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Design for manufacturing and assembly/disassembly: joint design of products and production systems

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Design for Manufacturing, Assembly, and Disassembly is important in today's production systems because if this aspect is not considered, it could lead to inefficient operations and excessive material usage, both of which have a significant impact on manufacturing cost and time. Attention to this topic is important in achieving the target standards of Industry 4.0 which is inclusive of material utilisation, manufacturing operations, machine utilisation, features selection of the products, and development of suitable interfaces with information communication technologies (ICT) and other evolving technologies. Design for manufacturing (DFM) and Design for Assembly (DFA) have been around since the 1980's for rectifying and overcoming the difficulties and waste related to the manufacturing as well as assembly at the design stage. Furthermore, this domain includes a decision support system and knowledge base with manufacturing and design guidelines following the adoption of ICT. With this in mind, 'Design for manufacturing and assembly/disassembly: Joint design of products and production systems', a special issue has been conceived and its contents are elaborated in detail. In this paper, a background of the topics pertaining to DFM, DFA and related topics seen in today's manufacturing systems are discussed. The accepted papers of this issue are categorised in multiple sections and their significant features are outlined.

Keywords: design for manufacturing; design for assembly; design for assembly and disassembly; design for additive manufacturing; disassembly line balancing

Introduction

The manufacturing sector is considered an essential part of any country's economic activity and it has a wealth generation mechanism to support the social growth through employment generation, while adhering to sustainability considerations. Since the inception of the first industrial revolution, several changes have been made in the manufacturing domain from the advancement of design to shop floor operations. Among these modifications, Design for Manufacturing (DFM) and Design for Assembly/Disassembly (DFAD) address the issue of waste maintenance, cost minimisation, and remanufacturing. To comprehend the difficulties presented in the current era of manufacturing domain, this special issue has been introduced as 'Design for manufacturing and assembly/disassembly: Joint design of products and production systems'. The Design for Assembly principle aims to reduce the number of parts for minimising the assembly time, fasteners, parts inventory, and overall cost of the products. Initially, DFA was proposed by Boothroyd and Dewhurst in the 1980s with the development of software packages of Design for Automatic and Manual Assembly (Boothroyd and Dewhurst 1983). Later, the concept was further extended to manufacturing features and named as Design for Manufacturing (DFM). The main idea of DFM is to develop a collective understanding of product design and manufacturing. The importance of DFM techniques has been evident in minimising the manufacturing time and operational difficulties by reducing shape and process complexity at the design stage. To envision the practical implication of DFM techniques in advanced manufacturing systems, researchers have developed decision support systems on the basis of manufacturing guidelines, materials, and manufacturing processes as mentioned in numerous case studies. Some research has also been conducted on Design for Quality (DfQ) by considering the dimensions of parameter control, quality yield, quality defect prediction and detection, follow-up of the quality standards, etc. (Das, Datla, and Gami 2000). Further, environmental aspects are also incorporated in this domain and identified as Design for Environment (Ghadimi et al. 2016). The Design for Environment (DfE) is developed to maintain product design and its environmental impact (Fitzgerald, Herrmann, and Schmidt 2010). To capture the emerging trends of manufacturing sector with the advancement of additive manufacturing, the domain is further

