Production Planning in Printed Circuit Board Assembly

Jouni Smed

ACADEMIC DISSERTATION

To be presented, with the permission of the Faculty of Mathematics and Natural Sciences of the University of Turku, for public criticism in the Auditorium of the Department of Computer Science on January 26th, 2002, at 12 noon.

University of Turku
Department of Computer Science
FIN-20014 Turku, Finland
2002

Supervised by

Professor Olli Nevalainen, Ph.D.
Department of Computer Science,
University of Turku
Turku, Finland

Professor Timo Järvi, Ph.D.
Department of Computer Science,
University of Turku
Turku, Finland

Assistant Professor Ville Leppänen, Ph.D.
Department of Computer Science,
University of Turku
Turku, Finland

Mika Johnsson, Ph.D.
R&D Manager,
Assembly Engineering
Valor Computerized Systems (Finland)
Turku, Finland

Reviewed by

Professor Pekka Kess, Dr.Tech.
Institute of Industrial Management,
University of Oulu
Oulu, Finland

Professor Jyrki Nummenmaa, Ph.D.
Department of Computer and Information Sciences,
University of Tampere
Tampere, Finland

ISBN 951-29-2241-X
ISSN 1239-1883
Painosalama Oy, 2002
Turku, Finland

Abstract

In this thesis, we approach production planning in printed circuit board (PCB) assembly from theoretical and practical point of view. We discuss technical aspects of PCB assembly concentrating on problems associated with component insertion. We review the literature and form a hierarchical classification scheme for production planning problems encountered in PCB assembly. In addition, we enlist the subproblems associated with each problem class and discuss their relevance. This study also includes three software systems developed for real-world production planning in PCB assembly. We present each of these systems, analyze their design and implementation, and review their effect on the production.

Keywords

printed circuit board assembly, production planning, electronics assembly, flexible manufacturing systems, setup strategy, fuzzy scheduling, group technology, multiple criteria, simulation

Acknowledgments

This dissertation is a record of a six-year journey into the world of industrial algorithms. First and foremost, I wish to thank professor Olli Nevalainen for introducing this world to me and for guiding me throughout the years. My gratitude extends to professor Timo Järvi and Turku Centre for Computer Science for providing me with the freedom to delve into this world without financial worries.

A second batch of thank-yous goes to two fellow travellers. None of the systems would have been of any use, if there has not been Mika Johnsson and his zest for solving real-world production planning problems. None of the systems would have ever come to be, if there has not been Tommi Johtela and his insight into problem modeling, software design and programming. I am grateful—and surprised they have put up with me for so long.

I thank the rest of the research team and everybody who have supported my work: professor Timo Leipälä, professor Timo Knuutila, assistant professor Ville Leppänen, Mikko Puranen, Kari Salonen, Timo Häyrinen, Risto Lehtinen (Nokia Display Products), Jouni Lehtinen (Teleste Corporation), and the folks at Valor Computerized Systems (Finland).

Lastly, I am obliged to Timo Kaukoranta, Antti Koski and Harri Hakonen for their creative and recreational support.

TURKU, FINLAND
DECEMBER 28, 2001

List of Original Publications

I Smed, Johnsson, Johtela, and Nevalainen, "Techniques and Applications of Production Planning in Electronics Manufacturing Systems", Technical Report 320, Turku Centre for Computer Science, December 1999. To appear in C. T. Leondes (ed.), *Computer-Aided Design, Engineering and Manufacturing (CADEM) Systems Techniques*, Gordon and Breach.

II Johtela, Smed, Johnsson, Lehtinen, and Nevalainen, "Supporting Production Planning by Production Process Simulation", *Computer Integrated Manufacturing Systems*, 10(3):193–203, 1997.

III Häyrinen, Johnsson, Johtela, Smed, and Nevalainen, "Scheduling Algorithms for Computer-Aided Line Balancing in Printed Circuit Board Assembly", *Production Planning & Control*, 11(5):497–510, 2000.

IV Smed, Johnsson, Puranen, Leipälä, and Nevalainen, "Job Grouping in Surface Mounted Component Printing", *Robotics and Computer-Integrated Manufacturing*, 15(1):39–49, 1999.

V Smed, Johtela, Johnsson, Puranen, and Nevalainen, "An Interactive System for Scheduling Jobs in Electronic Assembly", *International Journal of Advanced Manufacturing Technology*, 16(6):450–9, 2000.

VI Johtela, Smed, Johnsson, and Nevalainen, "A Fuzzy Approach for Modeling Multiple Criteria in the Job Grouping Problem", Technical Report 227, Turku Centre for Computer Science, December 1998.

VII Salonen, Johnsson, Smed, Johtela, and Nevalainen, "A Comparison of Group and Minimum Setup Strategies in PCB Assembly", in Hernández and Süer (eds.), *Proceedings of Group Technology/Cellular Manufacturing World Symposium—Year 2000*, pp. 95–100, San Juan, Puerto Rico, March 2000.

Contents

List of Tables

List of Figures

List of Acronyms

BB	Branch and Bound
BOM	Bill Of Materials
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CIM	Computer Integrated Manufacturing
CM	Contract Manufacturer
CRP	Component Retrieval Problem
CSP	Constraint Satisfaction Problem
DES	Discrete Event Simulation
DFM	Design For Manufacturing
FCSP	Fuzzy Constraint Satisfaction Problem
FFL	Flexible Flow Line
FMS	Flexible Manufacturing System
GA	Genetic Algorithm
GFFL	Generalized Flexible Flow Line
GSM	General Surface Mounting
GT	Group Technology
GUI	Graphical User Interface
IP	Integer Program(ming)
JIT	Just-In-Time
KCNS	Keep Component Needed Soonest
KTNS	Keep Tool Needed Soonest
LP	Linear Program(ming)
MRP	Material Resource Planning
MADM	Multiple Attribute Decision Making
MCDM	Multiple Criteria Decision Making
MODM	Multiple Objective Decision Making
NC, NCR, NCX, NCZ	Numerically Controlled Codes
OEM	Original Equipment Manufacturer
OWA	Ordered Weighted Averaging
PCB	Printed Circuit Board
PCBA	Printed Circuit Board Assembly
PNN	Pairwise Nearest Neighbor

PWB	Printed Wiring Board
SA	Simulated Annealing
SDS	Sequence Dependent Scheduling
SMD	Surface Mount Device
SMT	Surface Mount Technology
TS	Tabu Search
TSP	Traveling Salesperson Problem
WIP	Work-In-Process

Chapter 1

Introduction

> PLAN, *v.t.* To bother about the best method of accomplishing an accidental result.
>
> —Ambrose Bierce, *The Devil's Dictionary*

Electronics technology is pervasive in modern society, and electronic devices can be found every place imaginable: in office equipments, domestic appliances, cars, locks, navigational instruments, surgical instruments, musical instruments—just to name a few. In the current situation, there could hardly exist a more competitive industry. Fierce global competition and rapid technological advancements require continuous improvement in quality and productivity, and, as a result, the product life cycles have become ever shorter. Product longevity and mass production are privileges of few, while most of the manufacturers—even the big names—have to adapt to quick changes. This dynamic production results in that the production planning problems in electronics assembly are hard and need to be solved quickly.

The production planning problems provide a basis for software systems. Obviously, a general system, which would suit to different environments, would be ideal, but in reality we have to impose restrictions on the problem in order to solve it. This work is limited to problems arising from electronics manufacturing, more specifically, from printed circuit board (PCB) assembly.

Let us first briefly examine what production planning is.

1.1 Production planning

Production planning refers to the process of establishing strategies for producing finished products so that manufacturing resources are used efficiently. It represents the link between engineering design and shop floor manufacturing, which involves four kinds of activities [20, 22]:

- planning, where the production is planned without specifying every detail, with a relatively long time horizon and an aggregate view of the manufacturing system,
- scheduling, where the routing and timetabling of the various tasks associated with the production are worked out,
- loading, where the work for a single operator or machine is timetabled, and
- progressing, which is the checking that all is proceeding according to plan.

Production control refers to the tasks required to ensure a proper implementation of the production plan despite the occurrence of random events [20]. It includes the systematic planning, coordination and direction of all manufacturing activities to ensure that products are made on time and at reasonable cost. To put it briefly, the difference between production planning and production control is that production planning is about anticipating future events, conjuring up a plan and following the plan, whereas production control is about reacting to events as they occur during the production.

Production planning decisions are frequently formulated in a hierarchical framework where they are decomposed into a number of more easily manageable subproblems, which relate to a variety of decisions concerning long-term (*strategic*), medium-term (*tactical*) and short-term (*operational*) planning [30, 60]. The main reason for the decomposition is that the production planning problems are usually too complex to be solved globally, whereas it is easier to solve each subproblem one at a time. The solution to the global problem can then be obtained by solving the subproblems successively. Naturally, this solution is not likely to be globally optimal, even if all subproblems are solved to optimality. Nonetheless, this approach is a productive and popular way to tackle hard problems. We shall return to this subject in more detail in Chapter 2.

To realize a software system for production planning we have to establish an interaction between the computer, which performs the scheduling and loading activities, and the human who supervises the entire planning process. Especially in dynamic production environments, production planning is best realized by a synergy of the computer's algorithms and the human's effective internal heuristics. In other words, the personnel responsible for production planning should remain in control and be allowed to use their experience and intuition and let the computer do the onerous tasks.

This idea is illustrated in Figure 1.1 [113]. The main part of the production planning system is the model, which is an idealized description of the production environment. This model can be made visual or its information can be used to form an objective function. A production planning algorithm

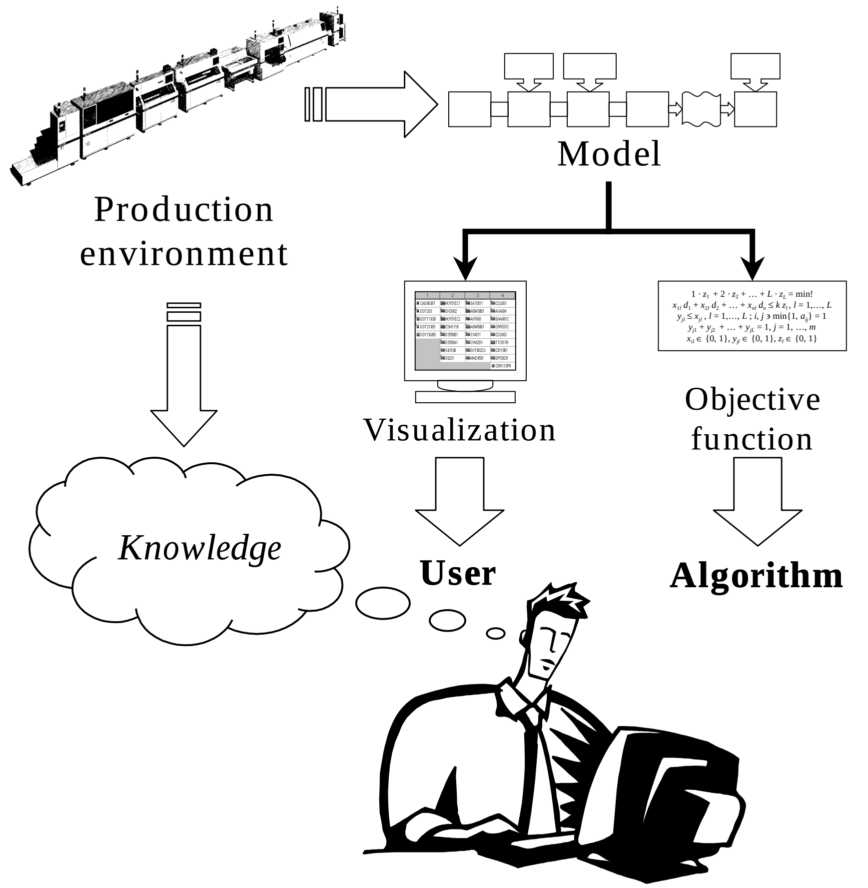

Figure 1.1: Production planning activities can be done by a user or an algorithm. The algorithm can solve a combinatorial problem inexhaustibly but it relies solely on the model. The user tends to try only few possible solutions before choosing one but has often useful “outside” knowledge about the problem environment.

uses the objective function to evaluate the solutions and, consequently, it sees the model only. Conversely, the user usually has some outside (i.e., not modeled) knowledge about the problem (e.g., has the machinery working properly or is it the last week before summer holiday). Since the model can never be accurate enough, the user must have the final word on the production plan, and the software system should provide the user with sufficient support for making the decisions.

The production planning applications described in Chapter 3 are based on this idea of distributing the planning activities. The algorithmic research coincided with the system design, which led us to adopt the approach. The systems discussed in this work were developed for production planning problems arising from printed circuit board assembly, which we shall review next.

1.2 Printed circuit board assembly

A *printed circuit board* (PCB), which connects components, integrated chips and other devices together, is the heart of every electronic apparatus. PCBs have evolved since the 1950s towards smaller and smaller board sizes with more functions, reliability and flexibility [82, 125]. For this reason, PCB assembly requires complete agility and reliability, which are only achievable with the use of robotics [55]. Manual assembly methods may provide the needed flexibility, but they cannot provide the reliability and speed of robotic automation. When properly tooled, robotic assembly allows quick change from one product to another, handling a higher mix of products with reliability rates well in excess of non-robotic systems.

PCB assembly is characterized by designs that range from simple and low-value board assemblies to very complex and high-value ones. Production volumes for different products vary in a very wide range—from millions to less than ten. One assembly system may encounter the assembly of PCBs with frequent design changes in small-batch production, whereas another system may assemble PCBs with a design that is fixed for six months or even longer. A recent development in PCB assembly is the growing role of contract manufacturing [97]. Many original equipment manufacturers (OEMs) have abandoned the assembly line in favor of outsourcing the manufacturing functions to contract manufacturers (CMs). CMs differ from OEMs in that they build a variety of products for many different customers, whereas OEMs build only their own products. Despite the wider product variety and more dynamic product demand, CMs are expected to operate more efficiently than OEMs. This trend further emphasizes the importance of developing better production methods and systems.

Although this thesis is not about the assembly process itself, some technical details and terms are needed in order to understand the problems at hand. Table 1.1 gives definitions for the technical terms used in this work. For further details on the fundamentals of PCB assembly, see the first publication reprint [113] or [47, 82, 136].

Table 1.1: Glossary of PCB assembly terms [82, 119, 126]

adhesive	a substance capable of holding material together by surface attachment
axial-lead component	a through-hole component where the leads run through the central axis
bare board	an unpopulated PCB
card	a PCB of smaller dimensions
chip	an individual circuit or component

continued on next page

continued from previous page

chip shooter	a high-speed surface mount component handler and placer
component	an individual functional element in a physically independent body (e.g., resistor, capacitor, or transistor)
conveyor	a machine that supports a PCB and moves it from one location to another
device	an individual electrical circuit element that cannot be further reduced without destroying its intended function
double-sided assembly	a PCB assembly with components on both sides of the substrate
feeder	an equipment that supplies components in the proper orientation and sequence for picking by a pick-and-place head
fiducial	a feature on the PCB used to provide a common measurement point for steps in the assembly process
head	an element of pick-and-place machine that positions (e.g., rotates, feeds back x-y location, and moves on z-axis) nozzles to pick and place components
manual assembly	an electronic assembly process carried out by an operator primarily using hand tools, including a soldering iron
multiple-lead component	a collection of components housed in one package and inserted as one unit (e.g., dual-in-line package and pin grid array)
nozzle	a tool selected to interface between pick-and-place head and each particular part being placed
panel	an array of, usually identical, separate circuits fabricated on a single substrate
pick and place	an assembly operation where a machine orients and places components on their pads on a substrate prior soldering
placement	a manual, semiautomatic, or automatic location of a component, device, or chip at its intended position
printed circuit board (PCB)	a pattern of conductors printed (screened) onto the surface of an insulating base to provide interconnection for parts

continued on next page

continued from previous page	
radial-lead component	a through-hole component where the leads exit from only one end of package
reflow soldering	a heat radiation or conduction soldering that brings PCBs into contact with heated air to melt solder
semiautomated assembly	a process for the manufacture of an electronic assembly carried out by an operator with a combination of manual and automated equipment
solder	a low melting point alloy, usually of lead and tin, that can wet copper, conduct current, and mechanically join conductors
solder paste	a homogenous combination of solder particles, flux, solvent, and a suspension agent used in the surface mount reflow soldering process
substrate	a supporting insulating material upon which parts, substrates, and elements are attached
surface mount technology (SMT)	a manufacturing process that attaches components on the surface of PCB
through-hole technology	a manufacturing technology, where the wire leads of components are inserted through predrilled holes on the PCB
turret head	a pick-up and placement head with multiple pick-up locations that generally rotates parallel to the PCB

In a typical PCB assembly line, the production is organized into successive work phases. In addition to component insertion and soldering, the phases may include inspection and testing. The PCBs are transferred from one phase to another either manually (e.g., in magazines which can hold 10–100 PCBs) or with a conveyor belt. Figure 1.2 illustrates the phases of a surface mount component placement line. However, the production plant may involve several lines and different types of component placements, which is discussed in Section 2.4.

