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A single machine carryover sequence-dependent group scheduling in PCB manufacturing

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A R T I C L E I N F O

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A B S T R A C T

This paper considers the problem of minimizing the makespan on a single machine with carryover sequence-dependent setup times. A similar problem with multi-machine flow shop usually arises in the assembly of printed circuit boards (PCBs). This research investigates the possibility of processing all components of PCBs using just one machine. By doing so the operational costs of having multi-machines can be reduced, and as a result, finding an optimal solution might be more plausible. The objective is to minimize the maximum completion time of all board groups, commonly known as makespan. The operational constraints are such that all board types within a board group must be completely kitted, as it is traditionally performed by kitting staff, before that board group begins its assembly operation. We introduce the external setup (kitting) time and require that it be performed solely by the machine operator during the run time of the current board group, and thereby completely eliminating the need for kitting staff. The carryover sequence-dependent setup time, namely the internal (machine) setup time, is realized when a new board group is ready for assembly operation and is dependent on all of the previously scheduled board groups and their sequences. To the best of our knowledge, this is the first time the external and internal setup times are integrated in PCB group scheduling research. We develop a branch-and-bound algorithm and a lower-bounding structure. The lower bound consists of two approaches, which enable the algorithm to simultaneously reduce performing unnecessary exploration. In order to test the efficiency of the algorithm, several problem instances with different board groups have been used. The algorithm developed requires a significantly large computation time to optimally solve very large problems. Thus to speak for the efficiency in terms of solving comparable large industry-size problems, we evaluate the deviation of the algorithm from the lower bound which turns out to be very small, with an average of only 6%, in all of the problem instances considered.

1. Introduction

The manufacturing of electronic products has become one of the successful, profitable and thus competitive industries due to increase in demand for such products. Since the main parts of electronic products are printed circuit boards (PCBs), focusing on having efficient PCB manufacturing systems and production plans that are time-cost effective may provide the opportunity to compete among PCB manufacturers. A PCB manufacturing line is equipped with one or more high speed placement machines to assemble a wide range of different components on different PCBs. Because of the nature of this competitive industry, companies operative in this field have always been looking for a time-cost effective throughput and it may be obtained only by employing optimal methods for using the machines and machine operators.

Group scheduling (GS) problems have been used in many industries with the aim of assembling different products, which share similar components. Thus, using GS concept may provide reduced lead times, work-in-process inventories, material handling costs and reduced setup times. This paper addresses the single-machine group scheduling problem with carryover-sequence dependent setup times for minimizing the makespan. To solve the problem introduced in this research, we develop a branch-and-bound algorithm together with a lower bound. This algorithm searches for the optimal solution by identifying appropriate solutions and comparing them with the best-found solution. Also, the branch-and-bound algorithm benefits from a lower-bounding structure in order to avoid the non-promising areas of the solution space that have no potential of identifying solutions with a better lower bound. The lower bound is developed using an approach which ensures that the search procedure

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is led in a direction which may provide a better solution with a lower makespan. Also in order to enable the algorithm to search in those unexplored areas of the solution space, an approach called the *Repeated Solutions Identifier* (RSI) is developed in this paper. The main purpose of RSI is to enumerate non-repetitively.

Generally, any kind of PCB manufacturing problems with different objectives and constraints may be considered as highly complex problems and as a result they have always challenged researchers to find more efficient solution approaches to identify a solution that would enhance the productivity. In doing so, the more we attempt to capture the operational constraints, the lesser the chances are to find an optimal solution for large industry-size problems. In other words, while it is possible to identify an optimal solution for small problems, it may not be possible or even computationally feasible to identify an optimal solution for large problems. Thus, it requires developing lower-bounding techniques that are capable of identifying effective lower bounds (or upper bounds), which is indeed another significant contribution of the research reported in this paper.

Typically, a large number of electronic components have to be placed on a PCB by an automated placement machine and the process is usually performed very quickly and with high precision. There are some feeders on which the components must be loaded before the assembly operations can begin. In order to select an appropriate feeder for each component, a setup operation is required. Since feeder changing for different components requires a setup time, the board types requiring similar components are grouped together with a single setup operation to lessen the frequent and unnecessary need for performing multiple-setups. As a result all board types in a board group are loaded with their required components and are produced sequentially without performing an additional setup.