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extended to Design for Additive Manufacturing by proposing the guidelines and requirements (Wang et al. 2018). Additive manufacturing is considered as one of the obligatory technologies in the Industry 4.0 era because of its importance predicted in future years (Ivanov, Dolgui, and Sokolov 2018). On the other hand, Design for Disassembly (DfD) has gained popularity from the perspective of design and manufacturing aspects. This concept has extended to Design for Assembly/Disassembly (DfAD). DfAD is important because of repair, maintenance, and recycling considerations for a product. It further includes restoration of parts from End of Life (EOL) or rejected products for reducing the pollution (Johnson and Wang 1998). The two processes of disassembly, destructive disassembly and the non-destructive disassembly differ in that destructive methods focus on materials rather than parts recovery and non-destructive methods focus on parts rather than materials recovery (Kuo, Zhang, and Huang 2000). The operations of assembly and disassembly are opposite in nature and are differentiated by controlling the quality, quantity, and reliability of parts. Therefore, design for disassembly plays a crucial role in restoring and reusing the parts and components of a product as much as possible (Tiwari et al. 2002). A significant volume of research on Design for Disassembly exists because of the challenge in developing a product that can be easily disassembled. Tools for measuring product complexity for assembly and disassembly have been established. In this regard, mathematical models have been developed and solved using heuristics, meta-heuristics, and exact methods along with simulation and other hybrid approaches. The line balancing problems mainly highlight the studies related to task assignment, workstation minimisation, machine allocation, cycle time reduction, etc. (Battaïa and Dolgui 2013). Researchers have also incorporated the functional requirements focusing on product architecture for selection and assessment of different types of mechanical joining methods in disassembly line balancing (Rai and Allada 2003). To further analyze disassembly line balancing problems, mean, standard deviation, and bounds have been included for task processing times, workstations, smoothening rate, and maximum hazard. A hybrid production system has been developed with the layout of two parallel lines of assembly as well as disassembly tasks using common workstations, Mete et al. (2018).

The implementation and development of many of these tools and software incurred a significant cost and time along with an impact on the manufacturing layout (Derakhshan Asl, Wong, and Tiwari 2016). Thus, cost estimation of DFA is an important economic strategy in the design for manufacturing and assembly/disassembly system. In light of this, numerous

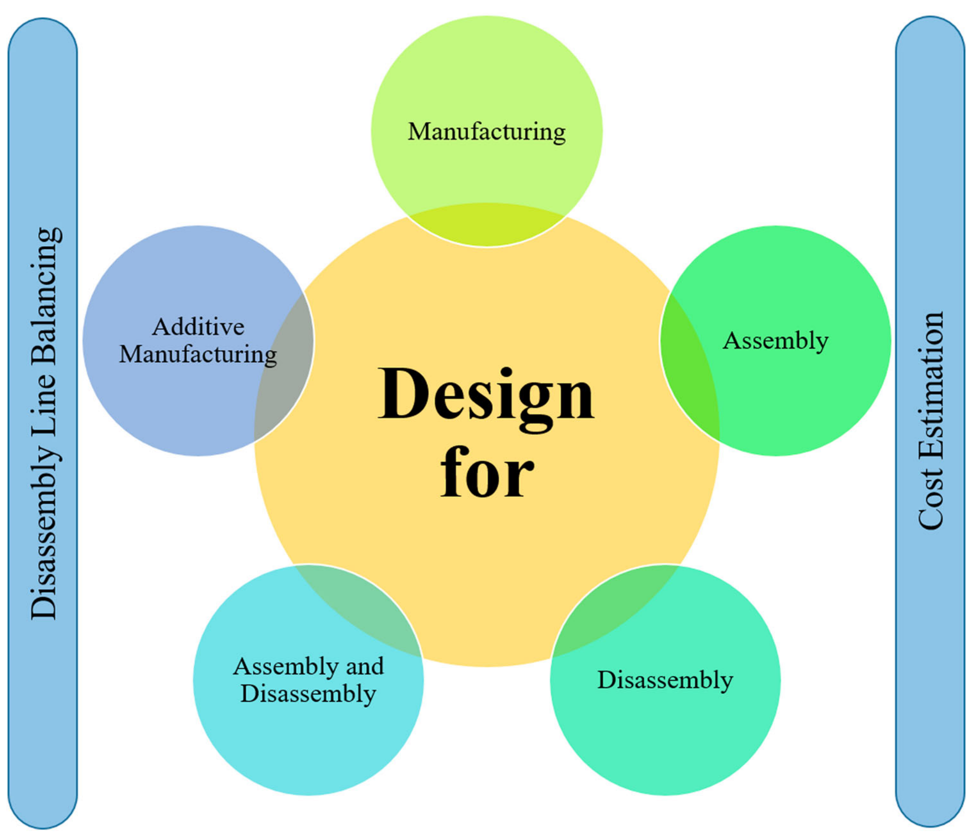

Figure 1. Topics covered in this special issue.

studies have been conducted by addressing the problems of assembly of helicopter blade, transportation fuel systems, etc. To provide accurate cost estimations in the design for assembly systems, several time-based cost models have been proposed by using various level of automation on workstations. To achieve the target of DFA and DFM, a proper setup planning is required by connecting the general process planning and operations planning.