In the component placment machine, the substrate is either placed by an operator or automatically transported to the staging area. After that, the components are picked from the feeders with nozzles by using a vacuum and usually realigned either mechanically or optically before they are placed into the appropriate locations on the board. Some machine types are flexible in the sense that they can handle a wide range of different substrate sizes as well as a wide range of different component types, whereas others are restricted to a condensed set of components, which they can operate at a much higher speed. The three most common machine types are insertion machines, pick-and-place machines, and rotary turret machines. An insertion machine has

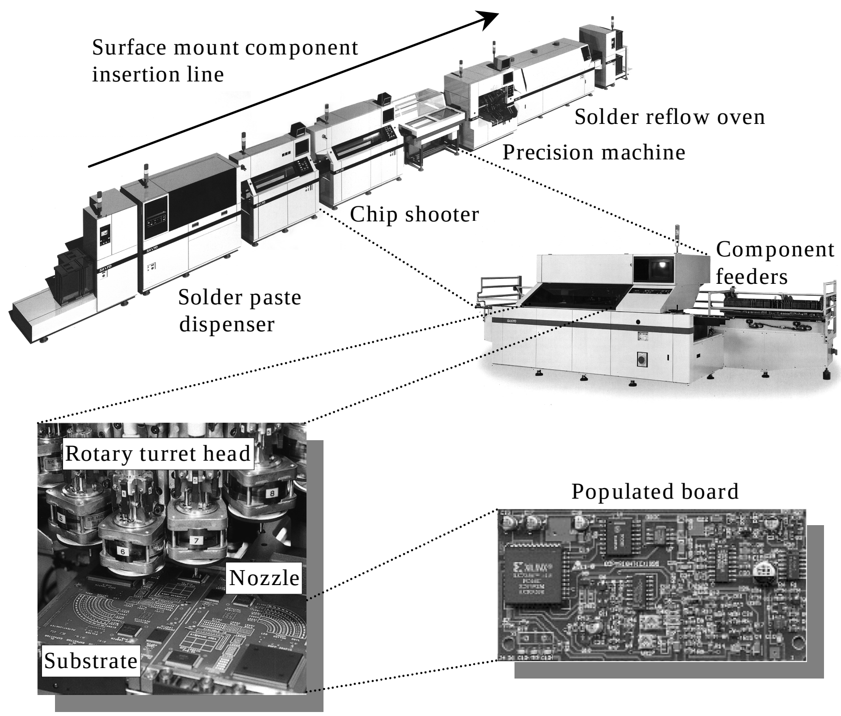

Figure 1.2: A PCB assembly line comprises subsequent operations. In a surface mount technology line, component placement is preceded and followed by solder paste insertion and reflow. The placement head picks a component from a feeder into a nozzle and, after inspection and orientation, places it on the substrate. When the substrate leaves the placment machines, the initially bare board is populated by components.

either a fixed head and a moving table (to which the substrate is attached) or a moving head and a fixed table. The head is connected to only one feeder, and a separate machine produces an appropriate feeder tape if different component types are needed. A pick-and-place machine has a moving head, a fixed table and fixed feeders. The head travels to pick a component from a feeder, moves it to the insertion location, prints the component, and finally moves back to the next feeder. A rotary turret machine has a revolving insertion head, a moving table and moving feeders (see Figure 1.2). There are several variations of the basic machine types—for example, the machine may have multiple insertion heads, duplicated feeders or duplicated tables—and the machine vendors are constantly improving and redesigning the machines to achieve better productivity.

No matter what the character of a particular production line is, the common goal of plant managers is to obtain a high yield of the best quality possible in the shortest time. To do that, each individual machine must be running at optimal capacity, every group of machines must be producing finished products efficiently and, in the light of this, decisions should be taken for the scheduling of tasks for the entire production process. Production planning in PCB assembly includes a number of different problems ranging from optimizing the operations on a single machine to scheduling the jobs of an entire plant, as we shall see in Chapter 2.

1.3 Research aims and contributions

The research of this thesis has been motivated by real-world production. The initial aim was to build software systems for production planning problems, but, it soon became evident that the problems had lumped together and needed a more subtle approach. Therefore, this thesis concentrates on two topics: (1) establishing a framework for the problems, and (2) building software systems for solving them. These endeavors support each other, since a solid framework enables us to pinpoint the critical problems, and the software applications provide us with a test ground for analyzing and improving the solution methods for these problems. Nevertheless, we have also tried to keep the focus on the users and usability of the system. This has led us to the idea of distributing the planning activities, which we discussed in Section 1.1.

This thesis has three major contributions:

1. A hierarchical classification scheme for PCB assembly problems.

2. Three software systems for production planning in PCB assembly.

3. Demonstrations of the benefits of Group Technology (GT) in PCB assembly.

The hierarchical problem classification, introduced in [100, 60], has been refined and enlarged on in the first paper of this thesis [113], where it forms the basis for a literature review. The previous problem classifications have been restricted to certain narrow areas of PCB assembly (e.g., the operations of a single placement machine), whereas our classification extends from individual machines and PCBs to the whole production environment. We shall elaborate on the scheme in Chapter 2

We discuss various aspects of the three production planning systems in several papers: *Interactive Production Scheduler* system for Nokia Display Products is the topic of papers two [66] and three [56], *PCB Grouper* system for Teleste Corporation paper four [116], and *ControlBOARD* system for Teleste Corporation papers five [117] and six [67]. We shall give a summary of the features and results of each system in Chapter 3.

This work concentrates specifically on setup strategy (see Section 2.2). We have applied Group Technology in both *PCB Grouper* and *Control-BOARD* systems. The observed increases in productivity have been considerable, and we report the results in papers four [116] and five [117]. GT also allowed us to use a fuzzy multiple criteria optimization, which we discuss in the sixth paper [67]. In the seventh paper [106], we compare GT methods to other suggested methods and show that the computational results further confirm the advantages of the GT approach in PCB assembly.

1.4 Outline of the thesis

We describe a hierarchical classification for the production planning problems in PCB assembly in Chapter 2. We give only a brief summary of the literature, since a more detailed survey can be found in the first paper [113]. In Chapter 3, we give a postmortem of each of the three production planning applications developed for real-work PCB assembly. In each case, we collect the system features, our observations, the lessons learned, and the feedback from users. Chapter 4 comprises summaries of the seven publications included in this thesis. Concluding remarks appear in Chapter 5. The seven publication reprints conclude the work.

Chapter 2

Hierarchical Problem Classification

I think you know what the problem is just as well as I do.
—HAL in *2001: A Space Odyssey*

The challenges in PCB assembly vary from deciding part printing sequence for an individual board to scheduling the entire production process for a plant efficiently. The vast variety of planning and control decisions involved has led to the widely used approach of hierarchical decomposition to solve problems, which means the breaking down of complicated tasks into simple ones. The main reason for this kind of approach is that the original problem is usually too complex to be solved globally, whereas it is easier to solve the subproblems successively one at a time. Naturally, the overall solution is not likely to be globally optimal, even if all subproblems are solved to optimality. Nonetheless, this approach is a productive and popular way to tackle hard problems, and the majority of production planning software systems utilize, in some way or another, the hierarchical decomposition technique.

A typical hierarchical classification scheme discerns three levels of production planning [30]:

1. *Strategic level* or long-range planning concerns the initial deployment and subsequent expansion of the production environments (e.g., the design and selection of the equipment and of the products to be manufactured).

2. *Tactical level* or medium-range planning determines the allocation patterns of the system production capacity to various products so that external demands are satisfied (e.g., by solving the batching and loading problems).

3. *Operational level* or short-range planning coordinates the shop floor

production activities so that the higher level tactical decisions are observed (e.g., by solving the release and dispatching problems).

Yet, these levels are not clear-cut, and the decomposition can depend on the product mix (e.g., the diversity of PCB types and batch sizes), the equipment (e.g., the number of machines and machine types), or the managerial policy (e.g., the setup frequency and the willingness to redesign the lines on a regular basis) [32].

We can break down the production planning problems of PCB assembly into these three levels [60, 95]. In the strategic level, the planning focuses on determining the best set of production equipment for the operation (e.g., running a simulation on how much money should be invested in new equipment and what kind of machines should be purchased). These decisions are usually made on economical basis, and they are revised over long operational periods, typically measured in several months. We do not consider these long-range planning problems in this work but concentrate on the two lower levels. At the tactical level, the decisions concern machine and line configurations, production schedules, batch sizes, and work-in-process levels. Finally, the operational level addresses the day-to-day operation of the equipment (e.g., how to manufacture a product).

We can classify tactical and operational PCB assembly problems according to the number of different board types (one or many) and machines (one or many) present in the problem [63, 113]. Accordingly, the four main problem classes are (see Figure 2.1):

- One PCB type and one machine (1–1) class comprises *single machine optimization* problems, where the goal is to minimize the printing time of the machine.
- Multiple PCB types and one machine (M–1) class comprises *setup strategies for a single machine.*
- One PCB type and multiple machines (1–M) class concentrates on *component allocation to sequential insertion machines.*
- Multiple PCB types and multiple machines (M–M) class represents *scheduling problems.*

The flow chart in Figure 2.2 illustrates the planning problems typifying these classes. At the tactical level, scheduling includes deciding how and in what order to operate the machinery to produce a set of different PCBs (i.e., allocation and sequencing). Here, a typical schedule would be executing the weekly production plan. At the operational level, we focus on assembly lines (i.e., balancing the workload) and individual machines (i.e., choosing a setup strategy). At the most basic operational level is the optimization of the

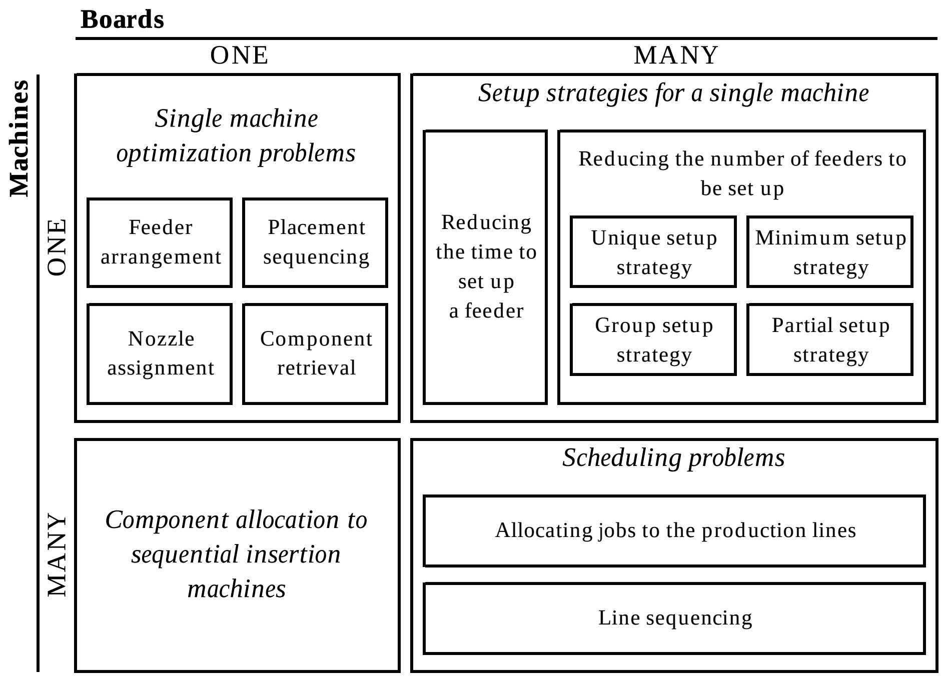

Figure 2.1: A hierarchical classification scheme of the PCB assembly problems [114]

single machine producing either a single product or a number of products. All these problems are connected to each other so that the solving of the complex problems requires the solutions of the simpler ones. For example, when solving line balancing, we must be able to optimize the feeder setups for the machines and optimize the insertion order for every board. Similarly, we need to solve the line balancing in order to build an efficient schedule.

The main advantage of the hierarchical classification scheme is that it makes it easier to recognize the problems and to find suitable and efficient approaches for solving them. In addition to theoretical interest, the scheme also provides support for practical issues. It provides a natural basis for a production planning system, where optimization is done separately for each subproblem. It has provided us with good results in both designing and implementing software systems for PCB manufacturers, as we shall see in Chapter 3. For the remainder of this chapter, let us go over each problem class individually.

2.1 Single machine optimization

Single machine optimization can be divided into four problems [19, 28, 44]:

- *feeder arrangement* problem (1–1a) concerns assigning components

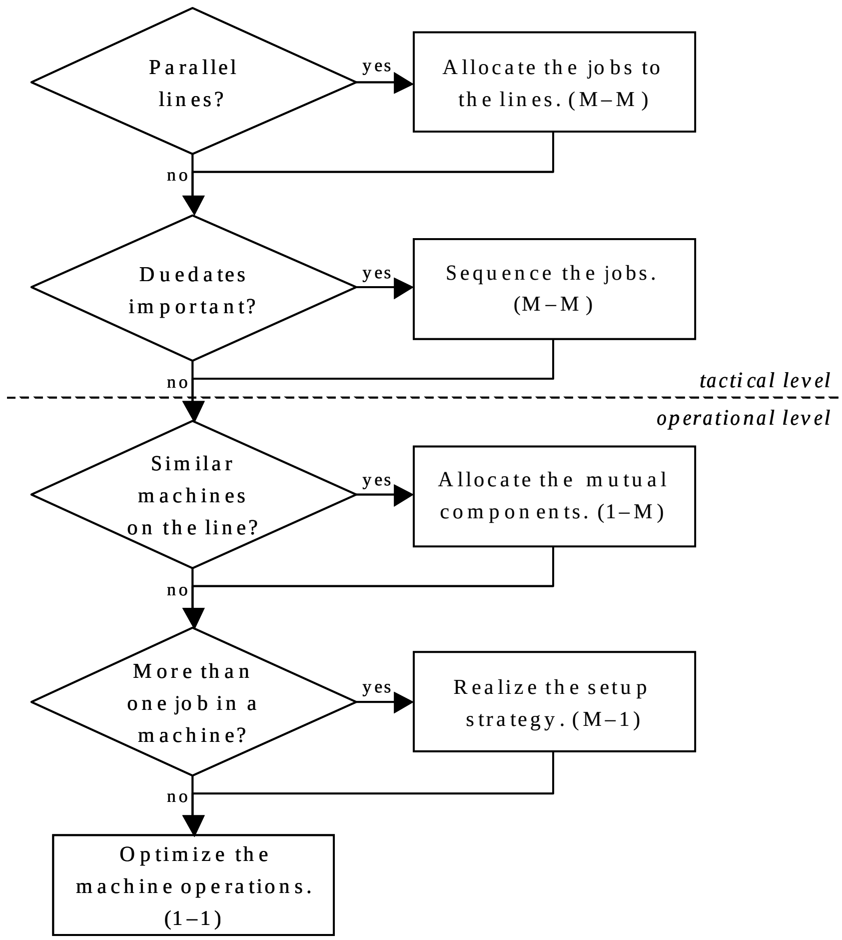

Figure 2.2: Tactical and operational production planning problems for a hierarchy, where the higher level problems require solution for the lower level problems.

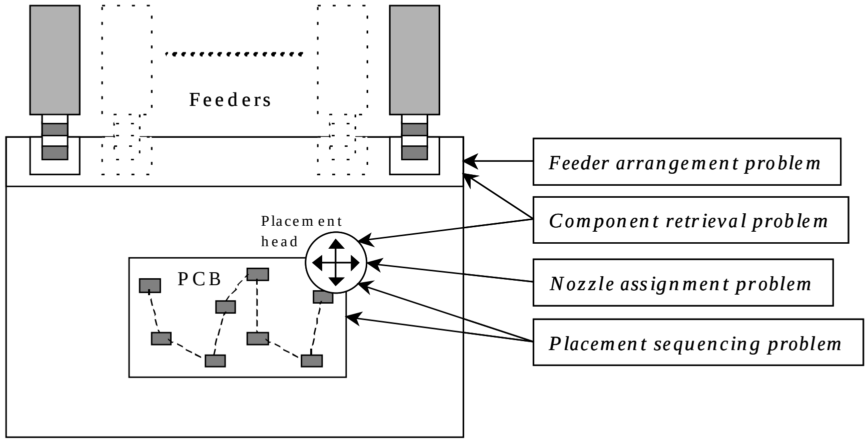

Figure 2.3: Single machine optimization problems are associated with the component placements, the placement head or the component feeders.

to the feeder slots,

- *placement sequencing* (or insertion order) problem (1–1b) concerns determining the sequence in which the components are printed on the board,
- *nozzle assignment* problem (1–1c) concerns the tool changes for the placement head, and
- *component retrieval* problem (1–1d) concerns selecting the feeder slot where the component is retrieved if it has been assigned to more than one slot.

