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CIRPJ 419 No. of Pages 11

ARTICLE IN PRESS

CIRP Journal of Manufacturing Science and Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

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

Designing a Cellular Manufacturing System featuring remanufacturing, recycling, and disposal options: A mathematical modeling approach

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ARTICLE INFO

Article history:
Available online xxx

Keywords:
Sustainable Manufacturing
Sustainable Manufacturing System design
Remanufacturing
Recycling
Mathematical programming

ABSTRACT

While “sustainability” in the manufacturing sector is becoming a pivotal issue, one should consequently expect a growing research interest in design problems in “Sustainable Manufacturing Systems” (SMSs). When a product ceases to be of any further use to the customer in it is current condition, it is relinquished. Accordingly, there is a need for a product recovery options in a sustainable environment. Recycling and remanufacturing are the most two advanced product recovery options. An efficient recycling and remanufacturing network leads to an efficient design of Sustainable Manufacturing enterprise. This article presents a simultaneous investigation of Reconfigurable Cellular Manufacturing Systems and Hybrid Manufacturing-Remanufacturing Systems (HMRSs), and proposes an integrated approach in design optimization, analysis, and process planning aspects as an attempt to address to a large number of design issues for Sustainable Manufacturing Systems. The options of remanufacturing, recycling, and disposing are introduced. A mixed integer linear programming (MILP) model, which considers a classical cell formation problem in Cellular Manufacturing Systems (CMSs), bridged with a production planning problem, in Hybrid Manufacturing-Remanufacturing Systems, while addressing to “reconfiguration” issues for the CMS for different production periods, has been developed. A numerical example is presented to illustrate the proposed model.

Introduction

Due to both economic incentives and legal pressure, more and more companies are going to be engaged in the product recovery business which refers to activities for regaining materials and value added in used products [41]. Recycling and remanufacturing are the mostly used two recovery methods nowadays. Recycling is the process of recovering material after a product has been discarded. Remanufacturing is the reprocessing of used products in such a manner that the product quality is as good as or better than new in terms of appearance, reliability and performance [58]. Manufacturers worldwide are focusing on remanufacturing option due to the fact that remanufacturing conserve the value added to the components during remanufacturing. When the products are collected from the customer and disassembled there will be three kinds of output components: end-of-use, end-of-life, and to-be-disposed components. End-of-use components can be remanufactured, and end-of-life parts can be recycled to be used to produce new parts. In recycling, products are first destroyed and the constituent materials are reused [25]. Hence, through remanufacturing and recycling options, the energy and resources expended in producing the parts and/or raw materials are, by varying degrees, recaptured. Unrecoverable components have to be properly disposed due to the infeasibility of a pure policy of no waste disposal technology [40].

As manufacturing enterprises are getting increasingly focused on sustainability and product recovery, design issues in Sustainable Manufacturing Systems (SMSs) employing appropriate product recovery options are expected to increasingly become amongst the important manufacturing research interests. One important subset of such SMSs is the Hybrid Manufacturing-Remanufacturing System (HMRS). Chen and Abrishami [18] defined the HMRS concept as a system where manufacturing and remanufacturing operations occur simultaneously with shared resources. According to Corum et al. [20], hybrid production systems have lower manufacturing and remanufacturing order variances than the traditional systems (without remanufacturing). Furthermore, the advantage of introducing the remanufacturing option is that the optimum expected cost incurred under mixed

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http://dx.doi.org/10.1016/j.cirpj.2017.04.005
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strategy which combines manufacturing, remanufacturing and disposal simultaneously, is lower than that incurred under pure strategy which combines manufacturing, remanufacturing or disposal alternatively [67]. HMRSs can greatly benefit from the *Reconfigurable Manufacturing* and the *Cellular Manufacturing* technologies. Garbie [31] stressed the appropriateness of the application of reconfigurable manufacturing technologies in a SMS. Additionally, the best layout for such a system is deemed to be the Cellular Manufacturing System (CMS), as recommended by Garbie [31]. CMS does well in the case of mid volume and mid variety demand, and it has high flexibility in dealing with customization and short term life cycle products. On the other hand, *reconfigurability* is a novel engineering technology that facilitates cost effective and rapid responses to market and product changes. Responsiveness enables manufacturing systems to quickly launch new products on existing systems, and to react rapidly and cost-effectively to: market changes, product changes, and system failure [49].

One should note that *Sustainable Manufacturing* requires simultaneous consideration of economic, environmental, and social implications associated with production and delivery of goods. *Sustainable Manufacturing* spans across more than individual unit manufacturing processes, or even process flows at the line level. It is critical that a sustainable supply chain be integrated with Sustainable Manufacturing processes, design, and systems in order to fulfill the *Sustainable Manufacturing* philosophy [38]. Achieving sustainability in manufacturing requires a holistic view spinning not just of the product and manufacturing processes involved in its fabrication, but also the entire supply chain including the manufacturing systems across multiple product life-cycles [43]. Accordingly, the scope, objectives, and contributions of this article should be viewed from this broader *Sustainable Manufacturing* framework in that we infer that designing a manufacturing system featuring remanufacturing, recycling, and disposal options will constitute one important step in reaching the *Sustainable Manufacturing Enterprise*.