This special issue includes seventeen papers which address several topics categorised in six sections, (1) Design for Assembly and Disassembly (2) Design for Manufacturing (3) Design for Additive Manufacturing (4) Disassembly Line Balancing (5) Cost Estimation, as depicted in Figure 1.

The remainder of this article explains the topics in each section as covered in the special issue.

Design for assembly and disassembly

The importance of disassembly has grown over the years because of the economic and environmental benefits that it brings. It primarily aims at salvaging valuable materials and parts from the End of Life (EOL) or discarded products which otherwise proceed to landfills and pollute the water bodies and air. It further helps in saving the resources and reduces the need for fresh materials (Brennan, Gupta, and Taleb 1994; Agrawal and Tiwari 2008).

Even though it seems that disassembly line is just a reversed assembly line, it has a relatively higher complexity as compared to the latter. One obvious difference between the converging assembly lines and disassembly lines is the divergence where End of Life (EOL) products are separated into their constituent components. However, in disassembly lines, quality, quantity, and reliability of parts and subassemblies are not considered as in an assembly line (Bentaha et al. 2015a). Disassembly could be a partial process as it could be left incomplete because of technical and economic factors. Technical limitations could include factors such as irreversible connection of parts while economic restrictions could include factors such as low revenue from retrieved parts. Though disassembly takes place at the end of the product life cycle, its planning must be embedded in the design of the product itself. Design for disassembly could help in creating a product in a way that enables a high percentage of reuse and recycle. However, products are traditionally designed only for improved assembly and to improve productivity at the production facility (Zhang et al. 1997).

In recent decades, a major challenge that has captured the attention of researchers is the design of a product such that it could be disassembled easily. Easy assembly and disassembly, however, does not go hand in hand. Some of the issues that have to be kept in mind during the design stage include ease of separation, better and improved fastening to avoid permanent integration, modular design for ease in handling and minimising variation in use of material (Zhang et al. 1997; Agrawal et al. 2013). The widely-used approach of design for assembly as well as disassembly was proposed by Boothroyd and Alting (1992) that aimed at reducing the cost of assembly and establishes principles to improve the sustainable performance of the product through disassembly. In line with this, special issue article by Mesa, Esparragoza, and Maury (2017a) described metrics that can measure the complexity of assembly and disassembly in case of open architecture products. Designers can use the tools proposed by the authors for assessing the product's complexity for assembly and disassembly of different modules while the product is under use. Two case studies are used to present the calculations involved in the metrics (Mesa, Esparragoza, and Maury 2017a). The first case study is related to a photographic camera and the second case was related to 3 in 1 machine tools. The authors mention that apart from assembly and disassembly tasks, adjustment tasks must be considered to generate variants of the product in the future.

Disassembly itself has received sufficient focus, and both deterministic and stochastic problems for complete disassembly without any target component have been considered in the literature. For example, Boothroyd and Alting (1992) discuss the complete deterministic case, Gungor and Gupta (1998) discussed the disassembly sequencing when uncertainty is involved when there is no specific target component. Taking the research forward, the paper by Kim, Park, and Lee (2018) dealt with selective disassembly where the aim is to extract one or more target components from the discarded product. Random operation time was considered in a parallel disassembly environment when the problem was to determine the order of disassembly operation. With the objective to minimise the sum of disassembly and penalty costs, the authors develop a stochastic integer programming model. The possible disassembly sequences are represented using an extended process graph (Kim, Park, and Lee 2018). The authors propose a solution algorithm that is based on sample average approximation technique and illustrate its efficacy using the case of handheld flashlight torch.