These four subproblems are strongly intertwined and usually cannot be solved independently. For example, an optimal placement sequence does not guarantee optimal printing time if the feeder assignment is not considered—it does not guarantee it even if the feeder assignment is optimized as well. On the other hand, the type and design of the placement machine has a major importance when solving the subproblems (e.g., the placement sequence for the same PCB in a pick-and-place machine and in a rotary turret machine can be totally different).

Feeder arrangement and placement sequence are the most commonly solved single machine problems. The combined problem can be formulated as follows [32]: Let n denote the number of components to be placed, $f(i)$ the feeder delivering component i ($i = 1, \ldots, n$) and C the number of available feeder slots. The decision variables are

$$x_{ij} = \begin{cases} 1, & \text{if component } j \text{ is placed directly after component } i \\ & (i, j = 1, \ldots, n) \\ 0, & \text{otherwise} \end{cases}$$

$$y_{f(i),s} = \begin{cases} 1, & \text{a feeder for component } i \text{ is stored in slot } s \ (i = \\ & 1, \ldots, n; s = 1, \ldots, C). \\ 0, & \text{otherwise} \end{cases}$$

Now, the problem is to

$$\begin{aligned} &\text{minimize} \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{s=1}^{C} c_{ijs} x_{ij} y_{f(j),s}, \\ &\text{s.t.} \quad x \text{ describes a Hamiltonian path,} \\ &\qquad\ \ y \text{ describes a feasible assignment,} \end{aligned}$$

where c_{ijs} denotes the time elapsed between placing component i and placing component j when the feeder $f(j)$ is stored in slot s. Obviously, if the feeder arrangement is fixed, the placement sequencing problem can be formulated as a traveling salesperson problem or the shortest Hamiltonian path problem. Conversely, if the placement sequence is given, the feeder arrangement problem can be reduced to a linear or quadratic assignment problem. Although this problem formulation seems simple, in reality the problems are hard to solve (see [12, 13, 28, 84]).

Apart from manufacturing a single product more efficiently, the research on optimization of single machines is motivated by the consideration of higher levels of the production planning hierarchy. The effective optimization of the higher levels of the planning hierarchy presupposes good knowledge of single machine problems. This property is essential in particular at the line balancing level which is important for the overall efficiency of the production. The vendor-supplied software systems optimize myopically the operations of a single machine by using simple heuristics, whereas the research on this thesis is based on the assumption that single machine problems do not exist by themselves without related higher level planning problems. This reality tends to be overlooked in the literature, thus reducing the applicability of the proposed solution methods.

2.2 Setup strategy

When the type of PCB changes, the insertion machine undergoes setup operations, which include the required component feeder changeovers. There are two approaches to reduce setup times: reduce the time to set up a feeder, or reduce the number of feeders to be set up [26]. In the latter case, the general problem arrangement resembles the tool switching or job grouping problem traditionally associated with flexible manufacturing (e.g., metal cutting) [30, 31, 77, 76, 123]. In PCB assembly, the setup strategies can be classified as follows [86]:

- *unique setup strategy*: Consider one board at a time and specify the component–feeder assignment and the placement sequence so that the placement time is minimized. This is a common strategy when dealing with a single product and a single machine in a high-volume production environment. Since the unique setup strategy considers only one board at a time, it corresponds to single machine optimization.

- *minimum setup strategy* (M–1a): Sequence the boards and determine feeder assignments to minimize the total component setup time. The idea is to change only the feeders required to assemble the next board. In general, similar product types are produced in sequence so that little changeover time incurs.

- *group setup strategy* (M–1b): Form families of similar parts so that setups are incurred only between the families. Therefore, any board within a group can be produced without changing the component setup. Because the placement time for a specific board is, in general, larger than in unique setup strategy, some efficiency can be potentially lost. However, this is compensated by less frequent setup operations, which compensates the losses in machine speed, especially in high-mix, low-volume production.

- *partial setup strategy* (M–1c): Sequence the boards and determine a subset of the feeders on a machine that are changed when switching from one product to the next. Because the goal is to minimize makespan, the partial setup strategy resides between the unique setup strategy (where only the placement time for each individual PCB is minimized) and the minimum setup strategy (where only the changeover time of each PCB is minimized).

The main difference between the strategies is that setups occur less frequently in the group setup strategy than in other strategies (see Figure 2.4). In group setup, all the boards in a group are printed successively, and there is no need for setup operations between the boards residing in the same group. In the other strategies, setups can occur before each batch (i.e., a set of successively assembled PCBs of the same type). Naturally, the size of the required setup differs from one method to another.

Figure 2.5 illustrates how the minimum setup strategy can be utilized in PCB assembly. In the example, there are six different component types and six different board types to be manufactured. If the feeder capacity is four, it is possible to sequence the boards so that at most one component

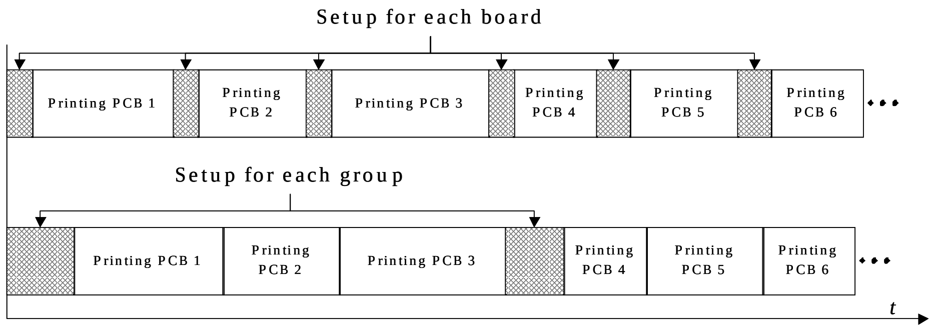

Figure 2.4: In the unique, minimum and partial setup strategies each board requires an individual setup (its size differs depending on the strategy). In the group setup strategy the boards are grouped so that no intervening setups occur.

is changed when the board changes. In Figure 2.6 the same board set is organized by using the group setup strategy. In this case, it is possible to divide the six boards into two groups which can share the same feeder setup.

In the group setup, the PCBs are grouped according to their component requirements. After that, the components of each group are assigned to feeder slots (i.e., feeder optimization), and the printing time of each PCB is minimized separately on the basis of the feeder set-up of the group (i.e., printing order optimization). The type of production determines whether the group setup strategy is *dynamic* or *static*. For example, if the whole production comprises fifteen PCBs that can be divided into two groups, it is probably preferable to form two static groups and alter the machine setup between them. Here, the grouping is static in the sense that it remains constant for a long period of time (e.g., for several months), whereas the dynamic groups are (re)formed on a much shorter timespan (e.g., daily or weekly). Nevertheless, the static group setup strategy requires that a new PCB can be inserted to (or obsolete PCBs removed from) a static group without having to form a new grouping. The static group setup strategy is recommended if few groups can be formed from the active product set; if the product diversity or the product variety is high, the dynamic group setup strategy often offers a better alternative. In practice, however, the production plants can usually settle on the static group setup.

We argue that the benefits of applying group setup strategy in high-mix, low-volume environment include [112, 118]:

- the throughput is improved since setups are done less frequently (see [116, 117]),

- less frequent setups also lead to that the human operator carrying out the component changeovers is less prone to make mistakes,

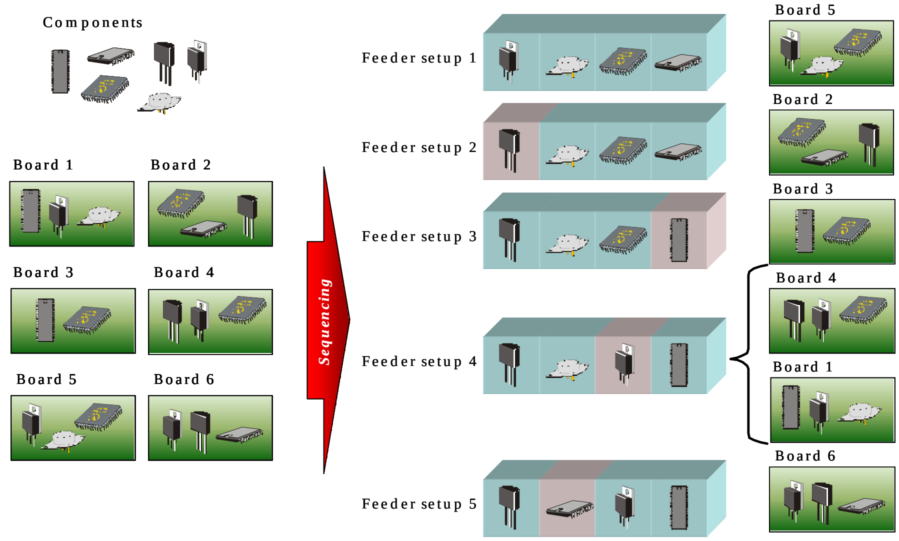

Figure 2.5: An example of the minimum setup strategy.

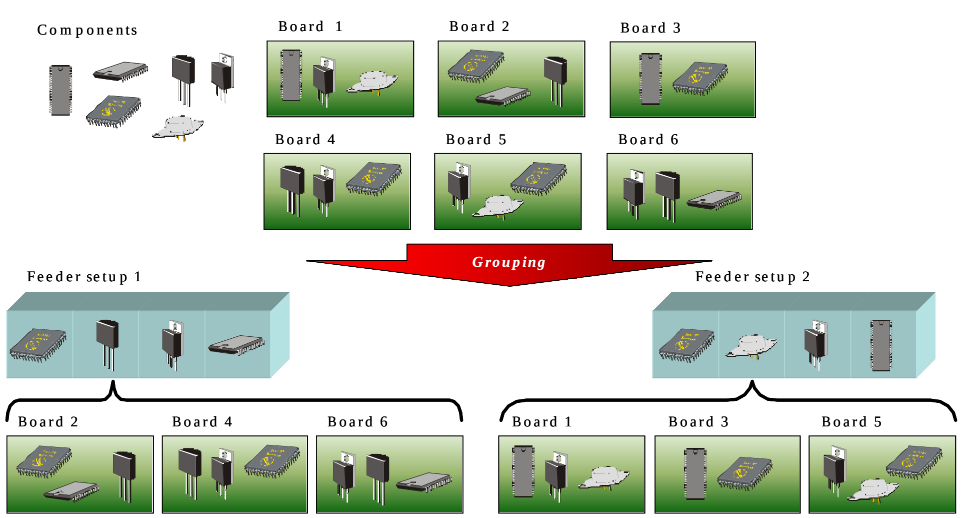

Figure 2.6: An example of the group setup strategy.

- smaller production batch sizes become economical, enabling to cut down the WIP levels,
- the production sequence within a group can be easily altered without affecting the predetermined feeder setup, and
- multiple criteria present in the production process can be accounted easily and intuitively (see [67]).

2.3 Component allocation to sequential machines

If the production line comprises similar sequential insertion machines, it may be possible to distribute the workload by allocating the components carefully. The situation is illustrated in Figure 2.7, where the set of all required components is divided into (possibly overlapping) subsets according to which machine can operate on which components. The component allocation problem can be formulated as follows [59, 98]: Let n denote the number of components to be placed, m the number of machines, and c_{ij} the cost (i.e., time) of placing component i on machine m. The component allocation is denoted by

$$x_{ij} = \begin{cases} 1, & \text{if component } i \ (i = 1, \ldots, n) \text{ is assigned to machine } j \\ & (j = 1, \ldots, m) \\ 0, & \text{otherwise.} \end{cases}$$

To balance the machine workloads, we must balance the total workload by the machine. This is accomplished by assigning the components so as to:

$$\text{minimize } w = \max_{j=1,\ldots,m} \sum_{i=1}^{n} c_{ij} x_{ij}$$
$$\text{s.t. } x \text{ describes a feasible component allocation.}$$

In other words, the optimization criterion is to minimize the workload of the machine with the maximum workload (i.e., to eliminate the bottleneck), see Figure 2.8. It must be emphasized that line balancing does not mean that each machine should have similar processing times—if that were the case, an obvious solution would be to slow down all the other machines to the speed of the machine with the maximum workload!

Another observation is that there are two kinds of balancing which must be differentiated: the workload can be balanced either among several parallel lines or among machines within the same single line [41]. The former clearly belongs to the problem class (M–M), whereas the latter is an instance of the problem class (1–M). The approaches for balancing parallel or single lines are different and, therefore, should not be lumped together.

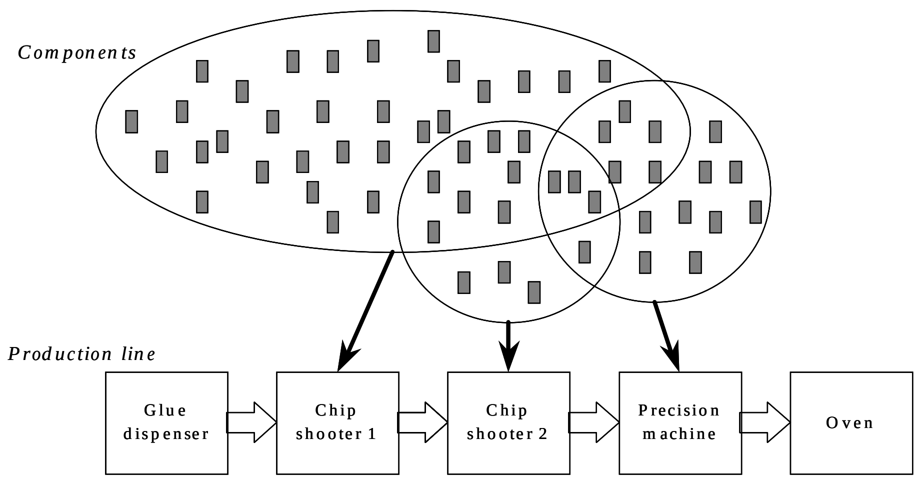

Figure 2.7: An example of component allocation to similar machines. The component set is divided into subsets, among which a setup for each machine must be decided.

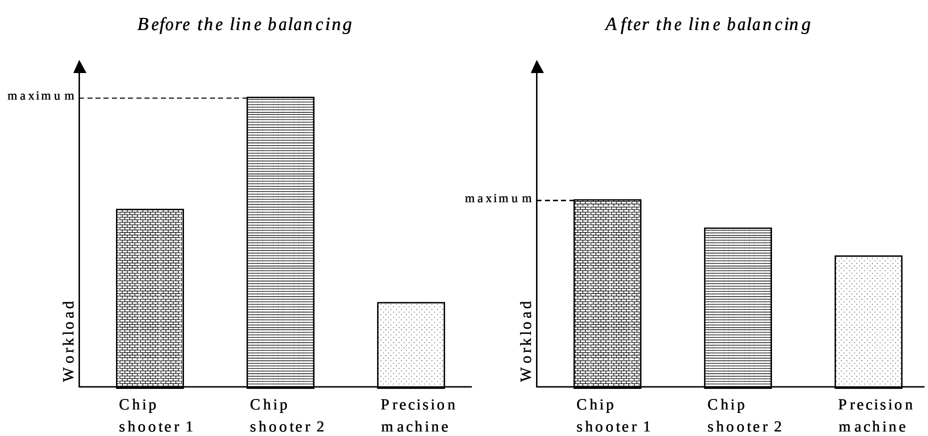

Figure 2.8: In the initial situation, chip shooter 2 is the bottleneck of the production line, since it has the maximum workload. By allocating the components differently, the maximum can be minimized.

In line balancing, it is important to have reliable estimates of lower level production times [80]. Because these estimates are generated for numerous solution candidates, they should be fast to compute. In commercial systems, the estimates are usually calculated from the nominal component time (i.e., the production time is the sum of a fixed constant for the start and finish of the assembly task, and a term which is a product of the number of components and the placement time per component). The benefit of this method is simplicity and, consequently, high speed. On the other hand, its accuracy is modest and it suits only for finding an initial approximative solution to the balancing problem. By refining this estimate to include, for example, the number of different component types and the board size, one can increase the accuracy considerably. A more detailed estimation can be achieved by using simulation times obtained from built-in simulators for each machine type. The simulators use, among other things, information about the placement sequence, operation sequence, machine timings, component coordinates, and machine geometry. The disadvantage of a simulator is that it does rather complex computations which require a substantial amount of running time. This limits its use in multi-product balancing and production scheduling.

