al. 2017). However, in the study of Ferrera et al. (2017), some main shortcomings related to the simulation method in the environmental assessment of manufacturing systems are mentioned as follows: Special resource allocation is rarely provided. Materials and direct emissions are not taken into account. High efforts are required for data collection and modeling. There is a lack of methodological guidance in practice. The level of detail is not sufficiently scalable.

Sproedt et al. (2015) develop a simulation-based approach to integrate eco-efficiency improvements into manufacturing systems. Fraccascia and Yazan (2018) propose an agent-based model for simulating self-organizing industrial symbiosis networks using three different scenarios aiming to measure environmental and economic contribution.

Baysan et al. (2019) present a methodology that includes energy value stream mapping, experimental design, and simulation to reduce energy consumption and also aims to improve the energy efficiency of manufacturing systems using lean tools and techniques.

4 Suggestions for Future Research Areas

In this section, some future research suggestions are listed to fill gaps in sustainable manufacturing systems. Due to the importance of sustainable manufacturing systems, the number of studies in the related literature is expected to increase in the future. Some suggestions indicated by various authors in the related literature are presented in Table 1.

Table 1. Some suggestions for future research areas related to sustainable manufacturing

Suggestions
• Considering life cycle assessment and stochastic demand for sustainable manufacturing (Galal and Moneim 2015) • Considering uncertain conditions in dynamic, sustainable cellular manufacturing systems and innovative algorithms to compare the results (Ghodsi et al. 2015) • Establishing a social network model that connects firms (Albino et al. 2016) • Including more factors such as intercellular and intracellular movement costs and recycling option, developing more (re)configuration strategies for hybrid cellular (re)manufacturing systems and generating meta-heuristic approaches (Aljuneidi and Bulgak 2016) • Considering various social and environmental factors such as occupational diseases and job severity and including uncertain, stochastic, and possibilistic parameters (Niakan et al. 2016) • Considering dynamic modeling techniques in industrial symbiosis (Yazan et al. 2016) • Considering meta-heuristic approaches for real size problems and including multi-objectives simultaneously for sustainable manufacturing systems (Aljuneidi and Bulgak 2017) • Increasing resource sharing in eco-industrial parks and focusing on optimization approaches that also consider multi-period and resiliency factors (Tiu and Cruz 2017) • Considering models that also include renewable energies (Ramos et al. 2018)

Additionally, some studies should focus on developing and using a framework and system performance measures, including various sustainability concepts for providing sustainable manufacturing systems. Moreover, some approaches can be addressed together with Industry 4.0 technologies such as cloud manufacturing, big data, and machine learning due to having the potential to solve some problems in sustainable manufacturing systems.

5 Conclusion

New industries and firms are established because of the rapidly growing world population and its demand, and hence, more products enter the markets (Ahmad and Wong 2018). Manufacturing sector consumes a large amount of energy and natural and environmental resources to meet the growing needs (Ahmad and Wong 2018). Therefore, sustainable manufacturing systems that include economic, social, and environmental factors are becoming increasingly important. In this study, many studies from related literature are evaluated in detail after basic concepts related to sustainable manufacturing systems are defined. These studies are presented by grouping as industrial symbiosis, eco-industrial parks, and sustainable cellular manufacturing systems, and then some methods used in the related research areas are mentioned. In conclusion, some future suggestions for research areas shown in Table 1 and other future recommendations that may be helpful to fill the gaps in sustainable manufacturing systems are stated.

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