Computers & Industrial Engineering 67 (2014) 146–159

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Selection of the optimal configuration for a flexible surface mount assembly system based on the interrelationships among the flexibility elements

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ARTICLE INFO

Article history:
Received 4 March 2013
Received in revised form 25 October 2013
Accepted 2 November 2013
Available online 14 November 2013

Keywords:
Manufacturing flexibility
Surface mount assembly
PCB assembly
Multi-criteria decision-making
Analytic network process
Consistent fuzzy preference relations

ABSTRACT

Flexibility has been widely recognized as a key competitive factor for manufacturing firms coping with the increasingly turbulent manufacturing environment today. Establishing a flexible surface mount assembly (SMA) system is critical for organizations to achieve a cost-effective assembly and gain competitive advantages in the printed circuit board (PCB) assembly industry. To find a practicable operating strategy, a multi-criteria decision-making framework that combines the analytic network process (ANP) with the consistent fuzzy preference relations (CFPR) is proposed to explore the interrelationships among the six dimensions and twenty-one criteria of manufacturing flexibility and resolve the uncertainty and divergence between decision-makers with the least amount of pairwise comparisons. Based on the results of prior analysis, an optimum configuration of a flexible SMA system is suggested for the capacity investment intended by a Taiwan electronics manufacturing service (EMS) provider to quickly respond to dynamic production requirements.

1. Introduction

Manufacturing firms are faced with increasingly intense competition today, which continues to make the manufacturing environment more uncertain and has increased demand variability in the printed circuit board (PCB) assembly industry. To gain a competitive advantage in this rapidly changing market, manufacturing organizations must increase flexibility to quickly respond to changing customer needs and adapt to both internal and external uncertainties (Ketokivi, 2006; Oke, 2013; Pellegrino, 2010).

Surface mount technology (SMT) is predominant in the fabrication of many modern electronic products incorporating the assembly of PCBs. A surface mount assembly (SMA) line may include several substitutable and reconfigurable machines, which may be either the same or different types, with the ability to assemble a variety of electronic products. Today's SMA system should be more flexible to deliver a superior manufacturing flexibility for coping with uncertain demand patterns and short product life spans (Karsak & Özogul, 2005; Lee, Srinivasan, & Yano, 2006). This is especially true for electronics manufacturing service (EMS) providers to establish a flexible PCB assembly system for quickly responding to dynamic production requirements.

Most multi-criteria decision-making (MCDM) problems are usually solved by evaluating the perceived values of the decision-makers based on a set of criteria and a set of alternatives. The perceived values represent the preference intensity for a given alternative in comparison with others. The analytic hierarchy process (AHP) is frequently used to solve MCDM problems. AHP only allows the problem to be resolved with a top-to-bottom hierarchy under the assumption of independency among decision criteria (Ayağ & Őzdemir, 2007; Meade & Sarkis, 1998). However, many real-world decision-making problems often involve interdependencies among the elements of the system (Liou, Wang, Hsu, & Yin, 2011). The analytic network process (ANP), as proposed by Saaty (1996) is the general form of the AHP. Saaty (1996) suggested to solve the problem of interdependency among criteria or alternatives using ANP instead of AHP. ANP has become one of the most comprehensive decision-making methods employed in dealing with complex interrelationships among clusters of elements and between clusters and the interactions originated from human decision-making process in which vague and uncertain information are involved (Saaty, 2000). Its applications have been successfully implemented in many real applications for such things as personnel selection (Lin, 2010), manufacturer-supplier partnership investigations (Theißen & Spinler, 2014), outsourcing provider selection (Liou et al., 2011), and new service management (Lee, Kim, & Park, 2010).

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http://dx.doi.org/10.1016/j.cie.2013.11.005

Nevertheless, a total of $n(n-1)/2$ judgments are required when using the ANP method for n criteria which are evaluated in a pairwise comparison matrix. This may lead to misleading solutions and weaknesses in uncertain information processing (Herrera, Herrera-Viedma, & Chiclana, 2001; Lin & Hsu, 2011). To remedy this problem, Herrera-Viedma, Herrera, Chiclana, and Luque (2004) proposed the consistent fuzzy preference relations (CFPR) method to draw consistent solutions from the MCDM process. The CFPR adopts additive transitive properties to establish preference decision matrices through pairwise comparisons, and allows decision-makers to present their preferences with the least amount of evaluation. Only $n-1$ pairwise comparisons are required to assure consistency at the structural level among n criteria. This leads to better consistency in terms of the preference relations (Chiclana, Herrera, Herrera-Viedma, & Martinez, 2003; Wang & Chang, 2007b). The CFPR approach has been adopted in many studies to efficiently resolve inconsistency problems in MCDM applications (Wang & Chen, 2007; Chao & Chen, 2009).