2.4 Scheduling

Scheduling problems usually concentrate on

- allocating jobs to lines, which includes routing, lot sizing and workload balancing between lines (M–Ma), and
- line sequencing (M–Mb).

Usually a good schedule must satisfy several objectives like meeting the due-dates, preserving the production sequence from stage to stage, balancing the workload, keeping the product families together, minimizing the size of the internal buffer storages, and minimizing the machine idle times. However, these goals are nearly always contradictory to each other, which makes the scheduling a complicated task.

In PCB assembly, the problem settings are based on the *flow shop* model, where the machine environment consists of a number of stages and each product runs in the same order through these stages [23, 103, 108]. Figure 2.9 illustrates the machine layouts of the most important flow shop variants. In a flow shop, there is only one machine in each stage and each product is processed only once in each machine. If several different products are manufactured in the same line, their sequence has an effect on the throughput of the line because the time demands can vary considerably between different schedules. In *flexible flow*, there is also one machine in each stage but the product can skip over some stages [110]. *Flexible flow shop* (also known

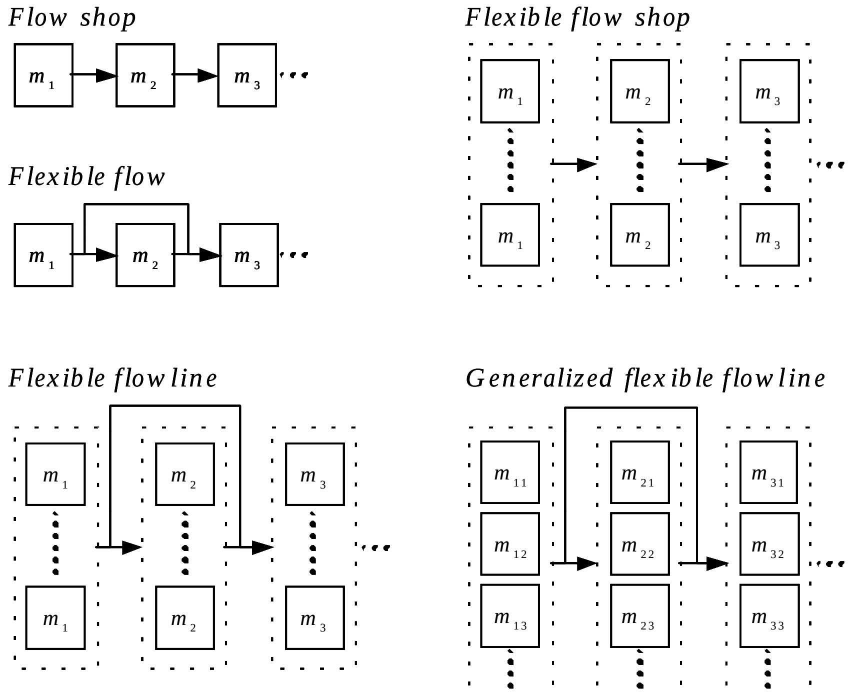

Figure 2.9: Typical production plant layouts for scheduling problems.

as network flow shop [79] or hybrid flow shop [51, 83]) is a generalization of the flow shop scheduling problem, where each stage can include several identical machines. The setup times or machine lines are not considered in this problem formulation.

Flexible flow line comprises several production stages [132, 133]. The machines in a stage are identical with each other. A product can therefore be processed in any machine belonging to the stage, or it can skip it without being processed at all (which is not allowed in flexible flow shop). Each product passes the stages in a predefined order, and the transfer between the stages is accomplished with the help of magazines or some other form of transport. The setup time between different products, which is assumed to be negligible, is ignored. Hence, the processing time is a function of the processed product and the stage.

Generalized flexible flow line broadens this model by allowing the type of the machines to vary inside a stage [62]. The machine type defines the speed of the machine, and thus the processing time is a function of the product and the machine type. Moreover, setup times are also taken into account. The problem can be expressed in the three-tuple notation (see [23]) as $FMPM/p_{ij}, d_i, \text{batch}/\min \sum T^2$ which stands for a flow shop with m machines; jobs with no preemption (i.e., the processing of a job on a machine may not be interrupted); no precedence relations; all jobs are ready for processing; processing demands differ; deadlines; batches; and the optimization criterion is the minimization of the total sum of squared tardinesses of the batches. For simplicity, the processing times can be assumed to be stochastic, but the averages of the processing times are accurate enough for evaluating different schedules. The schedule determines the machine allocation and the sequence of the jobs on each machine.

There are three different approaches to the flow line scheduling [56]: In the *algorithmic approach*, the scheduling task is expressed as a mathematical optimization problem and is usually solved with an approximation algorithm [36, 72, 74]. In the *interactive scheduling approach*, the production designer uses computer simulation to evaluate different schedules [57, 109]. The *hybrid approach* integrates these two approaches and uses the algorithms to produce a set of possible schedules which can be then evaluated and manipulated by the interactive scheduling tool [49, 66].

2.5 Summary of the literature

Table 2.1 collects the literature on PCB assembly problems. The problems addressed in each paper are identified using the hierarchical classification scheme. In addition, each entry includes information of the machines or the plant layout present in the problem and cross references to related papers or similar problem settings. For more details, see the first publication reprint [113].

Table 2.1: Literature on PCB assembly problems

Paper	Problem	Machine(s)	cf.	Brief summary
J.Ahmadi *et al.* (1995) [1]	1–1a	dual delivery pick-and-place	[2, 3, 4]	reel positioning problem: minimize the direction changes and the sum of movements of the feeder carriage
J. Ahmadi *et al.* (1986) [2]	1–1a	dual delivery pick-and-place	[3, 4, 1]	an emulator for studying the parameters of the printing process
J. Ahmadi *et al.* (1988) [3]	1–1ad	dual delivery pick-and-place	[2, 4, 1]	mathematical formulation and mixed integer programming solution
R. Ahmadi and Kouvelis (1994) [4]	1–1ad	dual delivery pick-and-place	[2, 3, 1]	IP formulation and Lagrangian relaxation based BB algorithm for single and multi product staging problems
R. Ahmadi and Kouvelis (1999) [5]	M–M	multiple		mathematical framework for designing and configuring the layout of assembly lines
R. Ahmadi and Matsuo (2000) [6]	M–1b 1–M M–Mab	multiple different		mathematical formulation for a hierarchical mini-line approach in JIT production
R. Ahmadi and Wurgaft (1994) [7]	M–Mab	synchronized flow		mathematical formulation to maximize the throughput rate
Altinkemer *et al.* (2000) [8]	1–1ab 1–M	rotary turret		allocate components to the machines, assign the feeders, and solve the printing order using an integrated formulation
Ammons *et al.* (1997) [9]	1–M	two or more, coupled	[98]	balance a combination of the assembly time and the machine setup time

continued on next page

continued from previous page

PAPER	PROBLEM	MACHINE(S)	CF.	BRIEF SUMMARY
Askin *et al.* (1994) [10]	M–1b 1–M	multiple, coupled or decoupled, identical		minimize the makespan for assembling a batch of boards and reduce the mean flow time
Balakrishnan and Vanderbeck (1999) [11]	M–1b M–Ma	multiple identical lines		group products and assign groups to the lines to balance to workload and to minimize the setup time
Ball and Magazine (1988) [12]	1–1ab	one		heuristic algorithm for solving the insertion sequence
Bard *et al.* (1994) [13]	1–1abd	rotary turret		solve placement sequence with nearest neighbor heuristic, and feeder assignment and component retrieval with Lagrangian relaxation
Barnea and Sipper (1993) [14]	M–1a	one		sequence the boards and apply KTNS to determine the component changes
Ben-Arieh and Dror (1990) [15]	1–M	two	[16]	assign components to the machines to maximize the output rate
Ben-Arieh and Maimon (1992) [16]	M–Mb	two different, sequential	[15]	form a permutation schedule to minimize the mean flowtime
Bhaskar and Narendran (1996) [17]	M–1b	one	[78, 104]	a graph theory approach for grouping the boards
Bodner *et al.* (1998) [18]	1–1ab	virtual	[19]	virtual prototyping

continued on next page

continued from previous page

Paper	Problem	Machine(s)	cf.	Brief summary
Bodner *et al.* (1997) [19]	1–1abc	virtual	[18]	virtual machine model
Brandeau and Billington (1991) [21]	1–M	multiple	[53, 54]	assign components to different workphases to minimize the total setup and processing cost for assembling all boards
Carmon *et al.* (1989) [24]	M–1ab	two	[96]	introduces the group setup (GSU) method
Chang and Young (1990) [25]	1–1ab	one with multiple heads		introduces a machine design for simultaneous mounting
Crama *et al.* (1996) [27]	1–1d	one		introduces the component retrieval problem (CRP)
Crama *et al.* (1997) [28]	1–1abd	line with different machines		hierarchical decomposition where subproblems are solved with local search heuristics when the goal is to minimize the sum of makespans on the bottleneck machine
Crama *et al.* (1990) [29]	1–1abc 1–M	line of 3-headed pick-and-place machines	[128]	hierarchical decomposition where the subproblems are solved with heuristic algorithms when the goal is to minimize the processing time of the bottleneck machine
Crama *et al.* (1999) [32]	1–1abd M–1abc 1–M M–Mab	various	[113]	a survey of literature and a hierarchical model of the optimization problems
Cyr *et al.* (1997) [33]	M–1ab	SMT line	[24, 81]	a comparison of GSU and SDS methods

continued on next page

continued from previous page

PAPER	PROBLEM	MACHINE(S)	CF.	BRIEF SUMMARY
Dagnino (1994) [34]	M–M	multiple different		a hierarchy of process planning in PCB assembly
Daskin *et al.* (1997) [35]	M–1b	one	[95, 111]	mathematical formulation for grouping problem, and a proof for its NP-completeness; solved with a BB heuristic
Dessouky *et al.* (1995) [36]	M–Mab	FFL		maximize throughput while keeping WIP at a minimal level
Dillon *et al.* (1998) [37]	M–1a	SMD machine		greedy heuristics which maximize the component communality when the PCB type changes
Driels and Kledga (1992) [38]	M–M	multiple different	[73]	an investigation of the economical aspects of a production line
Estremadoyro *et al.* (1997) [39]	M–M	multiple different		simulation tool for modeling and analysing assembly line layouts
Fathi and Taheri (1989) [40]	M–1b	sequencer for axial machine	[121]	group products to minimize the sequencer setup
Feldman and Feuerstein (1998) [41]	M–M	line	[42]	modeling the production line for educational and research purposes
Feldman *et al.* (1990) [42]	M–M	line	[41]	modeling the production line for research purposes
Feo *et al.* (1995) [43]	M–Mab	multiple different		decision support system for scheduling, inventory and throughput evaluation

continued on next page

continued from previous page

PAPER	PROBLEM	MACHINE(S)	CF.	BRIEF SUMMARY
Foulds and Hamacher (1993) [44]	1–1ab	one with bins on all four sides		method for identifying optimal bin locations and determining an insertion sequence
Fu and Su (2000) [45]	1–1b	one		a comparison of GA, SA and TS implementations
Gershwin *et al.* (1985) [46]	M–Mb	multiple different		determine dispatch dates for an FMS with unreliable machines
Gronalt *et al.* (1997) [48]	1–1a M–1a	SMD machine	[50]	component switching heuristic for KCNS policy
Grunow *et al.* (2000) [49]	1–1ab M–M	multiple different		simulation system for performance analysis and optimization
Günther *et al.* (1998) [50]	1–1a M–1a	SMD machine	[48]	heuristics for solving job sequencing, component setup and feeder assignment problems
Hernandez and Leon (1997) [52]	1–1ab	one with two arms		interference avoidance of the manipulators
Hillier and Brandeau (2001) [54]	1–M	multiple	[21, 53]	mathematical model with a workload balancing criterion
Hillier and Brandeau (1998) [53]	1–M	multiple	[21, 54]	mathematical model and BB heuristic
Häyrinen *et al.* (2000) [56]	M–Mab	GFFL	[66]	heuristics for the scheduling problem
Jackson and Johansson (1997) [57]	M–M	multiple different		DES simulator to support decentralized decision making

continued on next page

continued from previous page

Paper	Problem	Machine(s)	cf.	Brief summary
Jain *et al.* (1996) [58]	1–1a M–1a	one		determine initial processing sequence; assign feeders according to KTNS; rearrange jobs using 2-opt; preserve frequently used components for the next production period
Ji *et al.* (2001) [59]	1–M	line		IP model for minimizing the cycle time of the line; GA method for solving the problem
Johnsson *et al.* (1996) [61]	1–1a	one		sequencing for manual installation of components
Johnsson *et al.* (1997) [62]	1–M M–Mb	GFFL		introduces GFFL
Johri (1990) [64]	M–Mb	FFL	[65]	heuristic for loading a new work so that workload is balanced and duedates are met
Johri (1991) [65]	M–M	FFL	[64]	designing a line considering capacity and flowtime
Johtela *et al.* (1997) [66]	M–Mab	GFFL	[56]	simulation tool for creating and analysing schedules
Johtela *et al.* (1998) [67]	M–1b	SMD machine	[116, 117]	fuzzy multiple criteria model for the job grouping problem
Khoo and Loh (2000) [69]	1–1ab	rotary turret	[70]	GA method for solving the placement sequence and feeder arrangement
Khoo and Ng (1998) [70]	1–1b	semi-automatic	[107, 69]	GA method for solving the placement sequence

continued on next page

continued from previous page

Paper	Problem	Machine(s)	cf.	Brief summary
Khoshnevis *et al.* (1994) [71]	M–M	multiple different		integrated system for assembly planning and scheduling
Kim *et al.* (1996) [72]	M–Mb	multiple different, coupled		a comparison of sequencing heuristics, where the objective is to minimize the sum of tardiness
Kledga and Driels (1991) [73]	M–M	multiple different	[38]	an investigation of the economy of different production lines
Klincewicz and Rajan (1994) [74]	M–Mab	multiple		assign the components so that the number of machine visits is minimized and the workload is balanced
Klomp *et al.* (2000) [75]	1–1a 1–M	line		heuristic method for assigning the feeders
Kumar and Narendran (1997) [78]	M–1a	one	[17, 104]	sequence PCBs with duedates using similarity measures
Lambert *et al.* (1997) [81]	M–1ab	SMT line	[24, 33]	a comparison of GSU, SDS and scheduling rules
Leipälä and Nevalainen (1989) [84]	1–1ab	one		heuristic algorithms for feeder setup and insertion sequence
Leon and Peters (1996) [85]	M–1c	one	[86, 102]	introduces the partial setup strategy
Leon and Peters (1998) [86]	M–1abc	one	[85, 102]	a comparison of different setup strategies

continued on next page

continued from previous page

PAPER	PROBLEM	MACHINE(S)	CF.	BRIEF SUMMARY
Leu and Ji (1991) [87]	1–1b	one		heuristic methods for printing order optimization
Lin *et al.* (1997) [88]	M–Mab	FFL		integrates product-level and board-level scheduling to determine lot sizes and job sequences
Lin and Tardif (1999) [89]	M–Mb	one line		assign the components to the machines so that makespan is minimized and workload balanced
Lofgren and McGinnis (1986) [90]	M–1a	one	[91]	sequence the boards, assign a setup for each board, and use a heuristic to determine the component changeovers
Lofgren and McGinnis (1986) [91]	1–M	multiple identical	[90]	heuristics for workload balancing and minimizing machine visits under dynamic and static operating policy
Lofgren *et al.* (1991) [92]	M–Mab	multiple different		station routing problem: sequence the operations to minimize the number of workstation visits
Luzzatto and Perona (1993) [93]	M–1b	successive similar machines		heuristic for grouping PCBs to minimize the setup size
Maimon and Shtub (1991) [95]	M–1b	one	[111, 35]	mixed-integer programming formulation and a heuristic for grouping to minimize the total setup time

continued on next page

continued from previous page

Paper	Problem	Machine(s)	cf.	Brief summary
Maimon *et al.* (1993) [96]	M–1ab	two, flowshop	[24]	a comparison of group setup (GSU) method and SDS
McGinnis *et al.* (1992) [98]	1–1ab 1–M	one or many, coupled or decoupled	[9]	a survey of literature and a general model of PCB assembly
Nesbit (1998) [99]	M–M	multiple		requirements for a computer system for analyzing assembly processes
Ohno *et al.* (1999) [101]	1–1ab M–1b	one		hierarchical decomposition where the subproblems are solved with heuristic algorithms
Peters and Subramanian (1996) [102]	M–1c	one	[85, 86]	a comparison of partial setup strategies
Rajkumar and Narendran (1998) [104]	M–1a	one	[17, 78]	sequence the PCBs using similarity measures
Sadiq *et al.* (1993) [105]	1–1a	SMD machine		heuristic slot assignment, which is improved with a rearrangement process
Sanchez and Priest (1991) [107]	1–1b	semi-automatic	[70]	AI and expert systems with sequencing decision rules
Shevell *et al.* (1986) [109]	M–M	multiple different		simulation model for analyzing a PCB manufacturing system
Shtub and Maimon (1992) [111]	M–1b	one	[95, 35]	grouping heuristic based on cluster analysis and similarity measures

