Design of manufacturing cells: operation assignment in printed circuit board manufacturing

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We consider an operation assignment problem that arose from a printed circuit (PC) board assembly process. Components can either be inserted on boards manually or by machine. The objective is to determine an assignment of components (operations) to a set of capacitated machines (with the remainder of the components inserted manually) to minimize the total set-up and processing cost for assembling all boards. The problem can be formulated as a mixed integer linear program, but is too large to be practically solved. For the case of one machine, we present two different solution heuristics. We show that while each can be arbitrarily bad, on average the algorithms perform quite well. For the case of multiple machines, we present four different solution heuristics. We discuss implementation of our results at Hewlett-Packard.

Keywords: Manufacturing, operation assignment

1. Introduction

Along with the advent of powerful automated manufacturing systems has come a host of complex design and control problems. These problems include machine grouping, part type selection, operation assignment, fixture allocation, and tool loading (Stecke, 1983). In this paper we focus on an operation assignment problem, where the objective is to determine an assignment of operations to a set of capacitated machines to minimize total set-up and processing cost. These costs may be expressed in terms of time units required for set-up and processing, yielding an objective equivalent to minimizing the average time required to produce each board.

Our operation assignment problem is somewhat related to the tool loading problem of Flexible Manufacturing Systems (FMSs), identified by Stecke (1983). The problem is to allocate operations and required tools among groups of machines, while meeting technological and capacity constraints of the machines. Stecke suggested a number of different objectives, including balancing machine workloads and minimizing the number of movements of jobs between machines. One formulation of the FMS tool loading problem, introduced by Kusiak (1985), is an assignment problem with a linear objective—that of assigning job types to machines in order to minimize total variable processing cost per job, subject to machine capacity constraints. Other formulations are given by Ammons et al. (1985), Chakravarty and Schtub (1984), Kouvelis and Lee (1991), and Sarin and Chen (1987). The FMS tool loading problem considers the variable cost associated with each operation; in contrast, our assignment problem includes not only variable processing cost per operation, but also a one time set-up cost per job if any operations of a given job are carried out on a particular machine. This set-up cost is incurred because of the particular technology we are considering, as described below. In addition, the FMS tool loading problem is a tactical problem that is concerned with objectives such as maximizing throughput or minimizing makespan, given a
known set of jobs to be processed, while our problem is a
ger-term planning problem that has the objective of
minimizing expected production cost (or, equivalently,
minimizing the average expected cost per unit produced)
given estimates of expected future demand.

Related tool (component) assignment problems in
printed circuit board manufacturing have also been con-
sidered. For example, Crama et al. (1991) considered a
component assignment problem in which a required set
of component insertions is assigned to a group of machines in
order to minimize the maximum workload of any one
machine, where machine workload equals the sum of
component insertion time plus any tool switching time
required to insert all the assigned components. Ahmadi et
al. (1986) and Tang and Denardo (1988a and b) considered
related component assignment problems which are con-
cerned with minimizing component switches between jobs.

Our problem differs in that the objective is to minimize
production cost, and there is no switching of components,
as we describe below.

The problem we analyze arose from one faced by
Hewlett-Packard in one of its printed circuit (PC) board
assembly operations; a similar assembly process is de-
scribed in Welker (1988). The unit assembles a number of
different PC boards by inserting the appropriate com-
ponents. The process is not fully automated because a wide
mix of boards is produced, and the volume of production
does not justify automation. Component insertion in this
hand load cell can either be performed manually or by a
semi-automated machine. The manual insertion process
work as follows: the board is set up on a tray, the operator
locates the assembly instructions for this particular board in
an instruction manual, and then follows the assembly
instructions, obtaining individual components from
labeled bins that are located in the assembly area, and
inserting them manually onto the board. For the semi-
automatic insertion process, the board is set up on a tray on
a semi-automated component insertion machine, and the
operator enters the board identification number into a
computer that controls the machine. Then the machine
identifies, from a set of internal component bins, the bin
containing the first part that is needed, opens the bin, and
moves it to a location near the operator. At the same time,
the machine shines a point of light on the location on the
board where this component is to be inserted. The operator
removes a component from the open bin, inserts it
manually onto the board, and presses a switch indicating
that another component is now needed. The machine then
closes and removes the bin, pulls up the bin containing the
next component that is required, and the process continues
similarly until all components have been inserted. Note
that there are no set-up savings associated with producing
two of the same type of boards sequentially; each board
requires set-up on any process where it undergoes com-
ponent insertion.

Both set-up and processing are faster (i.e., cheaper) on a
machine. However, the machines have a limited capacity
for holding different components, and only a limited
number of the machines are available. Furthermore, it is
costly to change the assignment of components to bins of
the machine: such changes involve not only physical
replacement of components in the bins inside the machine,
but also reprogramming the machine's computer. In addi-
tion, costly reductions in board quality and yield may occur
when the production process is changed (e.g., when a
particular board is now assembled using a different
machine). Thus, component assignment must be per-
formed before any PC boards can be assembled, and
cannot be changed during the entire assembly process of all
boards. It is not possible to change the set of components
on the machine until all boards have been completely
assembled. In a typical situation (such as that faced by
Hewlett-Packard), a one-time tooling of machines (i.e.,
assignment of components to bins) for the next year or half
year is determined based on annual or semi-annual ex-
pected (high estimates of) demand for different types of
boards. At the end of that time period, new demand
estimates are generated, and the machines may be re-
tooled.

As is typical in PC board assembly operations, a large
number of different PC boards, assembled from an even
larger number of components, must be produced; for
example, in one manufacturing process at Hewlett-Pack-
ard, almost 500 types of PC boards are produced from some
4000 different parts. Another feature of interest is that
some components are used much more frequently than
others. Figure 1 shows cumulative component usage as a
percentage of total usage for a sample of 30 boards
assembled at Hewlett-Packard from over 300 components.
Finally, there is a low but not insignificant level of
component commonality between boards. Figure 2 shows
the distribution of the number of different boards that
components are used in for a representative sample of 58
boards and 180 components. In this example, approxima-
tely 35% of the components are used in more than one board,
and 5% of the components are used in 5 or more boards.