The evaluation of the interrelationship among flexibility elements and the configuration selection of a flexible SMA system is a complex MCDM problem. Evaluators often adopt linguistic terms to subjectively define or measure flexibility, which are difficult to express numerically in an objective decision-making process. The information needed to determine the configuration of a flexible assembly system may include the understanding and perceptions of experts, the variations in costs and functions related to manufacturing flexibility and production requirements (Ayağ & Őzdemir, 2007; Julka, Baines, Tjahjono, Lendermann, & Vitanov, 2007). In this study, we seek to develop a strategy to solve the aforementioned problems by a MCDM framework integrates the ANP and CFPR methods, to explore the interrelationships among six flexibility dimensions and twenty-one criteria firstly. The goal is to gain an insight of manufacturing flexibility and what are the best practices from the perspective of three Taiwan EMS providers in the PCB assembly industry. Based on these results, the optimum configuration for a flexible SMA system for one of the three Taiwan EMS providers (company O) is then suggested taking into account their capacity for investment to enable quick response times and satisfy production requirements.

The remainder of this paper is organized as follows. Section 2 reviews the literature related to SMA, manufacturing flexibility, and research methodologies. The proposed MCDM framework, which is a fusion of the ANP and CFPR methods, is empirically implemented to explore the interrelationships among the core flexibility elements and the determination of an optimum flexible SMA system in Section 3. Section 4 addresses some important findings derived from this study. Some concluding remarks are provided in Section 5.

2. Literature review

2.1. Surface mount assembly

A typical SMA line layout includes a PCB loader, a conveyor system, a glue dispenser, a stencil printer, a high-speed component placer(s), a multi-purpose placer(s), a reflow oven, and a PCB unloader, as shown in sequence in Fig. 1.

The surface mounting process includes glue dispensing or solder paste printing, component placement, and solder reflow operations, and the formation of strong solder joints (metal connections) between the surface mount devices (SMDs) and the PCBs. The process is totally automated, employing highly dedicated equipment. Production tasks which include production programs (e.g., the component pick-and-place sequence or stencil printing setting) for each machine are carried out according to predetermined sequential steps. Continuous material flow is achieved with an automated conveyor system. After the assembled boards have passed through the reflow oven, they are typically subjected to an automated visual inspection system or an automated optical inspection system to detect potential soldering defects.

The component placers are numerically controlled and can efficiently mount a variety of SMDs in a mass production. The component placers are distributed into five categories according to their capabilities, characteristics, and operational modes, which include dual-delivery, multi-station, turret-type, multi-head and sequential pick-and-place machines. The cost of the component placers varies from US$300,000 to US$1,000,000 based on their designated mechanisms and functions (Ayob & Kendall, 2008). Each distinct type of component placer has different functions, mechanisms and constraints that inevitably affect their ability for assembly of different SMDs onto the PCB. As a consequence of their dissimilar properties (i.e., the component size, weight, and shape), SMDs require the use of specific nozzle types to perform the associated pick-and-place operations. Additionally, a long setup time is needed for the computer-controlled placers to achieve flexibility for the fabrication of electronic products.

Therefore, in practice, the component placement is usually the bottleneck on an SMA line (Ayob & Kendall, 2008) and being the main determinants affecting the flexibility of PCB assembly task arrangements (Duman & Or, 2004). Modern electronic products usually have high component density layouts, and can include hundreds to thousands of SMDs assembled on a single PCB. To effectively resolve the assembly problem, the SMA lines have to be designed and configured with different numbers of component placers for the mounting of various types and numbers of SMDs onto PCBs according to the different board designs and production requirements.

2.2. Manufacturing flexibility

Although an extensive array of studies focusing on manufacturing flexibility over the last few decades. There is still no universally accepted definition of manufacturing flexibility (Beach, Muhlemann, Price, Paterson, & Sharp, 2000). Manufacturing flexibility can refer to a general class of typologies or dimensions (Vokurka & O'Leary-Kelly, 2000). Browne, Duboix, Rathmill, Sethi, and Stecke (1984) identified eight types of manufacturing flexibility, which Sethi and Sethi (1990) extended into eleven commonly cited dimensions (i.e., machine, material-handling, operation, process, routing, product, volume, expansion, program, production, and market flexibilities).

Nevertheless, some definitions concerning typologies of flexibility that have been highlighted in previous studies are overlapping or similar. For examples, Koste, Malhotra, and Sharma (2004) argued that both new product flexibility and product flexibility overlap with product-mix flexibility, because they all exhibit the ability to produce a variety of products and all involve the pursuit of a range of capability (Oke, 2003; Suarez, Cusumano, & Fine, 1996). Material-handling flexibility was determined to overlap with the functions of machine flexibility, which is associated with the options of material or product movement (Koste et al., 2004; Rogers, Ojha, & White, 2011). Ramasesh and Jayakumar (1991) noted that process flexibility is interchangeable with product-mix flexibility. Therefore, Watts, Hahn, and Sohn (1993) postulated that it is preferable to focus upon the primary elements of manufacturing flexibility rather than subordinate ones when arranging manufacturing functions (D'Souza and Williams, 2000). The primary flexibility elements and their interrelationships must be recognized to deliver a superior production flexibility (Petkova & van Wezel, 2006).