continued on next page

continued from previous page

PAPER	PROBLEM	MACHINE(S)	CF.	BRIEF SUMMARY
Smed *et al.* (1999) [113]	1–1abcd M–1abc 1–M M–Mab	various	[32]	a survey of literature and applications
Smed *et al.* (1999) [116]	M–1b	SMD machine	[67, 117]	IP formulation and heuristic algorithms for job grouping problem
Smed *et al.* (2000) [117]	1–1ab M–1b M–Mb	SMD machine	[116, 67]	integrated scheduler system for PCB grouping and single machine optimization
Spedding and Sun (1999) [120]	M–M	SMT line		development of an activity based cost model
Sule (1992) [121]	M–1b 1–M	one or many sequencers	[40]	heuristic to minimize the component change-over cost and to balance the workload
Supinski *et al.* (1991) [122]	1–1bc	one		printing order planning and robot code generation
Taylor (1990) [124]	M–Mab	multiple different		simulation tool for evaluating flexible control strategies
van Laarhoven and Zijm (1993) [128]	1–1abc 1–M	line of 3-headed pick-and-place machines	[29]	hierarchical decomposition where subproblems are solved with heuristics and SA, and the goal is to minimize the processing time of the bottleneck machine

continued on next page

continued from previous page

Paper	Problem	Machine(s)	cf.	Brief summary
Wang (1998) [129]	1–1b	dynamic pick-and-place machine	[130]	a comparison of different layout design methods
Wang *et al.* (1998) [130]	1–1ab	one	[129]	a model where the board and the feeders move along x-axis and the head along y-axis
Watkins and Cochran (1995) [131]	1–M	a line of similar machines		heuristic for rebalancing the workload by moving components from the bottleneck machine
Xu *et al.* (1998) [134]	1–1a M–1b	one		group PCBs and divide the feeders into fixed, semi-fixed and configurable setups
Yeo *et al.* (1996) [135]	1–1ab	rotary turret		rule-based approach with heuristics
Zhou and Leu (1991) [137]	1–1abc	one		Petri net models for analysing the system behavior and evaluating the system performance
Zijm and van Harten (1993) [138]	1–1ab 1–M	line of identical machines		hierarchical decomposition and heuristics for the subproblems

Chapter 3

Production Planning Applications

> PROGRAMMING, *n.* 1. The art of debugging a blank sheet of paper (or, in these days of on-line editing, the art of debugging an empty file). "Bloody instructions which, being taught, return to plague their inventor" ("Macbeth", Act 1, Scene 7). 2. A pastime similar to banging one's head against a wall, but with fewer opportunities for reward. 3. The most fun you can have with your clothes on (although clothes are not mandatory).
>
> —*The Jargon File*, version 4.1.0

The research for this thesis includes the development of three software systems for production planning. In this chapter, we summarize the lessons learned from both the software development process and the integration into the production plant. The *IPS* (*Interactive Production Scheduler*) system is discussed in Section 3.1 and in the second and third publication reprints [66, 56]. The *PCB Grouper* system is discussed in Section 3.2 and in the fourth publication reprint [116]. The *ControlBOARD* system is discussed in Section 3.3 and in the fifth and sixth publication reprints [117, 67]. The chapter is concluded by a summary of current research in Section 3.4.

3.1 Interactive Production Scheduler

The first system, *Interactive Production Scheduler* (*IPS*), was based on a previous work, which used simulation approach and where the bias was on replicating the work flow [62]. A full simulation turned out be an inefficient design for implementing a real-world production planning system, because the simulation runs took a long time. Also, the simulation results were too detailed for the production planner, who is not so keen to keep track where

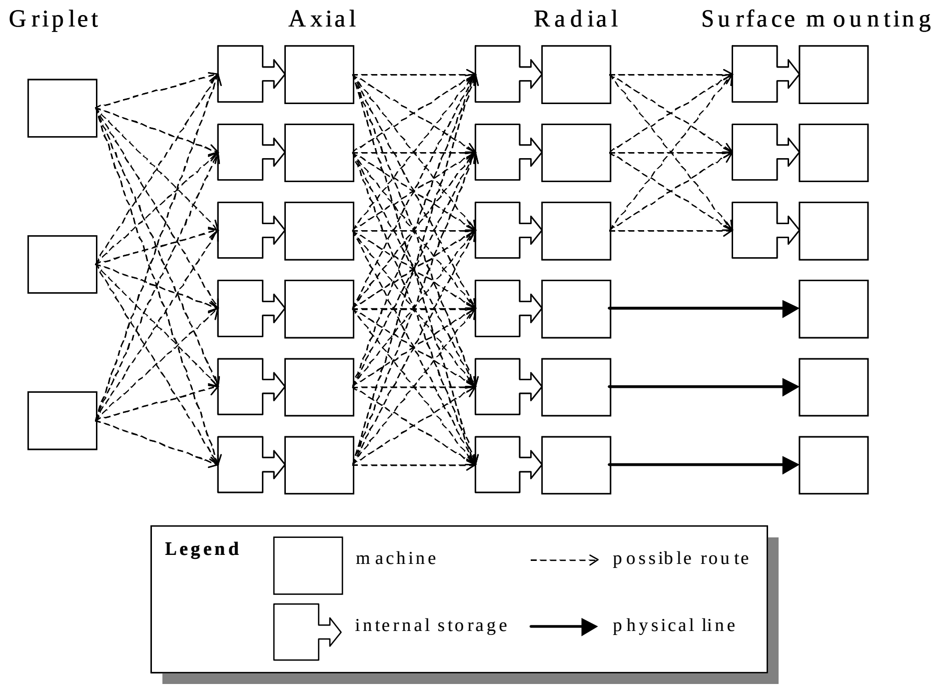

Figure 3.1: A generalized flexible flow line (GFFL) environment used in *IPS*. The internal storages buffer the products before they are transported to the machine. The dashed lines indicate possible routes between the machines. A physical line is usually a conveyor belt which couples two (or more) machines together. Similar environments are described in [57, 71, 88].

a particular product is at the moment but wants to know whether it will be finished on time.

The motivation behind the *IPS* system was to provide support for the production planners who schedule PCB assembly operations in a GFFL environment (see Figure 3.1). Previously, the production planners had to calculate and estimate on paper the machine allocation and the sequencing of the batches. The amount of information concerning this task is large, and the decisions are hard to make, even if they are based on years of experience. Moreover, planning the production without any computational support is slow and subject to human errors. The planners can use their experience and try to find a solution that fulfills the main criterion of scheduling, which is meeting the duedates. The purpose of the *IPS* system was to give the production planners support needed in the evaluation and comparison of different solution alternatives. This way, they can allocate and sequence the batches so that they meet the duedates, the idle periods are short, and the machine load is balanced all the time.

The idea behind *IPS* is that production planners load and update the previous situation to correspond to the current state of the production. The system computes a tentative update to which the planners can make changes. Next, new batches are added to the updated situation. Different sequences and allocations of the batches can be experimented by observing their effect on the finishing times and machine statistics. Alternatively, schedules can be produced by using algorithms. During this editing process the problems in meeting the duedates are (possibly) removed until the solution is satisfactory. The plan is then printed and the situation is saved for the next update session.

3.1.1 System features

The system is based on an interactive graphical user interface (see Figure 3.2). Allocation and sequencing are represented by simple graphical components which can be easily operated. The system supports decision making by giving feedback of the solution (e.g., graphical charts).

The basic operations of the system include moving batches inside a machine and inside a machine bank (i.e., a set of parallel machines), inserting or removing a batch. Additional data like the size, the duedate, the starting and finishing time of processing are hidden by default and shown if wanted. Several different forms for the data input are supported, and they can be launched from the main window. The user can move batches freely inside a phase, from one machine to another (allocation), reorder the batches (sequencing), or fix batches to certain machines.

The system computes the finishing time of each batch of the current situation. This reveals the batches being late. The processing time of a single PCB is obtained from previous production or calculated from the speed of the machine and the number of components in each phase or the time. The user receives graphical feedback as well as numerical data of the situation.

The update operation uses the simulation model and updates situation to a given moment of time in the future. If the situation suggested by the update operation does not correspond to reality (e.g., a batch is actually not yet finished or is finished but not in the system), the planners can make changes to the situation maintained by the system. After that they can either accept the update or cancel it. If the update is accepted, the system automatically removes all finished batches.

The schedule can be built algorithmically, and these generated schedules can be used either directly or they can be enhanced further by manual editing. The algorithms consist of four distinct stages: initial allocation, allocation enhancement, initial sequencing and sequencing enhancement. The enhancement is achieved by using local search methods based on swapping techniques as described in the third publication reprint [56].

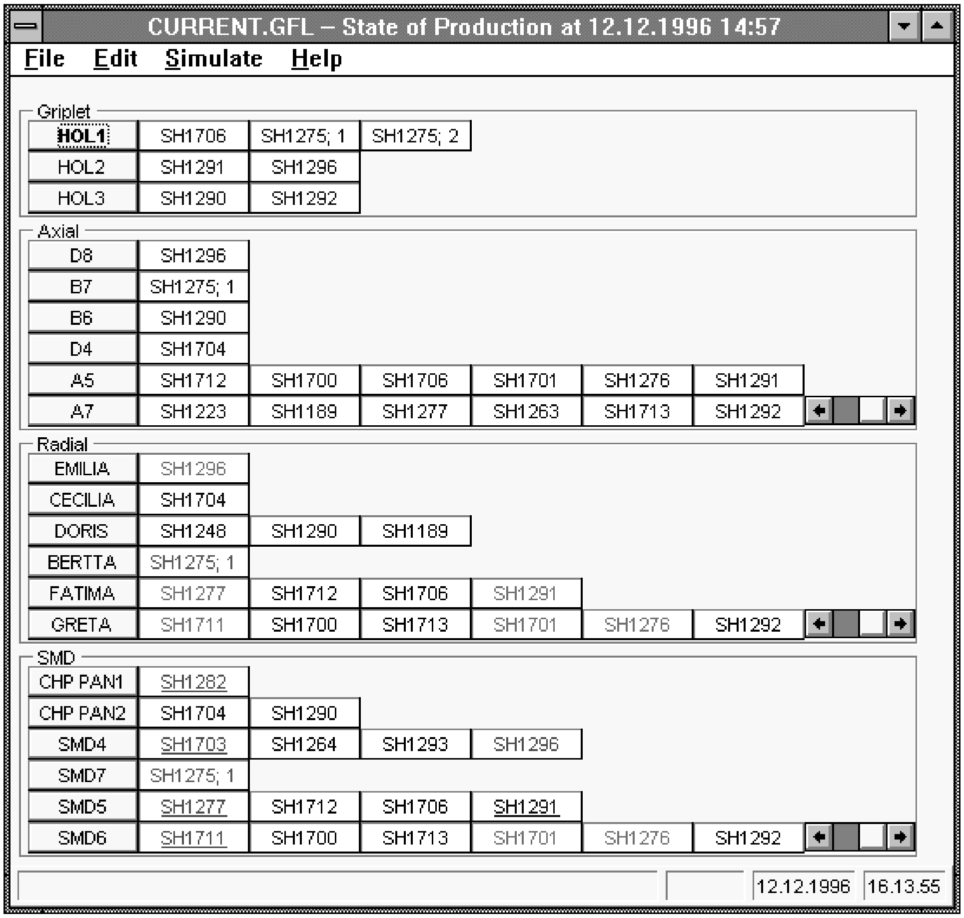

Figure 3.2: A screenshot from the *Interactive Production Scheduler* system.

3.1.2 Observations and discussion

IPS did not succeed in becoming a tool for daily use. One of the reasons for this was that, initially, the system did not offer much more than automated estimations for a given schedule. There were no actual scheduling algorithms in the first version of the system, and, therefore, it was only a slight improvement to the pen-and-paper method used in the plant. However, the algorithms, which were being developed separately, were included in the system later on, but then the circumstances at the plant had altered drastically, and most of the production had been transferred abroad, leaving behind only a small line for assembling prototype series.

There were also other reasons why the first system was not so successful. We did not realize how dynamic the actual production plant really is. We did anticipate that we should make as few assumptions about the production as possible but, nevertheless, the system was too crude for real-world use. For example, batch splitting (which leads to preemptive scheduling) was considered in design phase but not implemented since it complicates the system (e.g., if a batch is split in one phase, can it still be merged together in another? what if only a part of it is merged or the batches were not originally together?). However, batch splitting turned out to be an important aspect in the planning process—and the first feature requested by the users. In production, it is often necessary to allow to halt the batch being currently processed, because some other urgent batch (e.g., a prototype series) must be processed before it.

Another important aspect, which *IPS* initially did not support, is machine interruptions (caused by breakdowns or maintenance), which turn out to be rather common. The normal operation of a machine can be interrupted by a breakdown, and the machine has then to be temporarily put off-line. Also, the maintenance and preproduction series, which cause delays which are known beforehand, must be taken into consideration when planning the production. Therefore, the user needs an option for taking the machine off-line for either a predetermined or indeterminate period of time. This is a cumbersome task to realize in a generalized flexible flow line (GFFL) environment, since it requires both batch splitting and rerouting, and it still poses an open question how to handle the interruptions smoothly.

On the theoretical side, we designed algorithms for a complex scheduling problem. In our previous work, we had already recognized the properties of the GFFL environment and analyzed it using simulation [62]. The algorithms introduced in the third publication [56] were tested on both real-world cases provided by our industrial partner and randomly created cases resembling normal production.

We realized already in the start that the production planners have experience and knowledge of the problem environment that our system cannot surpass. Therefore, the system should be supportive rather than controlling. *IPS* realizes this in two ways: It provides a graphical representation of the schedule for easy editing, and it includes algorithms for doing exhaustive searching. *IPS* as well as our later systems have demonstrated that this idea of distributing the planning activities (which we discussed in Section 1.1) is a fruitful approach for developing production planning software.

During the design phase of *IPS*, we observed how the production planners process the scheduling problem on paper when they try to solve it, and adopted those ideas for the visual layout. During the testing it turned out that the users liked our ideas for the GUI and were keen to adopt it since it resembled much of their previous working procedures. Moreover, we realized early on that although the production plan is made for a given period of time, the production does not begin with an empty line, and neither does the line remain empty, when the last batch in the current plan has been completed. In addition, we seldom know the whole production program at the beginning of the weekly planning period. The planning is dynamic in the sense that new batches will be inserted during the planning period. This is known as a

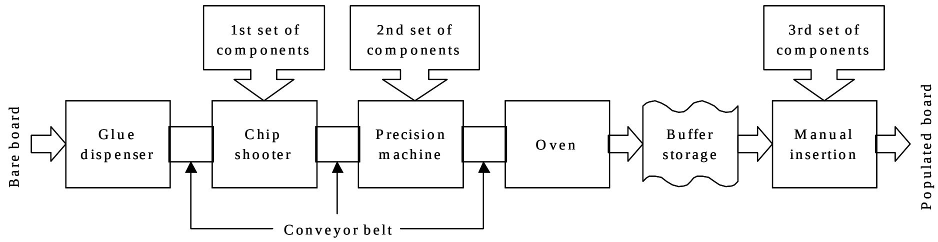

Figure 3.3: The work phases of an SMT assembly line. First, a bare board passes a glue dispenser. Next, the actual printing is done by a fast chip shooter and a slow but flexible precision machine. Finally, the PCB visits an oven that hardens the glue. The board is then stored before manual component insertion. Similar lines are described in [33, 50, 120, 135].

rolling schedule, where the scheduling problem is solved for the immediate decision period, and the problem is then updated and resolved one period later. Observing and realizing these aspects of the problem solving enabled us to make the system less rigid (or algorithm dependent) and more dynamic than was our original intention. The subsequent software developments proved this approach to be productive.

3.2 PCB Grouper

The second system, *PCB Grouper*, focused on a production line for SMT component printing (see Figure 3.3), which is a common layout in high-mix, low-volume production environments. The problem is different from the GFFL environment of the *IPS* system because it concentrates on one machine on the production line. More specifically, the *PCB Grouper* system concentrates on realizing the group setup strategy (see Section 2.2) in the chip shooter machine (for a study on the precision machine, see [94]). Consequently, the system is closely associated with single machine optimization problems (feeder arrangement and placement order) but since systems for these problems were already developed, it was possible to incorporate them in the *PCB Grouper* system (for further details on the single machine optimization, see [60]).