Another aspect of design for assembly and disassembly includes design and balancing of the line. Taking up the problem of disassembly line design, the paper by Bentaha et al. (2018) considers the impact of partial disassembly, uncertain time for task processing, and the presence of hazardous parts on overall profit maximisation. The authors argue that most of the articles in the literature focus on complete disassembly while ignoring revenue potentials from an incomplete exercise. Therefore, the authors use AND/OR graph for modelling the precedence relationship between tasks (Bentaha et al. 2018). Stochastic programming models are developed and solved using an exact-solution approach that combines an algorithm with

Monte Carlo sampling using Sample Average Approximation (SAA). The efficacy of the proposed technique is established by solving problem instances present in the disassembly literature.

Similarly, Jiao and Xing (2017) have developed a new heuristic-based sequential optimisation model for a sheet-metal clamping activity. Initially, they analyze the parts, clamps and supporting locators to fulfil the purpose of assembly deformation. Then, they evaluate the effectiveness of the clamping plan based on using the proximity of the actual geometry.

Design for manufacturing

Design for Manufacturing (DFM) has been an important topic in product or process development for the past three decades. Researchers have extensively explored this domain and presented numerous variants of DFM including Design for Manufacturability, Design for Production (DfP), Design for Environment (DfE), Design for Variety (DfV), Design for Additive Manufacturing (DFAM), and so on. The basic idea of DFM is to develop the connection or integration between product design and manufacturing (Xie et al. 2003). Hague, Mansour, and Saleh (2004) consider DFM as a mindset or philosophy to make the production process simple and economical by providing the manufacturing input at the initial phase of design of components or whole products. Ramana and Rao (2005) consider DFM as one of the vital elements of Concurrent Engineering. In the research community, the term DFM was initially coined by Stoll (1986) by extending the concept of Design for Assembly (DFA). DFA was invented, implemented, and exercised by Boothroyd and Dewhurst (1983) with the development of the software packages such as Design for Automatic and Manual Assembly (DFA) and Design for Manufacturing (DFM) in 1981 and 1985, respectively. To investigate the utilisation of DFM tools and techniques, Dean and Salstrom (1990) conducted a survey in industries near the San Francisco Bay area. The findings of the research suggest to both industry and academia a refinement of DFM agenda and provide training by analyzing the benefits and effectiveness of DFM techniques. Reducing the manufacturing cost, product complexity, and production time are the targets of DFM as reported by ElMaraghy et al. (2012). According to Dereli, Filiz, and Baykasoglu (2001), DFM is also used for inspecting the critical regions among the component's features to determine their possibility of manufacturing under the given machining operations. Giachetti (1998) creates a decision support system for material and manufacturing process selection (MAMPS) with a database of material characteristics. Chang, Rai, and Terpenny (2010) adopt the concept of Ontologies in DFM to structure the design knowledge and manufacturing guidelines for developing the decision support system in this domain. In the development of Computer Integrated Manufacturing System, the DFM methods have been used for incorporating the design, bending feasibility analysis, process planning, manufacturing, and automatic inspection in tube bending (Ding et al. 2012). To resolve the conflict among product functionality and environmental impact at conceptual design phase, the DFM is further extended to Design for Environment (DfE). Fitzgerald, Herrmann, and Schmidt (2010) have introduced an approach for generating and organising the knowledge relevant to DfE tools for handling the tradeoff between product design, and its environmental impact by analyzing few successful products and designs. The discussed strategies and methods highlight the collective effort of designers and their interconnected tasks of designing the products as well as systems to reduce the design time, production cost, and product complexity along with system agility for achieving market competitiveness. Therefore, it is required to further explore the concept of DFM by publishing a collection of research articles focusing on product complexity, manufacturability, environmental concerns, variety, and variability. In this section of the special issue, a total of four papers have been accepted as briefly described below.