In this paper, we will present a comprehensive model in an attempt to integrate all the above-mentioned SMS design aspects together; recycling, remanufacturing, disposing, reconfigurability, and cellular manufacturing in a Hybrid Manufacturing-Remanufacturing System. The reminder of this paper is organized as follows. Section "Literature review" presents a review of the relevant literature. Detailed descriptions of the problem and the proposed model are given in Section "The proposed model". A numerical example, along with in-depth discussion of the results are presented in Section "Numerical example", as well as deep analysis of the model with respect to problem parameters. In Section "Computational experiments", the computational results are shown. Finally, in Section "Conclusion and future research" conclusion and future research are presented.

Literature review

In this section relevant research articles related to Closed-Loop Supply Chains (CLSCs), CMSs, Reconfigurable Manufacturing Systems (RMSs), as well as on Remanufacturing Systems and SMSs are presented. Given the magnitude of published research in CLSCs, CMSs, and RMSs, our review will mostly focus on literature reviews made and published in these areas. In this section, we will also review the relevant literature on remanufacturing systems as well as SMSs.

Closed loop supply chains

Unlike that related to the design and analysis of SMSs, there is a significant amount of research related to design and analysis of closed loop supply chains reported in the literature. Comprehensive reviews of the literature on Sustainable Manufacturing, services, and closed loop supply chains have been made by Guide and Van Wassenhove [35], Chanintrakul et al. [17], Atasu and Van Wassenhove [13] and Aras et al. [10]. In addition, Dubey et al. [26] recently provided a good literature review on supply chain network design from sustainable perspective as well as responsiveness. Amin and Zhang [9] presented a mixed integer linear programming model for designing a closed loop supply chain with disposing, recycling, and repair options. A mixed integer linear programming model for designing a reverse logistics network, where carbon emission is also introduced, is presented by Kannan et al. [46]. Giri and Sharma [34] presented two mathematical models for designing a closed loop supply chain while considering the production quality, algorithms developed for sequential and global optimization where used in order to solve both models. Difrancesco and Huchzermeier [61] provided a guideline for companies on how to switch from an open loop supply chain to a closed loop supply chain. A multi objective mathematical model which considers many aspects and features of closed loop supply chain developed by Govindan et al. [45], three main objectives are considered namely; profit maximization, maximization of the cost saved by CLSC activities, and social benefits maximization. Customer perceptions of remanufactured products in closed loop supply chain studied by Abbey et al. [1].

Cellular Manufacturing Systems

There exist a vast amount of literature on the design of Cellular Manufacturing Systems design. Comprehensive reviews and taxonomies of Cellular Manufacturing Systems, classifications, and design techniques can be found in Refs. [64,66,44,11]. In a robotic Cellular Manufacturing System design, Izui et al. [42] used the genetic algorithm in order to solve the proposed multi-objective layout optimization problem. In their two stage mathematical programming model, by using the tabu search approach, Chang et al. [16] incorporated the cell formation, cell layout, and intracellular machine sequencing issues together, while taking into consideration an alternative process routing, operation sequences, and production volume. Askin [12] presented an overview of manufacturing cell design concepts and introduce a comprehensive formulation for the design of manufacturing cells. In order to accept a new part within an existing manufacturing cell, based on the processing requirements, a novel similarity coefficient was introduced by Garbie et al. [33]. Defersha and Chen [22] proposed a nonlinear mathematical model for designing a CMS, in which they considered various aspects of manufacturing, such as: dynamic cell reconfiguration, work load balancing among cells and machine adjacency constraints. Ahkioon et al. [3] presented a comprehensive mixed integer non-linear model for designing a cellular system. In addition, Ahkioon et al. [4] introduced routing flexibility and system reconfiguration, while designing a CMS. Aljuneidi and Bulgak [7] considered the worker assignments in the CMS design problems. Design approaches for layered Cellular Manufacturing Systems, where one cell can process more than one part family, discussed and compared by Erenay et al. [27]. A framework for designing a lean Cellular Manufacturing System proposed by Kant et al. [47]. Niakan et al. [56] proposed a multi objective model for designing a Cellular Manufacturing System taking into consideration the three pillars of sustainability; namely the economic, social, and environmental pillars, as a further step for designing a Sustainable Manufacturing system. A recent paper, Schonberger and Brown [63] proposed a concurrent production approach (CP) which emphasizes the major role that