The overall design process included the introduction of a new operation policy for the plant. Before the *PCB Grouper* system, the line operated on a unique setup strategy with a standard setup for the most frequently used components. The printing programs were laborious to update, which caused that the standard setup components were seldom changed. As a consequence, the standard setup gradually corrupted to contain components whose demand was not maximal any more. In addition, there was no efficient method for solving a new standard setup. Each product required a separate setup because each printing program required a new setting for the custom setup components. Furthermore, it was seldom possible to print one product during the setup of another. The order of the components in the feeders was not very efficient, which further reduced the productivity.

Our analysis suggested that group setup strategy would be suitable for the line; however, the idea of a standard setup was retained, since it could be easily included in the machine's symmetrical layout. The total number of different jobs (or PCB batches) processed on the line is high but the amount of PCBs in a job is usually small, and thus the setup times form a significant part of the total production time. Therefore, the main objective is to minimize the setup times by grouping the products efficiently. The system tries to minimize the number of groups by using a repair-based local search heuristic. Repair-based in this case means that capacity constraints can be violated occasionally to broaden the scope of the search after which the repair operations are used to bring the search back to the set of feasible solutions. The algorithm can be stopped at any time and the currently best solution is available to the user.

The revised production planning system solves the observed inefficiencies by introducing a method for choosing the standard setup, forming groups of jobs with the same feeder setup, optimizing the feeder setup for groups, and optimizing the component placement sequence for each job in the group using the same feeder setup. The new ideas were adopted in the plant and they changed the way the work was organized.

3.2.1 System features

The system includes tools for grouping the jobs of the production plan and optimizing the setup for each group (see Figure 3.4). When using the system, the production planners can

- choose the products from a product list,
- choose which heuristic method is applied to form the groups,
- assign the standard setup,
- assign a custom setup for a given group,
- optimize component placement sequence for a whole group or for some jobs within a group,
- compare two groups in order to discern mutual components and their respective locations,
- view the current groups by listing the jobs, the components or the feeder setup,

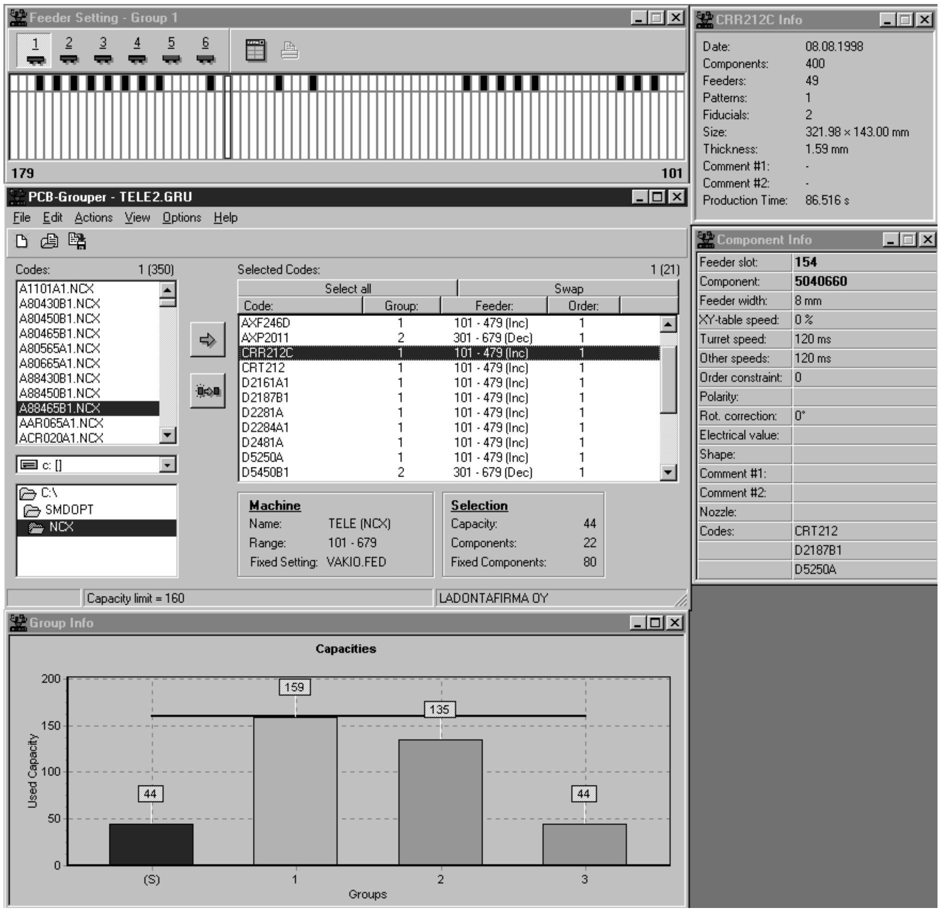

Figure 3.4: A screenshot of the *PCB Grouper* system.

- remove groups,
- move jobs between groups,
- get graphical and numerical information of the groups and the jobs,
- inspect whether a new job can be inserted to some existing group, and
- edit the component library.

The groups and the jobs within a group can be resequenced freely. The latter does not affect the setup times since no setup is needed for jobs in the same group. This allows the production planners to form a feasible schedule for the production by providing their knowledge on the duedates, the batch sizes, the required conveyor widths and the availability of required components.

3.2.2 Observations and discussion

We compared several different heuristic algorithms for realizing the grouping before deciding to use repair-based local search heuristic [115, 116]. The chosen heuristic performed well on our tests; for example, in the cases with a realistic size (30 jobs) it found always the optimum solution. The same method was also used in the succeeding *ControlBOARD* system.

The *PCB Grouper* system was commenced in real-world production in May 1997, and, right from the start, the response was exceedingly positive. Again, the production planners find the system easy to adapt to, and the group setup strategy suited their work rhythm (one planner even commented that he could now enjoy his coffee breaks without being forced to rush back to the machine every once in a while).

The effect on the production was even more significant. To evaluate the difference the manufacturer collected statistical data from the production. We compared the first ten-week period after the change to *PCB Grouper* with the preceding twenty-week period and observed the following improvements:

- The average number of component placements per hour (of total time) increased by 57.6 percent.
- The average number of component placements per hour (of the actual printing time) increased by 16 percent.
- The average number of completed jobs in a week increased from 22 to 28.
- The average time to change from one job to another (including machine setup and other delays) on the whole line decreased 35.5 percent.

To summarize, the introduction of the *PCB Grouper* system entailed a major improvement in productivity—and won for the production planners the manufacturer's yearly awarded efficiency trophy.

3.3 ControlBOARD

At the same time that *PCB Grouper* was being developed, we were already experimenting with new ideas for a better model of the plant [68]. The improved model considers also the line configuration and its characteristics. This time we decided to base the system on *fuzzy multiple criteria optimization.* Our other goal was to improve the GUI, which in the *PCB Grouper* had been down-to-earth and without much of the features that we tested in *IPS*. Thus, the premise of the new system, *ControlBOARD*, was to incorporate the algorithms from *PCB Grouper*, the GUI from *IPS*, and a more accurate model of the production environment.

In *ControlBOARD*, the main objective is to minimize the setup times by grouping the products more efficiently than in *PCB Grouper*. First, the system forms an initial solution by minimizing the number of groups heuristically. After that, the grouping is improved by considering the following additional criteria:

- The conveyor track widths of the PCBs in a group should be equal.
- Opposite sides of a double-sided PCB should be processed in the same group.
- The number of different components needed for the group setup should be minimal.
- Jobs belonging to the same urgency class should be in the same group.
- A group should comprise only boards with similar solder reflow oven temperature.
- The number of groups should be minimal.
- The sum of setup sizes of all the groups should be minimal.

Each criterion is associated with a fuzzy set and a weight indicating its relative importance. Weights ensure that the more important criteria have a greater effect on the objective function than the less important ones. A good solution is one that satisfies all the criteria but the objective function has also compensatory properties so that the effect of one poorly satisfied criterion is not too drastic on the result.

In *ControlBOARD*, the work process of the production planners has three stages: PCBs are grouped according to their components (job grouping problem), the components of each group are assigned to feeder slots (feeder optimization), and the printing time of each PCB is minimized separately on the basis of the feeder setup of the group (printing order optimization).

3.3.1 System features

The graphical user interface (see Figure 3.5) provides the production planners with a clear visualization of the production plan, a set of possible operations for altering the grouping (e.g., moving jobs between groups), warning for exceptional situations (e.g., component starvation), numerical information (e.g., estimated printing times) and tight integration with other systems (e.g., printing order optimization).

The production planners' responsibilities include data input (e.g., adding new jobs to the schedule), grouping the jobs manually, setting the importance of each criterion for the schedule improvement algorithm, and running

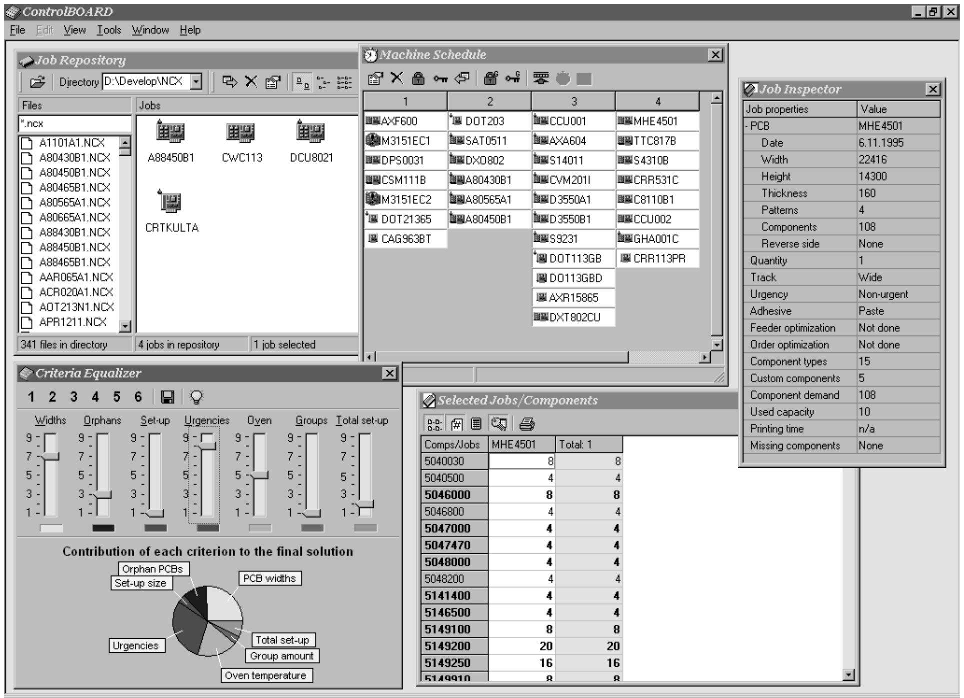

Figure 3.5: A screenshot of the *ControlBOARD* system.

feeder and print order optimization for selected jobs or groups. *ControlBOARD* system provides an algorithm for improving the schedule according to user-defined criteria, feeder optimization for a given set of jobs, printing order optimization for a given set of jobs using a given feeder setup, and an overall drag-and-drop user-interface, which allows the production planner to arrange the jobs in the schedule (and a repository for the unscheduled jobs) and gives a visual representation of the schedule. The system uses external data files for defining the machine characteristics and deriving the required product data. Furthermore, the system features include

- a visual presentation of the overall state of the production,
- a possibility to edit the schedule manually (the system checks the capacity constraints automatically) or improve it algorithmically,
- information about products, jobs, components, simulated times etc., and
- a possibility to employ feeder and printing order optimizers selectively.

3.3.2 Observations and discussion

As we expected, the new system did not bring off such drastic and immediate improvements as *PCB Grouper*, but it helped to visualize the situation and allowed the production planners to participate more actively in refining the schedule. Generally speaking, the system included so many minor but important improvements and upgrades that it is hard to give a comprehensive list.

Also in this case, we observed the changes in productivity. Before the system was introduced, the productivity had decreased almost back to the same level where it had been before *PCB Grouper* because the type of production was somewhat altered: the batch sizes had decreased (i.e., there were more jobs to be scheduled) and component starvations had narrowed the usability of the grouping. *ControlBOARD*, however, coped better with the new type of production and the net amount again increased. Also, after the introduction of *PCB Grouper*, the setup time had increased (while the number of completed jobs had not increased in the same proportion) because the system could not adapt to the unexpected changes in the production. Again, *ControlBOARD* managed to restore—and even reduce—the setup time, which was essential in the new situation. Furthermore, the number of jobs completed weekly increased 65 percent while the average batch size remained on the same level.

The system benefits the production planners as well as the workforce assigned to operate the machine. The job grouping approach increases the accuracy of the production because there are less setup operations (e.g., the risk of misplacing a component feeder diminishes). It also allows to produce smaller batches efficiently and to reduce the size of the work-in-process storage. Printing order optimization enhances the component placement speed and, consequently, increases the productivity. To put it briefly, the system enables better reactivity to changes in the production and provides an easy-to-use tool for the production planners.

3.4 Current research

Recently, parts of the systems described in this chapter have been included and adapted to the *Trilogy 5000* system of Valor Computerized Systems [127]. The systems are now being developed commercially to be integrated into a broader context of manufacturing software (e.g., CAD, CAM, assembly analysis). Also, the work for supporting more machine types and more machine vendors (e.g., Panasonic, Siemens, Sony) has been carried out.

Our current research interests include workload balancing in a single line. The modern production environments usually comprise different types of placement machines—possibly even from several different vendors. This complicates the line balancing problem, since it requires an efficient and accurate method to evaluate the production times in each machine. There are several different techniques to do this, and we are currently developing suitable estimation methods by applying regression analysis [80].

Besides new research problems, it has become evident that the (genuine) scheduling problems, which we were considering in the *IPS*, are now more topical, since there is a demand for easy-to-use and flexible scheduling systems in plants with complex shopfloor layouts. In this respect, we outlined in [113] the six key topics for future research:

1. supporting rolling horizon production planning,
2. applicability in real-world environments,
3. coping with dynamic production,
4. multiple criteria optimization,
5. interaction of the production planner and the software, and
6. integration with other software systems.

In the three applications described in this chapter, we have taken the first steps into the right direction but our goal still lies far ahead.

Chapter 4

Summary of Publications

> Every paper published in a respectable journal should have a preface by the author stating why he is publishing the article, and what value he sees in it. I have no hope that this practice will ever be adopted.
>
> —Morris Kline

In the first paper [113], we summarize the concepts behind production planning in electronics manufacturing. We argue that PCB assembly can be treated as a flexible manufacturing system (FMS), since the production almost always uses the same machinery to produce different product types. We recognize three levels of planning problems: (1) strategic or long-range planning (e.g., deciding the equipment and the products to be manufactured), (2) tactical or medium-range planning (e.g., solving the weekly production schedule), and (3) operational or short-range planning (e.g., optimizing the manufacturing operations for a product). Existing production planning systems concentrate on levels 2 and 3. We summarize technical details of PCB assembly, and introduce different placement machine types and production plant layouts. The major part of the paper is dedicated to a survey of the relevant literature for which we present a hierarchical classification scheme. After the survey, we give a summary of the existing commercial production planning systems, and, as an example, present a more detailed description of one production planning system.

In the second paper [66], we consider the scheduling and sequencing of products in an automated PCB assembly plant comprising subsequent production stages and parallel placement machines. We describe an interactive production planning system, which simulates the production from an initial situation to a given moment in the future. Based on the simulation, the system presents graphical and numerical data including lateness, machine workload, machine usage, and internal storage level graphs. In addition, the simulation gives estimated starting and finishing times for each job in the schedule. Apart from simulation, the system includes an interactive GUI, which allows the production planners to edit the schedule, the machine properties, and the plant layout. The system can be used as a basis for testing scheduling algorithms, which is done in the third paper.

In the third paper [56], we continue by comparing different scheduling algorithms in the system described in the second paper. The objective function used in the comparison tries to minimize the sum of squared tardiness of the jobs, the sum of internal buffer size of the machines, the sum of internal waiting time of the jobs, and the sum of number of families of the jobs. The algorithms allocate the batches to machines and then try to improve the allocation; after that they sequence the batches and then try to improve the sequence. We conclude from the experiments that initial allocation by batches with an improvement with globally best pair algorithm and improving the sequence by alternating the method works best.

In the fourth paper [116], we discuss the job grouping problem in a typical SMT production line. The production environment comprises a single assembly line, where one placement machine is the bottleneck. The production is high-mix, low-volume which causes several setup operations daily. By applying job grouping, the number of setup operations decreases, since all the products within one group can be manufactured with the same setup. We use approximative algorithms and give a mathematical 0/1 integer program to obtain the exact result. Test cases with realistic size (30 jobs) confirm that approximative solutions are nearly always also the optimum. We report that the system had a major impact on the productivity of the company: the average number of component placements per hour increased by 58 percent and the average job changeover time decreased by 35 percent.