The paper by Goswami (2017) focuses on mainly two vital competitive factors – time to market (TTM) and market share – while addressing the problem of modular engineering. The goal of this work is to support the industries for redesigning the current product line with consideration of product functionality, modularity, and market sharing. The author captures the background of the problem in the literature section and identifies research issues related to TTM, mathematical modelling for product line design, and multiple attributes of the products. A constrained multi-objective optimisation model has been developed for minimising the market time and maximising the product premium. For creating a real-life scenario in the proposed work, the author has adopted a case example of a power drill useful in concrete, metal, and wood works. The insights of the article are demonstrated by forming four assertions related to competitive TTM performance, enlarged product functionality, redesigning effort, and competitive offerings. The author has also presented the future scope with consideration of probabilistic demand, supplier integration in the value chain, and consumer reviews.

The paper by Modrak and Soltysova (2018) presents operational complexity measures (OCM) of a layout design. It proposes a method to measure the operational complexity with consideration of mainly two complexity features: variability of partial complexity and process complexity equilibrium point. In developing the OCM methodology, machine complexity indicator (MCI), balanced complexity indicator (BCI), process complexity indicator (PCI), and complexity equilibrium points (CEPs) are defined and calculated. For an extensive illustration of the work, the authors have presented one theoretical and two real-life case studies in the article. In their findings, the authors highlight the significance of PCI during comparison of two or more dissimilar types of manufacturing processes. The PCI also helps in the classification of the manufacturing processes in size groups. The measurement of deviations among CEPs indicates the economic benefits of the presented method.

The third paper of this section authored by Løkkegaard, Mortensen, and Hvam (2018) introduces a novel approach for developing new architecture using business-critical design rules (BCDRs). The purpose of the article is to tackle the issues of miscellaneous customer demands, short product lifecycle, minimum market to time, and improvement of flexibility. The authors present the visualisation of Products Lines (PLs) and Manufacturing Lines (MLs) in three levels – portfolio, architecture, and module as depicted on the radar plots. To show the efficiency of the work, the BCDRs have been applied on large and global original equipment manufacturer (OEM) who design, produce, and deliver the electrical control units with consideration of product family design and commonality among variants. The authors state that the proposed methodology is able to help the companies in reducing the time-to-market while launching a new item.

Another article in this special issue by Keivanpour and Ait Kadi (2017) fulfils the gap of environmental concerns by proposing a tactical eco-design map for handling the product complexity under the Design for Environment (DfE). A phase-wise systematic flowchart is presented to explain the methodology of eco-design in complex products. The phases include eco-design assessments, database preparation, visualisation of eco-design map, and identification of insights and discussion. To show the implementation of the developed approach, a product of five modules from 20 components and 500 parts is analyzed. The authors use a Self-organizing Map (SOM) in MATLAB environment for applying Clustering Method. Furthermore, the Stock Market Metaphor is utilised for comparing the eco-design features of complex products and financial data of the companies. The authors mention that the presented DfE tools enhance the environmental performance, technical features, and strategic objectives by offering visualisation techniques. However, the adoption of the approach is not easy because of the integration of information from engineers, experts, and managers. The future scope of this work is a 3D extension of treemaps, consideration of multi-criteria methods, and joint application of DfE tools.

Design for additive manufacturing

The concept of Additive Manufacturing was introduced in the 1980's with Stereolithography (Gardan 2016), but it is still considered a relevant topic in academia as well as industry. Per traditional DFA and DFM guidelines, minimising the number of parts in an object is the highest priority, and Additive Manufacturing (AM) is the most suited approach amongst the available manufacturing technologies. Hague et al. (2004) develop a tool to enable the 'Design for Rapid Prototyping' with consideration of material and design. Similarly, by adding the DFM concept in additive manufacturing, Kerbrat, Mognol, and Hascoët (2011) propose combing machining with additive manufacturing. Wang et al. (2018) present the concept of Design for Additive Manufacturing (DFAM) in the IoT-based cloud manufacturing system. The researchers have mainly considered the shape complexity, hierarchical complexity, material complexity, and functional complexity while addressing the problems of Design for Additive Manufacturing. Under this category of the special issue, one paper has been accepted related to material properties.

