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Combining and solving sequence dependent traveling salesman and quadratic assignment problems in PCB assembly[☆]

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ABSTRACT

In this study we undertake the optimization of chip shooter component placement machines which became popular in assembling printed circuit boards (PCB) in recent years. A PCB is usually a rectangular plastic board on which the electrical circuit to be used in a particular electronic equipment is printed. The overall optimization of the chip shooter placement machines leads to a very complicated optimization problem which we formulate here for the first time (without any simplifying assumptions). However, it is possible to decompose the problem into placement sequencing problem and feeder configuration problem which turn out to be sequence dependent traveling salesman problem (SDTSP) and Quadratic Assignment Problem (QAP), respectively. We use simulated annealing metaheuristic approach and the heuristics developed for the SDTSP in an earlier study to solve these two problems in an iterative manner. We also attempt to solve the combined overall optimization problem by simulated annealing and artificial bee colony metaheuristics and compare their performances with the iterative approach. The results are in favor of iterative approach.

1. Introduction

In this study, we tackle one of the most difficult combinatorial optimization problems arising from the use of component placement machines that are used to populate electronic components on printed circuit boards (PCB). These machines brought speed and reliability to the component placement operations however, no matter how fast they are, their operations are needed to be optimized if their capacities are wanted to be utilized to the fullest extent. Therefore, optimization issues regarding the automated assembly of printed circuit boards attracted the interest of researchers for several decades.

A PCB is usually a rectangular plastic board on which the electrical circuit to be used in a particular electronic equipment is printed and the locations of the electronic components to be mounted are identified. PCBs are used extensively in a variety of products such as: computers, calculators, robots, remote controllers, business telephones, cellular phones, and many electronic instruments. In fact, the PCB market revenue is expected to have a compound annual growth rate of 7.3% through 2016 [40].

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The PCB production process is an assembly line that involves solder paste, component placement, and solder reflow operations. A placement is very expensive and therefore, the assembly lines are typically designed such that the placement machine is the limiting resource or bottleneck, which is the key issue for assembly line optimization [13,42]. Nowadays, there are many types of placement machines available, such as sequential pick-and-place, multi-head, dual-delivery, turret type, multi-station, concurrent pick-and-place, etc. [29,30,8,7,26]. Various types of placement machines have different characteristics and restrictions [43,33,44]. Thus, the PCB production scheduling process is highly influenced by the type of SMT placement machine being used. For a complete survey on PCB assembly, see [12,31].

Basically, the operations of these machines yield four major problems [16]. These are allocation of component types to machines, determination of board production sequence, allocation of component types to feeder cells (also called the feeder configuration problem) and determination of component placement sequence. In many other studies, this list is extended or shortened but the last two have great influence and hence importance in optimizing the PCB placement machines [12,41]. All of these problems are interdependent, that is solution of one affects the other. Depending on the principles of the machine, some may be trivially solved while in most cases they yield NP-Complete problems. Hence a solution aiming to achieve the optimum in all problems simultaneously is very difficult to find, if not impossible.

Generally, the determination of component placement sequence is akin to traveling salesman problem (TSP) or its variants such as the Precedence Constrained TSP, the multiple TSP or vehicle routing problem [19,18,25]. On the other hand, feeder configuration problem turns out to be a Quadratic Assignment Problem (QAP) in machines having movable feeder magazine [20].

In this study, we focus on optimizing the operations of chip shooter placement machines because they are widely accepted as the latest technology high speed placement machines [10,27,28,39,6]. Basically, these machines have multiple rotating pick and place heads and a linear feeder carriage that moves horizontally and makes available one of the next components to be placed in line with the placement head. At the same time, the placement head makes a placement over the PCB once the placement location is adjusted below it by the two dimensional movements of the PCB carrier. The operations of these machines yield two major and interdependent problems: the placement sequencing problem and the feeder configuration problem. Given the feeder configuration, the placement sequencing problem actually turns out to be a newly introduced Sequence Dependent TSP (SDTSP) [4] while given the placement sequence, the feeder configuration problem turns out to be a QAP.

The objectives in the two problems are not exactly parallel. For the SDTSP the objective is to minimize the total assembly time needed to complete the assembly of a board. In this regard, it is parallel with the objective of the planner and thus it is a better representative of the real problem faced. However, in QAP, the objective is to minimize the total movement of the feeder carriage which might help in decreasing the total assembly time in return.

For the optimization of chip shooter machines, in the literature there are a few studies which solve the placement sequencing and the feeder configuration problems in an iterative manner [23,35]. In those studies however, a simplified version of placement sequencing problem is assumed which results in a standard TSP. On the other hand, the problems can be solved simultaneously using meta-heuristics. In our study we use both approaches and compare their performances with a SDTSP setting for the placement sequencing problem.

Specifically, we implement the simulated annealing (SA), and the artificial bee colony (ABC) meta-heuristic approaches and use them both for the solution of the combined problem and the solution of the QAP in the iterative approach. The reason for choosing SA is that it performed pretty well for feeder configuration problem in an earlier study [20]. On the other hand, the reason for choosing ABC is that it is relatively a new approach and its performance is not explored yet for combinatorial optimization problems [32].

In this paper, our contribution is providing a nonlinear integer programming formulation of the combined problem of placement sequencing problem and feeder configuration problems arising from the operation principles of chip shooters. In these formulations every detail is considered and no simplifying assumptions are made. We use simulated annealing metaheuristic approach and the heuristics developed for the SDTSP in an earlier study to solve these two problems in an iterative manner. We also attempt to solve the combined overall optimization problem by simulated annealing and artificial bee colony metaheuristics and compare their performances with the iterative approach. The results are in favor of iterative approach. It outperforms the metaheuristic approach by up to 18% where even a 1% improvement in assembly time has a significant impact for the manufacturer.

In the next section the operation principles of chip shooter machines and problems arising from them are given in detail. In section three, we give the notation used for the formulations and then the formulations of the problems. In section four, solution methodologies proposed for these problems are given. Section five includes the discussion on the results obtained on both real life PCB assembly problems and on PCB problems generated synthetically. Section six concludes by providing a summary of the study and directions for further study.

2. Chip shooter placement machines

There are various models of chip shooters with different operation parameters. However, in basic terms, they consist of three parts (see Fig. 1):

- A board carrier: The PCB lies on this carrier which is able to move horizontally and vertically in a concurrent manner. To achieve this concurrency, the carrier is controlled by two independent motors.