In the fifth paper [117], we introduce an improved production planning system for the same environment as in the fourth paper. The new system observes multiple criteria, has a seamless integration to the other optimization software and includes an improved GUI. We use the repair-based local search method which has proven to work best in job grouping. Multiple criteria are included in problem formulation by refining the objective function with fuzzy sets and aggregation operators, which are described in the sixth paper. We report that the new system provided flexibility and robustness that the previous system lacked. After installation, it increased the number of jobs completed weekly by 65 percent.

In the sixth paper [67], we describe the fuzzy multiple criteria optimization of the job grouping problem in detail. Some constraints (e.g., component capacity) are regarded as hard constraints in the sense that they cannot be violated, while others (e.g., priority) are considered to be soft constraints and they can be violated if necessary. All the soft constraints can be represented as fuzzy sets to form a multiple criteria objective function. Different importance of the criteria can be considered by weighting the fuzzy sets. After that, the criteria are combined together by an aggregator to get the final, single-valued objective function. We demonstrate that our objective function for the job grouping problem has the desired effect on the solution in test cases and that the results are in accord with the real-world results of the fifth paper.

IN THE SEVENTH PAPER [106], we compare group and minimum setup strategies and review the implementations suggested in literature. Each algorithm is used to solve test cases documented in the literature as well as problems based on real-world production data. To evaluate the results of the computational experiments we use a cost function which accounts both the number of machine setup occasions and the total number of component setup operations. Based on the evaluation results we conclude that the group setup methods tend to yield better overall results.

Chapter 5

Concluding Remarks

> Whatever you do will be insignificant, but it is very important that you do it.
>
> —Mahatma Gandhi

We studied production planning problems arising from printed circuit board assembly. We argued that by distributing the production activities between the user and algorithm we can increase the usability of a production planning system. This turned out to be essential in PCB assembly where the production is highly dynamic and includes uncertainties. On the theoretical section, our intention was to recognize the production planning problems of PCB assembly, form a hierarchical classification for them, and review aspects of each problem class. This decomposition scheme is used as a basis for the three production planning software systems, which were developed for real-world use. We described the features of each of these systems and discussed our observations and experiences on development process. Finally, we outlined six key topics that the production planning systems should concern.

If one lesson can be learned from production planning, it is that it is hard to predict the future. The development of PCB assembly technology (in the machinery as well as in the products) is carried out with great pace. The manufacturers are keen to adopt each new invention, and the modes of production evolve in accordance with financial situation. Nevertheless, the general ideas and lessons learned, which we have discussed in the preceding pages, should last—even if the PCB assembly in the current form does not. To put it briefly, you cannot rely solely on planning; for that matter, you cannot rely solely on control, but you must find where they are best utilized. Unexpected events will occur and accidents will happen, and you should be able to control the production also at these times. But, hopefully, most of the time you can carry out the plans you have made. In this respect, manufacturing is like any other human endeavor: susceptible to forces unknown but still worth planning ahead.

Bibliography

> If you steal from one author it's plagiarism; if you steal from many it's research.
>
> —Wilson Mizner

[1] AHMADI, J., AHMADI, R., MATSUO, H., AND TIRUPATI, D. Components fixture positioning/sequencing for printed circuit board assembly with concurrent operations. *Operations Research 43*, 3 (1995), 444–57.

[2] AHMADI, J., GROTZINGER, S., AND JOHNSON, D. Emulation of concurrency in circuit card assembly machines. Tech. Rep. RC 12161, IBM T. J. Watson Research Center, Yorktown Heights, NY, 1986.

[3] AHMADI, J., GROTZINGER, S., AND JOHNSON, D. Component allocation and partitioning for a dual delivery placement machine. *Operations Research 36*, 2 (1988), 176–91.

[4] AHMADI, R. H., AND KOUVELIS, P. Staging problem of a dual delivery pick-and-place machine in printed circuit card assembly. *Operations Research 42*, 1 (1994), 81–91.

[5] AHMADI, R. H., AND KOUVELIS, P. Design of electronic assembly lines: An analytical framework and its application. *European Journal of Operational Research 115*, 1 (1999), 113–37.

[6] AHMADI, R. H., AND MATSUO, H. A mini-line approach for pull production. *European Journal of Operational Research 125* (2000), 340–58.

[7] AHMADI, R. H., AND WURGAFT, H. Design for synchronized flow manufacturing. *Management Science 40*, 11 (1994), 1469–83.

[8] ALTINKEMER, K., KAZAZ, B., KÖKSALAN, M., AND MOSKOWITZ, H. Optimization of printed circuit board manufacturing: Integrated modeling and algorithms. *European Journal of Operational Research 124*, 2 (2000), 409–21.

[9] Ammons, J. C., Carlyle, M., Cranmer, L., DePuy, G., Ellis, K., McGinnis, L. F., Tovey, C. A., and Xu, H. Component allocation to balance workload in printed circuit card assembly systems. *IIE Transactions 29*, 4 (1997), 265–75.

[10] Askin, R. G., Dror, M., and Vakharia, A. J. Printed circuit board family grouping and component allocation for a multimachine, open-shop assembly cell. *Naval Research Logistics 41* (1994), 587–608.

[11] Balakrishnan, A., and Vanderbeck, F. A tactical planning model for mixed-model electronics assembly operations. *Operations Research 47*, 3 (1999), 395–409.

[12] Ball, M. O., and Magazine, M. J. Sequencing of insertions in printed circuit board assembly. *Operations Research 36*, 2 (1988), 192–201.

[13] Bard, J. F., Clayton, R. W., and Feo, T. A. Machine setup and component placement in printed circuit board assembly. *International Journal of Flexible Manufacturing Systems 6* (1994), 5–31.

[14] Barnea, A., and Sipper, D. Set-up reduction in PCB automated assembly. *Computer Integrated Manufacturing Systems 6*, 1 (1993), 18–26.

[15] Ben-Arieh, D., and Dror, M. Part assignment to electronic insertion machines: Two machine case. *International Journal of Production Research 28*, 7 (1990), 1317–27.

[16] Ben-Arieh, D., and Maimon, O. Annealing method for PCB assembly scheduling on two sequential machines. *International Journal of Computer Integrated Manufacturing 5*, 6 (1992), 361–7.

[17] Bhaskar, G., and Narendran, T. T. Grouping PCBs for setup reduction: A maximum spanning tree approach. *International Journal of Production Research 34*, 3 (1996), 621–32.

[18] Bodner, D. A., Damrau, M., Griffin, P. M., McGinnis, L. F., and McLaughlin, A. Virtual prototyping of electronics assembly systems. In *Proceedings of the 1998 Industrial Engineering Research Conference* (1998).

[19] Bodner, D. A., Damrau, M., Griffin, P. M., McGinnis, L. F., McLaughlin, A., Spearman, M. L., and Zhou, C. Virtual machine models in electronic assembly. In *Proceedings of the 1997 Deneb International Conference and Technology Showcase* (Troy, MI, 1997).

[20] Bolton, W. *Production Planning & Control*. Longman Scientific & Technical, Essex, UK, 1994.

[21] Brandeau, M. L., and Billington, C. A. Design of manufacturing cells: Operation assignment in printed circuit board manufacturing. *Journal of Intelligent Manufacturing 2* (1991), 95–106.

[22] Brandimarte, P., and Villa, A. *Advanced Models for Manufacturing Systems Management*. CRC Press, 1995.

[23] Brucker, P. *Scheduling Algorithms*. Springer-Verlag, 1995.

[24] Carmon, T. F., Maimon, O. Z., and Dar-El, E. M. Group set-up for printed circuit board assembly. *International Journal of Production Research 27*, 10 (1989), 1795–810.

[25] Chang, C.-M., and Young, L. A simultaneous-mounting process for automated printed circuit board assembly. *International Journal of Production Research 28*, 11 (1990), 2051–64.

[26] Coble, S. B., and Bohn, R. E. Setup time reduction for electronics assembly: Combining simple (SMED) and sophisticated methods. Tech. Rep. 97-03, University of California, San Diego, CA, 1997.

[27] Crama, Y., Flippo, O. E., van de Klundert, J., and Spieksma, F. C. R. The component retrieval problem in printed circuit board assembly. *International Journal of Flexible Manufacturing Systems 8* (1996), 287–312.

[28] Crama, Y., Flippo, O. E., van de Klundert, J., and Spieksma, F. C. R. The assembly of printed circuit boards: A case with multiple machines and multiple board types. *European Journal of Operational Research 98*, 3 (1997), 457–72.

[29] Crama, Y., Koleen, A. W. J., Oerlemans, A. G., and Spieksma, F. C. R. Throughput rate optimization in the automated assembly of printed circuit boards. *Annals of Operations Research 26* (1990), 455–80.

[30] Crama, Y., Oerlemans, A., and Spieksma, F. *Production Planning in Automated Manufacturing*, vol. 414 of *Lecture Notes in Economics and Mathematical Systems*. Springer-Verlag, 1994.

[31] Crama, Y., and van de Klundert, J. Worst-case performance of approximation algorithms for tool management problems. *Naval Research Logistics 46*, 5 (1999), 445–62.

[32] Crama, Y., van de Klundert, J., and Spieksma, F. C. R. Production planning problems in printed circuit board assembly. Tech. rep., DONET Publications, 1999. http://www.cwi.nl/donet/publications.html.

[33] Cyr, B., Lambert, S., Abdul-Nour, G., and Rochette, R. Manufacturing flexibility: SMT factors study. *Computers & Industrial Engineering 33*, 1–2 (1997), 361–4.

[34] Dagnino, A. Integrated architecture for assembly planning in an electronics manufacturing environment. *Integrated Manufacturing Systems 5*, 4/5 (1994), 77–86.

[35] Daskin, M. S., Maimon, O., Shtub, A., and Braha, D. Grouping components in printed circuit board assembly with limited components staging capacity and single card setup: Problem characteristics and solution procedures. *International Journal of Production Research 35*, 6 (1997), 1617–38.

[36] Dessouky, M. M., Adiga, S., and Park, K. Design and scheduling of flexible assembly lines for printed circuit boards. *International Journal of Production Research 33*, 3 (1995), 757–75.

[37] Dillon, S., Jones, R., Hinde, C. J., and Hunt, I. PCB assembly line setup optimization using component commonality matrices. *Journal of Electronics Manufacturing 8*, 2 (1998), 77–87.

[38] Driels, M., and Klegka, J. S. An analysis of contemporary printed wiring board manufacturing environment in the USA. *International Journal of Advanced Manufacturing Technology 7* (1992), 29–37.

[39] Estremadoyro, D. N., Farrington, P. A., Schroer, B. J., and Swain, J. J. Simulation of memory chip line using an electronics manufacturing simulator. In *Proceedings of the 1997 Winter Simulation Conference* (Atlanta, GA, Dec. 1997), S. Andradóttir, K. J. Healy, D. H. Withers, and B. L. Nelson, Eds., pp. 1330–7.

[40] Fathi, Y., and Taheri, J. A mathematical model for loading the sequencers in a printed circuit pack manufacturing environment. *International Journal of Production Research 27*, 8 (1989), 1305–16.

[41] Feldmann, K., and Feuerstein, R. Developments and challenges in automatic assemblies of electronic products. Tech. rep., Institute for Manufacturing Automation and Production Systems, 1998.

[42] Feldmann, K., Franke, J., and Zöllner, B. Optimization of SMT-systems by computer-aided planning, simulation and monitor-

ing. In *IEEE/ISHM '90 IEMT Symposium* (Italy, 1990), pp. 102–113.

[43] Feo, T. A., Bard, J. F., and Holland, S. D. Facility-wide planning and scheduling of printed wiring board assembly. *Operations Research 43*, 2 (1995), 219–30.

[44] Foulds, L. R., and Hamacher, H. W. Optimal bin location and sequencing in printed circuit board assembly. *European Journal of Operational Research 66* (1993), 279–90.

[45] Fu, H.-P., and Su, C.-T. A comparison of search techniques for minimizing assembly time in printed wiring assembly. *International Journal of Production Economics 63* (2000), 83–98.

[46] Gershwin, S. B., Akella, R., and Choong, Y. F. Short-term production scheduling of an automated manufacturing facility. *IBM Journal of Research & Development 29*, 4 (1985), 392–400.

[47] Golding, D. PCB assembly. *Assembly Automation 15*, 2 (1995), 10–3.

[48] Gronalt, M., Grunow, M., Günther, H. O., and Zeller, R. A heuristic for component switching on SMT placement machines. *International Journal of Production Economics 53* (1997), 181–90.

[49] Grunow, M., Günther, H. O., and Föhrenbach, A. Simulation-based performance analysis and optimization of electronics assembly equipment. *International Journal of Production Research 38*, 17 (2000), 4247–59.

[50] Günther, H. O., Gronalt, M., and Zeller, R. Job sequencing and component set-up on a surface mount placement machine. *Production Planning & Control 9*, 2 (1998), 201–11.

[51] Gupta, J. N. D. Two stage hybrid flowshop scheduling problem. *Journal of Operational Research Soc. 39*, 4 (1988), 359–64.

[52] Hernandez, W., and Leon, V. J. An overview of the operations analysis of a two-head flexible assembly machine with interference avoidance. *Computers & Industrial Engineering 33*, 1–2 (1997), 405–8.

[53] Hillier, M. S., and Brandeau, M. L. Optimal component assignment and board grouping in printed circuit board manufacturing. *Operations Research 46*, 5 (1998), 675–89.

[54] HILLIER, M. S., AND BRANDEAU, M. L. Cost minimization and workload balancing in printed circuit board assembly. *IIE Transactions 33*, 7 (2001), 547–57.

[55] HOLCOMB, G. W. Justifying flexible automation for PCB assembly. *Assembly Automation 15*, 2 (1995), 14–6.

[56] HÄYRINEN, T., JOHNSSON, M., JOHTELA, T., SMED, J., AND NEVALAINEN, O. Scheduling algorithms for computer-aided line balancing in printed circuit board assembly. *Production Planning & Control 11*, 5 (2000), 497–510.

[57] JACKSON, M., AND JOHANSSON, C. Real time discrete event simulation of a PCB production system for operational support. In *Proceedings of the 1997 Winter Simulation Conference* (Atlanta, GA, Dec. 1997), S. Andradóttir, K. J. Healy, D. H. Withers, and B. L. Nelson, Eds., pp. 832–7.

[58] JAIN, S., JOHNSON, M. E., AND SAFAI, F. Implementing setup optimization on the shop floor. *Operations Research 43*, 6 (1996), 843–51.

[59] JI, P., SZE, M. T., AND LEE, W. B. A genetic algorithm of determining cycle time for printed circuit board assembly lines. *European Journal of Operational Research 128*, 1 (2001), 175–84.

[60] JOHNSSON, M. *Operational and Tactical Level Optimization in Printed Circuit Board Assembly*. PhD thesis, University of Turku, 1999. TUCS Dissertations 16.

[61] JOHNSSON, M., LEIPÄLÄ, T., AND NEVALAINEN, O. Determining the manual setting order of components on PC boards. *Journal of Manufacturing Systems 15*, 3 (1996), 155–63.

[62] JOHNSSON, M., PELTONEN, S., LEIPÄLÄ, T., AND NEVALAINEN, O. Work load balancing of a generalized flexible flow line in printed circuit board production. In *Proceedings of the Fifth IASTED International Conference on Robotics and Manufacturing* (Cancun, Mexico, May 1997), R. V. Mayorga, Ed., IASTED, IASTED/ACTA Press, pp. 382–9.

[63] JOHNSSON, M., AND SMED, J. Observations on PCB assembly optimization. *Electronic Packaging & Production 41*, 5 (Apr. 2001), 38–42.

[64] JOHRI, P. K. A heuristic algorithm for loading new work on circuit pack assembly lines. *International Journal of Production Research 28*, 10 (1990), 1871–83.

[65] JOHRI, P. K. Engineering a circuit board assembly line for a desired capacity and flowtime. *Journal of Manufacturing Systems 10*, 6 (1991), 492–500.

[66] JOHTELA, T., SMED, J., JOHNSSON, M., LEHTINEN, R., AND NEVALAINEN, O. Supporting production planning by production process simulation. *Computer Integrated Manufacturing Systems 10*, 3 (1997), 193–203.

[67] JOHTELA, T., SMED, J., JOHNSSON, M., AND NEVALAINEN, O. A fuzzy approach for modeling multiple criteria in the job grouping problem. Tech. Rep. 227, Turku Centre for Computer Science, Dec. 1998.

