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The modular tool switching problem

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ABSTRACT

This article analyzes the complexity of the modular tool switching problem arising in flexible manufacturing environments. A single, numerically controlled placement machine is equipped with an online tool magazine consisting of several changeable tool feeder modules. The modules can hold a number of tools necessary for the jobs. In addition to the online modules, there is a set of offline modules which can be changed to the machine during a job change. A number of jobs are processed by the machine, each job requiring a certain set of tools. Tools between jobs can be switched individually, or by replacing a whole module containing multiple tools. or a whole module, containing multiple tools can be replaced. We consider the complexity of the problem of arranging tools into the modules, so that the work for module and tool loading is minimized. Tools are of uniform size and have unit loading costs. We show that the general problem is NP-hard, and in the case of fixed number of modules and fixed module capacity the problem is solvable in polynomial time.

1. Introduction

In the assembly of printed circuit boards (PCB), flexible component placement machines are used to mount components onto a bare PCB. The placement machines are highly automatized, configurable and suitable for the assembly of a wide range of PCB product types. The flexibility and configurability of these machines results in various efficiency problems. The planning and control of PCB assembly machines is a task that consist of multiple interconnected problems (see Ayob & Kendall, 2008; Crama, 1997; Crama, van de Klundert, & Spieskma, 2002).

One of these problems arises when several different PCB product types are manufactured on a single machine, with each product type requiring a specific set of component types to be placed on the boards. The component placement machines are equipped with a feeder unit that can hold a sufficient number of component input reels to manufacture a single product type. Due to the capacity constraints of the feeder unit, it is not possible to load at once all the component reels required for all the PCB jobs.

In the case of multiple PCB types, as one PCB type batch ends, the content of the feeder unit must be reconfigured, by loading the component reels required for the next PCB type. This replacement can occur only between processing jobs, because the machine must be stopped. Replacing one component reel causes extra delay in production, and the total delay between two jobs is determined by the number of component reel swaps.

The above discussion deals with the organization of job switching in the context of PCB assembly manufacturing. The same situation occurs in many other Flexible Manufacturing Systems (FMS), where tools (above component reels) are stored in tool magazines (feeder units). Minimizing the setup delay is known in literature as the *Tool Switching Problem* (TS) (see Tang & Denardo, 1988), in this more general context.

Many variants of the tool switching problem have been extensively studied in literature. The order in which the jobs are processed may be fixed or arbitrary. If the job order is arbitrary, the tool switching cost can be further reduced by finding a better job sequence (this is also known as the *job sequencing problem*). The cost of switching tools may be uniform or tool specific. Further, the size of the tools may be uniform, or tool specific, causing fragmentation of the feeder unit in the latter case. The job sequencing problem is NP-hard even in the case of uniform tool sizes and equal switching costs (Crama, Kolen, & Oerlemans, 1994).

When the job sequence is fixed, the tool switching problem with uniform tool sizes and equal change costs can be solved optimally in polynomial time by the means of the KTNS procedure of Tang and Denardo (1988). When tool sizes are non-uniform, the problem is NP-hard even for the fixed job sequence (as shown in Crama, Moonen, Spieskma, & Talloen, 2007, where the problem is called the tool loading problem).

Over the past decade, component placement machines have increasingly employed modular feeder units to improve versatility, flexibility and efficiency of these equipments. Such examples are Fuzion from Universal, iFlex from Assemblon, and BM/NPM from Panasonic. These machines employ several feeder module units that are online at the same time. The modules contain component reels, and can

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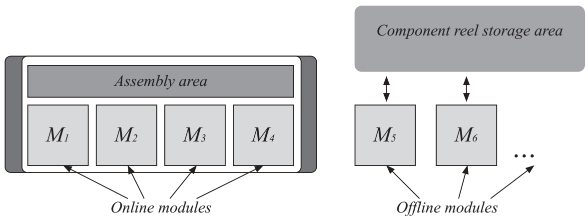

Fig. 1. A placement machine with modular component feeder unit. Individual modules (M_i) can be replaced in one step with offline modules. The content of offline modules can be prepared in parallel with the processing of the previous assembly batch.

be swapped with readily available offline modules, that have been prepared in parallel to the processing of the current assembly job.

The present work focuses on the practical problem of switching component reels (tools) in a single placement machine containing multiple removable feeder modules of equal capacity. Each feeder module contains a number of component reels (typically 40), and one or more online modules can be replaced by another module which has been prepared to contain a different set of component reels. Swapping a feeder module with another one incurs a much smaller delay (cost) than swapping some individual component reels. Therefore, switching components in groups can reduce the overall setup time required when transitioning between PCB job types. Component reels can also be swapped individually in the online modules if that is preferred (in case of small setup changes), making the problem more difficult than the basic tool switching problem.