The paper 'Mechanical properties of biocompatible functional prototypes for joining applications in clinical dentistry' authored by Singh, Sharma, and Davim (2017) mainly contribute to the additive manufacturing with the development of biocompatible fused deposition modelling (FDM). The study emphasises the impact of three parameters of FDM, infill percentage, layer thickness, and speed of nozzle, and examines their mechanical properties. A thermal analysis also carried out on infill percentage, layer thickness, and speed of the nozzle for verifying the results.

Disassembly line balancing

Today, there is renewed focus on product recovery due to the government regulations and consumer awareness about environmental factors. Landfill waste can be curbed by recovering materials using disassembling, recycling, refurbishing and sorting to achieve the preferred product quality level. The disassembly line balancing problem is one of the major sub-problems arising in the disassembly operations in addition to the planning, scheduling, and sequencing (Agrawal and Tiwari 2008). This problem is utilised to allocate a set of tasks to every workstation for every product to be disassembled (Özceylan et al. 2018). The number of researchers and practitioners working in the field of environmentally conscious manufacturing has grown up in the last few decades. The operational complexities of products and uncontrollable nature of quality, quantity, and reliabilities of parts and subassemblies are some of the challenges in DLB problem. Due to these challenges, the balancing phase of DLB needs special attention and efficient tools to optimise performance and effectiveness (Bentaha et al. 2014).

On the basis of different characteristics and properties of DLB problem models, several authors have addressed various sub-problems in DLB. These authors have considered different criteria such as product types, parameter types, objectives, line types, disassembly levels, models and solution approaches, complication, disassembly process, and disassembled product. The single, multiple or mixed product can be disassembled on the disassembly line. Straight, U-shaped, parallel and two-sided layouts are generally utilised for disassembling the products. The minimisation of a number of workstations, eliminating hazardous parts early, minimisation of idle or cycle times, removing high demand parts only, maximisation of line efficiency, maximisation of profit and revenue, and smoothing workload are some of the objectives of DLB problem models. In the case of parameter types, deterministic, stochastic or fuzzy parameters are observed in most of the articles. The disassembly level is an important aspect of DLB and a product may be disassembled partially or completely. Non-destructive disassembly and the destructive disassembly are two processes used for disassembly. Many authors have developed various mathematical models based on linear programming, non-linear programming, stochastic programming, and fuzzy programming (Bratcu and Dolgui 2009; Mishra et al. 2011). These models have been solved by means of heuristics and metaheuristics, exact methods, multi-criteria decision making, simulation, and hybrid approaches. In the following section, papers relevant to the aforementioned criteria are discussed.

Özceylan et al. (2018) present a critical and in-depth analysis of the DLB problems and provided various future directions. In order to tackle the different structure of returned products and task-time variability, Agrawal and Tiwari (2008) proposed a mixed model U-Shaped disassembly line with stochastic task times and employed a novel collaborative ant-colony optimisation algorithm considering bilateral colonies of ants. Altekin (2017) presented two second-order cone programming and five piecewise linear, mixed-integer programming models for stochastic disassembly line-balancing problem with complete disassembly to minimise the number of workstations. The uncertainty of task processing times has been taken into consideration while developing a decision tool to select the best disassembly process for end-of-life product and assignment of disassembly tasks to workstations (Bentaha, Battaïa, and Dolgui 2015b). Hezer and Kara (2015) introduce the parallel DLB problem with single product U-type layout and present a network-based shortest route model for tackling the parallel DLB problem.