[68] JOHTELA, T., SMED, J., JOHNSSON, M., AND NEVALAINEN, O. Single machine scheduling with fuzzy multiple criteria optimization in electronic assembly. In *TOOLMET'98 Symposium* (Oulu, Finland, Apr. 1998), L. Yliniemi and E. Juuso, Eds., pp. 121–6.

[69] KHOO, L. P., AND LOH, K. M. A genetic algorithms enhanced planning system for surface mount PCB assembly. *International Journal of Advanced Manufacturing Technology 16* (2000), 289–96.

[70] KHOO, L. P., AND NG, T. K. A genetic algorithm-based planning system for PCB component placement. *International Journal of Production Economics 54*, 3 (1998), 321–32.

[71] KHOSHNEVIS, B., BOTTLIK, G., AND AZMANDIAN, A. R. Simultaneous generation of assembly plans and schedules in electronics assembly operations. *Integrated Manufacturing Systems 5*, 4/5 (1994), 30–40.

[72] KIM, Y.-D., LIM, H.-G., AND PARK, M.-W. Search heuristics for a flowshop scheduling problem in a printed circuit board assembly process. *European Journal of Operational Research 91* (1996), 124–43.

[73] KLEGKA, J. S., AND DRIELS, M. Case studies in printed wiring assembly. *Manufacturing Review 4*, 4 (1991), 286–92.

[74] KLINCEWICZ, J. G., AND RAJAN, A. Using GRASP to solve the component grouping problem. *Naval Research Logistics 41* (1994), 893–912.

[75] KLOMP, C., VAN DE KLUNDERT, J., SPIEKSMA, F. C. R., AND VOOGT, S. The feeder rack assignment problem in PCB assembly: A case study. *International Journal of Production Economics 64* (2000), 399–407.

[76] Knuutila, T., Puranen, M., Johnsson, M., and Nevalainen, O. Exact solution of the job grouping problem by constraint programming. In *Proceedings of Group Technology/Cellular Manufacturing World Symposium—Year 2000* (San Juan, Puerto Rico, Mar. 2000), W. Hernández and G. A. Süer, Eds., pp. 125–30.

[77] Knuutila, T., Puranen, M., Johnsson, M., and Nevalainen, O. Three perspectives for solving the job grouping problem. *International Journal of Production Research 39*, 18 (2001), 4261–80.

[78] Kumar, K. R., and Narendran, T. T. A heuristic for sequencing PCBs with due-dates. *International Journal of Operations & Production Management 17*, 5 (1997), 446–67.

[79] Kuriyan, K., and Reklaitis, G. V. Scheduling network flowshops so as to minimize makespan. *Computers & Chemical Engineering 13*, 12 (1989), 187–200.

[80] Laakso, T., Johnsson, M., Johtela, T., Smed, J., and Nevalainen, O. Estimating the production times in PCB assembly. Tech. Rep. 392, Turku Centre for Computer Science, Feb. 2001.

[81] Lambert, S., Cyr, B., Abdul-Nour, G., and Drolet, J. Comparison study of scheduling rules and set-up policies for a SMT production line. *Computers & Industrial Engineering 33*, 1–2 (1997), 369–72.

[82] Landers, T. L., Brown, W. D., Fant, E. W., Malstrom, E. M., and Schmitt, N. M. *Electronics Manufacturing Processes*. Prentice-Hall, Englewood Cliffs, NJ, 1994.

[83] Lee, C.-Y., and Vairaktarakis, G. L. Minimizing makespan in hybrid flowshops. *Operations Research Letters 16* (1994), 149–58.

[84] Leipälä, T., and Nevalainen, O. Optimization of the movements of a component placement machine. *European Journal of Operational Research 38* (1989), 167–77.

[85] Leon, V. J., and Peters, B. A. Replanning and analysis of partial setup strategies in printed circuit board assembly systems. *International Journal of Flexible Manufacturing Systems 8*, 4 (1996), 389–412.

[86] Leon, V. J., and Peters, B. A. A comparison of setup strategies for printed circuit board assembly. *Computers & Industrial Engineering 34*, 1 (1998), 219–34.

[87] LEU, M. C., AND JI, Z. Computer-aided process planning for printed circuit board assembly. In *Proceedings of NEPCON East Conference* (Boston, MA, June 1991), pp. 289–97.

[88] LIN, F.-R., SHAW, M. J., AND LOCASCIO, A. Scheduling printed circuit board production systems using the two-level scheduling approach. *Journal of Manufacturing Systems 16*, 2 (1997), 129–49.

[89] LIN, W.-L., AND TARDIF, V. Component partitioning under demand and capacity uncertainty in printed circuit board assembly. *International Journal of Flexible Manufacturing Systems 11*, 2 (1999), 159–76.

[90] LOFGREN, C. B., AND MCGINNIS, L. F. Dynamic scheduling for flexible printed circuit card assembly. In *Proceedings IEEE Systems, Man, and Cybernetics* (Atlanta, GA, 1986), pp. 1294–7.

[91] LOFGREN, C. B., AND MCGINNIS, L. F. Soft configuration in automated insertion. In *Proceedings of the 1986 IEEE International Conference on Robotics and Automation* (San Francisco, CA, 1986), pp. 138–42.

[92] LOFGREN, C. B., MCGINNIS, L. F., AND TOVEY, C. A. Routing printed circuit cards through an assembly cell. *Operations Research 39*, 6 (1991), 992–1004.

[93] LUZZATTO, D., AND PERONA, M. Cell formation in PCB assembly based on production quantitative data. *European Journal of Operational Research 69*, 3 (1993), 312–29.

[94] MAGYAR, G., JOHNSSON, M., AND NEVALAINEN, O. On solving single machine optimization problems in electronics assembly. *Journal of Electronics Manufacturing 9*, 4 (1999), 249–267.

[95] MAIMON, O., AND SHTUB, A. Grouping methods for printed circuit boards. *International Journal of Production Research 29*, 7 (1991), 1370–90.

[96] MAIMON, O. Z., DAR-EL, E. M., AND CARMON, T. F. Set-up saving schemes for printed circuit boards assembly. *European Journal of Operational Research 70*, 2 (1993), 177–90.

[97] MANGIN, C.-H. Line efficiency and productivity measures. *Surface Mount Technology* (Oct. 1999), 114–6.

[98] MCGINNIS, L. F., AMMONS, J. C., CARLYLE, M., CRANMER, L., DEPUY, G. W., ELLIS, K. P., TOVEY, C. A., AND XU, H. Automated process planning for printed circuit card assembly. *IIE Transactions 24*, 4 (1992), 18–30.

[99] Nesbit, A. Maximising throughput of the component assembly process. *Soldering & Surface Mount Technology 10*, 1 (1998), 6–9.

[100] Nevalainen, O., and Johnsson, M. Optimoinnilla tuottavuutta. *Prosessori 4* (1998), 70–1. In Finnish.

[101] Ohno, K., Jin, Z., and Elmaghraby, S. E. An optimal assembly mode of multi-type printed circuit boards. *Computers & Industrial Engineering 36*, 2 (1999), 451–71.

[102] Peters, B. A., and Subramanian, G. S. Analysis of partial setup strategies for solving the operational planning problem in parallel machine electronic assembly systems. *International Journal of Production Research 34*, 4 (1996), 999–1021.

[103] Pinedo, M. *Scheduling: Theory, Algorithms, and Systems.* Prentice-Hall, Englewoods Cliffs, NJ, 1995.

[104] Rajkumar, K., and Narendran, T. T. A heuristic for sequencing PCB assembly to minimize set-up times. *Production Planning & Control 9*, 5 (1998), 465–76.

[105] Sadiq, M., Landers, T. L., and Taylor, G. D. A heuristic algorithm for minimizing total production time for a sequence of jobs on a surface mount placement machine. *International Journal of Production Research 31*, 6 (1993), 1327–41.

[106] Salonen, K., Johnsson, M., Smed, J., Johtela, T., and Nevalainen, O. A comparison of group and minimum setup strategies in PCB assembly. In *Proceedings of Group Technology/Cellular Manufacturing World Symposium—Year 2000* (San Juan, Puerto Rico, Mar. 2000), W. Hernández and G. A. Süer, Eds., pp. 95–100.

[107] Sanchez, J. M., and Priest, J. W. Optimal component insertion sequence-planning methodology for semi-automatic assembly of printed circuit boards. *Journal of Intelligent Manufacturing 2* (1991), 177–88.

[108] Scholl, A. *Balancing and Sequencing of Assembly Lines.* Physica-Verlag, Heidelberg, 1995.

[109] Shevell, S. F., Buzacott, J. A., and Magazine, M. J. Simulation and analysis of a circuit board manufacturing facility. In *Procedings of the 1986 Winter Simulation Conference* (1986), J. Wilson, J. Henriksen, and S. Roberts, Eds., pp. 686–93.

[110] Shmoys, D. B., Stein, C., and Wein, J. Improved approximation algorithms for shop scheduling problems. *Siam Journal on Computing 23* (1994), 617–32.

[111] SHTUB, A., AND MAIMON, O. Role of similarity in PCB grouping procedures. *International Journal of Production Research 30*, 5 (1992), 973–83.

[112] SMED, J., JOHNSSON, M., JOHTELA, T., AND NEVALAINEN, O. Group technology in electronics assembly. In *Automaatio 1999* (Helsinki, Finland, Sept. 1999), R. Heinonen, Ed., pp. 379–84.

[113] SMED, J., JOHNSSON, M., JOHTELA, T., AND NEVALAINEN, O. Techniques and applications of production planning in electronics manufacturing systems. Tech. Rep. 320, Turku Centre for Computer Science, Dec. 1999. To appear in *Computer-Aided Design, Engineering and Manufacturing (CADEM) Systems Techniques*, C. T. Leondes, Ed. Gordon and Breach.

[114] SMED, J., JOHNSSON, M., AND NEVALAINEN, O. A hierarchical classification scheme for electronics assembly problems. In *Proceedings of TOOLMET2000 Symposium—Tool Environments and Development Methods for Intelligent Systems* (Oulu, Finland, Apr. 2000), L. Yliniemi and E. Juuso, Eds., pp. 116–9.

[115] SMED, J., JOHNSSON, M., PURANEN, M., LEHTINEN, J., LEIPÄLÄ, T., AND NEVALAINEN, O. On the work process organization of surface mounted component printing. Tech. Rep. 139, Turku Centre for Computer Science, Oct. 1997.

[116] SMED, J., JOHNSSON, M., PURANEN, M., LEIPÄLÄ, T., AND NEVALAINEN, O. Job grouping in surface mounted component printing. *Robotics and Computer-Integrated Manufacturing 15*, 1 (1999), 39–49.

[117] SMED, J., JOHTELA, T., JOHNSSON, M., PURANEN, M., AND NEVALAINEN, O. An interactive system for scheduling jobs in electronic assembly. *International Journal of Advanced Manufacturing Technology 16*, 6 (2000), 450–9.

[118] SMED, J., SALONEN, K., JOHNSSON, M., JOHTELA, T., AND NEVALAINEN, O. A comparison of group and minimum setup strategies in PCB assembly. Tech. Rep. 327, Turku Centre for Computer Science, Jan. 2000.

[119] SMTNET. SMTnet library, 2001. http://www.smtnet.com/library/.

[120] SPEDDING, T. A., AND SUN, G. Q. Application of discrete event simulation to the activity based costing of manufacturing systems. *International Journal of Production Economics 58* (1999), 289–301.

[121] SULE, D. R. A heuristic procedure for component scheduling in printed circuit pack sequencers. *International Journal of Production Research 30*, 5 (1992), 1191–208.

[122] SUPINSKI, M. R., EGBELU, P. J., AND LEHTIHET, E.-A. Automatic plan and robot code generation for a PCB assembly. *Manufacturing Review 4*, 3 (1991), 214–24.

[123] TANG, C. S., AND DENARDO, E. V. Models arising from a flexible manufacturing machine. *Operations Research 36*, 5 (1988), 767–84.

[124] TAYLOR, JR., G. D. Simulation of memory chip line using an electronics manufacturing simulator. In *Proceedings of the 1990 Winter Simulation Conference* (New Orleans, LA, Dec. 1990), O. Balci, R. P. Sadowski, and R. E. Nance, Eds., pp. 567–9.

[125] TENG, S.-H. G., AND GARIMELLA, S. S. Manufacturing cost modeling in printed wiring board assembly. *Journal of Manufacturing Systems 17*, 2 (1998), 87–96.

[126] UNIVERSAL INSTRUMENTS CORPORATION. Glossary of site terms, 2001. http://www.uic.com/wcms/wcms.nsf/index/.

[127] VALOR COMPUTERIZED SYSTEMS. Trilogy 5000 overview, 2001. http://www.valor.com/t5kover.html.

[128] VAN LAARHOVEN, P. J. M., AND ZIJM, W. H. M. Production preparation and numerical control in PCB assembly. *International Journal of Flexible Manufacturing Systems 5* (1993), 187–207.

[129] WANG, C. Layout designs for robotic PCB assembly. *Soldering & Surface Mount Technology 10*, 2 (1998), 36–48.

[130] WANG, C., HO, L.-S., AND CANNON, D. J. Heuristics for assembly sequencing and relative magazine assignment for robotic assembly. *Computers & Industrial Engineering 34*, 2 (1998), 423–31.

[131] WATKINS, R. E., AND COCHRAN, J. K. A line balancing heuristic case study for existing automated surface mount assembly line setups. *Computers & Industrial Engineering 29*, 1–4 (1995), 681–5.

[132] WITTROCK, R. J. Scheduling algorithms for flexible flow lines. *IBM Journal of Research and Development 29*, 4 (1985), 401–12.

[133] WITTROCK, R. J. An adaptable scheduling algorithm for flexible flow lines. *Operations Research 36*, 3 (1988), 445–53.

[134] XU, Z., CARLSON, K., KURSCHNER, R., AND RANDHAWA, S. An integrated methodology for surface mount PCB configuration. *Computers & Industrial Engineering 35*, 1–2 (1998), 53–6.

[135] YEO, S. H., LOW, C. W., AND YONG, K. H. A rule-based frame system for concurrent assembly machines. *International Journal of Advanced Manufacturing Technology 12*, 5 (1996), 370–6.

[136] ZARROW, P. Automatic components placement systems. *Circuits Assembly Magazine* (Oct. 1996).

[137] ZHOU, M., AND LEU, M. C. Petri net modeling of a flexible assembly station for printed circuit boards. In *Proceedings of the 1991 IEEE International Conference on Robotics and Automation* (Sacramento, CA, Apr. 1991), pp. 2530–5.

[138] ZIJM, W. H. M., AND VAN HARTEN, A. Process planning for a modular component placement system. *International Journal of Production Economics 30–31* (1993), 123–35.

Publication Reprints

Smed, Johnsson, Johtela, and Nevalainen, “Techniques and Applications of Production Planning in Electronics Manufacturing Systems”, Technical Report 320, Turku Centre for Computer Science, December 1999. To appear in C. T. Leondes (ed.), *Computer-Aided Design, Engineering and Manufacturing (CADEM) Systems Techniques*, Gordon and Breach.

Johtela, Smed, Johnsson, Lehtinen, and Nevalainen, “Supporting Production Planning by Production Process Simulation”, *Computer Integrated Manufacturing Systems*, 10(3):193–203, 1997.

Häyrinen, Johnsson, Johtela, Smed, and Nevalainen, "Scheduling Algorithms for Computer-Aided Line Balancing in Printed Circuit Board Assembly", *Production Planning & Control*, 11(5):497–510, 2000.

Smed, Johnsson, Puranen, Leipälä, and Nevalainen, "Job Grouping in Surface Mounted Component Printing", *Robotics and Computer-Integrated Manufacturing*, 15(1):39–49, 1999.

Smed, Johtela, Johnsson, Puranen, and Nevalainen, "An Interactive System for Scheduling Jobs in Electronic Assembly", *International Journal of Advanced Manufacturing Technology*, 16(6):450–9, 2000.

Johtela, Smed, Johnsson, and Nevalainen, "A Fuzzy Approach for Modeling Multiple Criteria in the Job Grouping Problem", Technical Report 227, Turku Centre for Computer Science, December 1998. A shortened version of the paper has been published in Dessouky, Waly, and Eid (eds.), *Proceedings of the 25th International Conference on Computers & Industrial Engineering*, pp. 447–50, New Orleans, LA, March 1999.

Salonen, Johnsson, Smed, Johtela, and Nevalainen, “A Comparison of Group and Minimum Setup Strategies in PCB Assembly”, in Hernández and Süer (eds.), *Proceedings of Group Technology/Cellular Manufacturing World Symposium—Year 2000*, pp. 95–100, San Juan, Puerto Rico, March 2000.