Traditional research in PCB manufacturing considers the setup time required to transfer from one board group to another as sequence-independent or sequence-dependent and the dependency is assumed only due to the *immediately preceding* board group. This assumption may not accurately capture the operational requirements of a real PCB assembly system. A study of hardware manufacturing with sequence-independent setup times can be found in [1], while Strusevic [2] and Eom et al. [3] consider the effects of sequence-dependent setup times. McGinnis et al. [4] developed a setup strategy named decompose-and-sequence (DAS) method, which focuses only on changing the feeders not required by the next board type, not the next board group. The work by Tang and Denardo [5] considers tool changes, which might appear similar to feeder changes. However, the KTNS (Keep Tool Needed the Soonest) rule they suggested considers only the type of tool change needed, and the position to which this new tool is assigned has no impact whatsoever, unlike in our research.

A special kind of traditional setup strategy which is called group setup strategy can be defined as the setup operation needed for transferring from a board group to another when there are groups of similar board types. The big difference between our work and this kind of setup operation is that it does not take into account of all the previously scheduled board groups for transferring to the next board group, thus the objective function which must be evaluated based on this setup time is entirely different from the actual value in a real situation. The group setup strategy, together with two other setup strategies, is studied in [6]. A group setup strategy for a single machine with the aim of minimizing the total makespan for a given number of batches of PCBs is studied in the work of Yilmaz and Günther [7]. Also a study of minimizing total weighted tardiness on a single machine with sequence-dependent setup times can be found in Neammanee and Reodecha [8] where a memetic algorithm-based heuristic is proposed. Leon and Jeong [9] considered a group setup strategy on a single machine with the objective of minimizing makespan composed of two groups, the feeder change time and the placement time.

The challenge in our research is to capture the operational constraints that arise in PCB manufacturing, which are different from many of the classical studies considered in PCB manufacturing. In reality, the setup time for transferring to a new board group is carried over from all of the previously scheduled board groups. To tackle a real situation in PCB industry, we assume the assembly of a new board group must be provided with a setup time, which is not only dependent on the immediately preceding group, but on all of the previously scheduled board groups and their sequence. Thus, any sequence of the previously scheduled board groups may result in a different setup time for transferring to a new board group. This kind of setup time is called carryover sequence-dependent setup time. The carryover sequence-dependent setup strategy has never been considered in single-machine PCB assembly studies before. In multi-machine group scheduling problems, the only study which considers the carryover sequence-dependent setup times is the work of Gelogullari and Logendran [10]. In their paper, a problem of minimizing the mean flow time is considered where all PCBs are assumed to be static or being available at zero time.

In PCB industries, there is a process of preparing the components called kitting in which components required by different board types must be prepared to be loaded on board types in an area outside of the production line before the assembly operation begins. Traditionally, the kitting operation is performed by kitting staff that might otherwise be able to perform other tasks on the shop floor, thus reducing the total cost of assembling PCBs. During the time in which the machine is kept automatically running to assemble components required by board types of the current group, the machine operator can be tasked with performing the kitting operation of the components required of the next board group. The idea of considering the kitting setup time together with the carryover sequence-dependent setup time in PCB industries is considered for the first time in this paper. We refer to external setup time as the time to perform the kitting operation and refer to internal setup time as the machine setup time required to transfer from one board group to another. This construct provides the opportunity to integrate both the internal and external setups in a way the kitting operations are fully performed by the machine operator. Classical research has assumed the availability of board types belonging to the various board groups at time zero, which is commonly referred to static scheduling in the literature. Thus the work of Gelogullari and Logendran [10] falls under the category of static PCBs as the arrival time of board types, or them being available is assumed to be zero. This leads to a fundamental difference between their paper and our work since the focus of integrating both the external and internal setup times in our research has allowed us to have various board types of the board groups arrive dynamically, as and when they are needed, for assembly on the machine. This concept of assuming dynamic arrival of board types has also enabled us to embrace the idea of the just-in-time manufacturing, which has never been considered in the previous traditional studies.

Typically for assembling components in PCB industries, the placement machines are utilized in pairs without considering the nature of the components themselves. The combined 8 mm feeder capacity of two machines is typically 160–200 components. With this capacity, any kind of PCBs can be assembled on a pair of machines. Operating two machines is the price that PCB manufacturing companies pay to ensure that they are capable of accepting orders of any size. In reality, there are so many PCBs whose components can be assembled on just one machine and