In order to balance a mixed-model disassembly line, Ilgin, Akçay, and Araz (2017) propose a linear physical programming-based disassembly line balancing methodology which allows the decision makers to express their preferences using physically meaningful preference ranges. In the domain of profit maximisation of DLB problem, Ren et al. (2017) examine a profit-oriented partial disassembly line-balancing problem and formulate a mathematical model which aims to maximise the profit for dismantling a product in the DLB problem. Bentaha et al. (2018) address a profit-oriented disassembly line design and balancing problem with partial disassembly, existence of hazardous components and uncertain task processing times. Disassembly is an essential process for retrieving the components from a product. Most of the disassembly processes are manually performed because automation has a high investment cost. Often, disassembling a product manually incurs significant labour cost because of the inefficient disassembly design of several products (Duflou, Willems, and Dewulf 2006). Therefore, several researchers are working in the domain of Design for Disassembly (DFD) to simplify and improve the disassembly process. DFD is the process of designing products such that they can be effortlessly, cost-effectively and quickly be retrieved at the end of the product lifecycle. Disassembly processes are closely related to the design specifications of a product. Thus, designers should include the disassembly considerations at the initial stage of product design to make the disassembly process easier (Harivardhini, Murali Krishna, and Chakrabarti 2017). In this special issue of 'Design for manufacturing and assembly/disassembly: Joint design of products and production systems', five papers related to DLB problem are included.

Mesa et al. (2017b) propose a functional characterisation in the form of a framework focusing on open architecture products for the robust selection and assessment of different types of mechanical joining methods. They also suggest a taxonomy of joining methods, a joint complexity metric evaluation and a selection process for the conceptual design. Disassembly line design with the assumption of known mean, standard deviation and an upper bound of task processing times is investigated and a distribution-free model for the DLB problem is proposed by Zheng et al. (2018). They also introduce a decomposition colour graph for better understanding the disassembly process of end-of-life products. A multi-objective mathematical model is formulated to minimise the number of workstations, maximise the smoothening rate and minimise the average maximum hazard involved in the disassembly line (Zhu, Zhang, and Wang 2018). A Pareto firefly algorithm using a random key encoding method based on the smallest position rule is proposed and the algorithm is employed to solve a refrigerator disassembly line problem. A hybrid production system with the layout of two parallel lines with common workstations and assembly as well as disassembly tasks is studied by Mete et al. (2018). The conventional product flow in assembly lines and the reverse flow in the disassembly line are incorporated in this paper. A novel mathematical model to design a hybrid production system and an approximate approach based on ant colony optimisation to solve practical instances is also proposed. Feng, Li, and Sethi (2018) consider an assembly system consisting of two suppliers and a manufacturer, and illustrate the problem as a Stackelberg game where the manufacturer is considered as a leader deciding the wholesale price and the suppliers act as a follower determining production quantity under the pull contract.

Cost estimation

Cost estimation of DFA is an important business level strategy in a changing market environment. Target costing has been applied as a cost management tool in conjunction with the value engineering and other operations management tools (Zengin and Ada 2010). A set of constraints related to manufacturing cost and time need to be considered for estimating the cost of a production system (H'mida and Vernadat 2009). Tuli and Shankar (2015) have delivered a cost estimation model for lean product and process development by developing a decision support system for estimating the product cost and related values. Furthermore, this model eliminates the errors at initial phase and enables the designers to take right decisions from the alternative solutions. In addition, Lin, Lee, and Bohez (2012) present an integrated manufacturing cost estimation method and implement it at the conceptual design stage of the helicopter blade assembly. Mukherjee and Ravi (2005) develop cost estimation model for mould and die with consideration of feature-based method, activity-based costing and parametric costing approaches (Mukherjee and Ravi 2005). Fiorentino (2014) create a cost-driver based approach using several cost drivers at manufacturing phases of die. In addition, James, Spisak, and Colella (2014) conduct a case study of transportation fuel cell systems (FCS) based on the design for manufacture and assembly (DFMA) technique. In the literature, it is observed that cost estimation models have significant importance as per the DFM and DfAD equipped systems.

In this special issue, Salmi et al. (2018) incorporate a time-based cost structure for providing the approximate cost estimation in the early stage design of assembly systems using level of automation (LoA). Ho (2018) estimates the cost for a manufacturing system in collaborative environment of supply chain partners during production of a new product in the competitive market. The study presents cost distribution rate for the competitive market within the product lifecycle. Collaborations among the supply chain partners are considered to realise the final product from an incumbent manufacturer and assembly plant.

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