The problem of switching tools in groups to improve production efficiency is not considered by the tool switching literature to our knowledge. Let us call this problem the *modular tool switching (MTS) problem*, where in the present context, tools are component reels required to manufacture PCB jobs (see Fig. 1). In the present work, the tools have *uniform sizes* and the delay caused by switching tools to online modules is also uniform across tool types. The delay of switching a feeder module is a constant, different from the tool switching delay. We show that by introducing online and offline modules into the tool switching problem, the problem becomes NP-hard even in the case of a fixed job sequence, uniform tool sizes and equal tool switching delays.

1.1. Literature review

The tool switching literature focuses mainly on solving two problems. The first one deals with a fixed job sequence (see Matzliach & Tzur, 2000). The second problem also includes the task of finding an order of the jobs that minimizes the tool switching costs. The general tool switching problem was introduced by Tang and Denardo (1988). They proposed a polynomial time, optimal algorithm called Keep Tool Needed Soonest (KTNS), for the case of a fixed job sequence, uniform tool sizes and tool switching costs.

The case of fixed job sequence, uniform tool size, and tool specific changeover cost was discussed by Privault and Finke (1995). They show that if the changeover costs are of the form d_{ik}, where tool i is inserted after removing tool k, then the problem can be solved optimally by formulating it as a min-cost flow problem.

For non-uniform tool sizes and arbitrary magazine capacity C Stecke (1983), the problem becomes NP-hard even for a fixed job sequence, as shown by Crama et al. (2002). Heuristic methods for solving the problem were given in Hirvikorpi, Salonen, Knuutila, and Nevalainen (2006) and in Tzur and Altman (2004). However, when the magazine capacity C is fixed, Crama et al. (2002) show that the problem admits a polynomial-time optimal algorithm, albeit with a very large exponent, making it unpractical for industrial application.

For the case of job sequencing with uniform tool sizes, Crama et al. (1994) show that the problem is NP-hard, even for $C = 2$. Heuristics to solve the problem have been proposed in Bard (1988), Hertz, Laporte, Mittaz, and Stecke (1998), Djellab, Djellab, and Gourgand (2000), Salonen, Raduly-Baka, and Nevalainen (2003), Song and Hwang (2002) and Zhou, Xi, and Cao (2005). The approximability of the problem was discussed by Crama and van de Klundert (1999). Al-Fawzan and Al-Sultan (2003) use a tabu search approach to find better job sequences, that minimize the number of tool switches.

For the case of job sequencing with non-uniform tool sizes, two NP-hard problems (tool switching and job sequencing) are combined into a single optimization objective. Heuristics to solve the combined problem have been discussed in Matzliach and Tzur (2000) and Raduly-Baka, Knuutila, and Nevalainen (2005).

While the case of modular tool magazine and extra offline modules is an important practical application, previous research on it seems to be missing.

1.2. Problem definition

Next, the definition and assumptions of the *modular tool switching problem* (MTS) are given, in the context of loading component reels into feeder modules of a PCB assembly machine. Suppose, that a list J of n PCB assembly jobs is given. The jobs are processed by a single component placement machine. The order in which these jobs are processed is fixed by the list J. Each job j ($j \in [1 \ldots n]$) requires the insertion of a set T_j of different component types (these are considered tools) and the components of a job are supplied by the means of a modular feeder unit (tool magazine).

The feeder unit has sufficient capacity to hold all the component reels required for a job. The feeder unit contains a number of F changeable modules (typically from 2 to 6). Each module has the same fixed capacity C to hold the component reels. A number of E offline modules are available in the vicinity of the machine. The capacity of each offline module is the same C, and their content can be manually rearranged, in parallel to the processing of the current job, having no impact on the production time.

The available capacity in all the online modules is $F \cdot C$, and it is not sufficient to hold all the component reels for all the PCB types: $|\cup_{j \in [1 \ldots n]} T_j| > F \cdot C$. Therefore, component reel changes are possibly required between jobs. Reels can be changed individually, incurring a delay of t_c for each change, or in group by changing a whole module, incurring a delay of t_m for each module change. By changing a module, one can change a total of C component reels in one step (C is typically 20–40) and incur a single t_m delay that is much smaller than a $C \cdot t_c$ delay of changing all reels of a module while changing jobs. (In practice the t_m/t_c ratio tends to be between 2 and 4, and it is 2.5 for the machine types studied here.) Therefore, arranging component reels into offline modules, so that they can be swapped in a group when transitioning to the next job, is advantageous in terms of the incurred delay.

Next, the parameters and assumptions of the MTS problem are listed:

- C the capacity of a feeder module. All feeder modules have equal capacity.
- F the number of online feeder modules.
- E the number of offline modules. It is assumed that at least one offline module is available. Otherwise the problem simplifies to the well known tool switching problem which can be solved optimally by the means of the KTNS procedure.
- n the number of PCB assembly jobs. The order in which jobs are processed is given and fixed by list J.
- T_j the set of component types required for job j. It is assumed that a single job will always fit into the available online capacity ($|T_j| \leq F \cdot C$), and that there is no sufficient online capacity for all the jobs: ($|\cup_{j \in [1 \ldots n]} T_j| > F \cdot C$). All components are of uniform size, i.e. demand a unit space (single slot) in the feeder module.