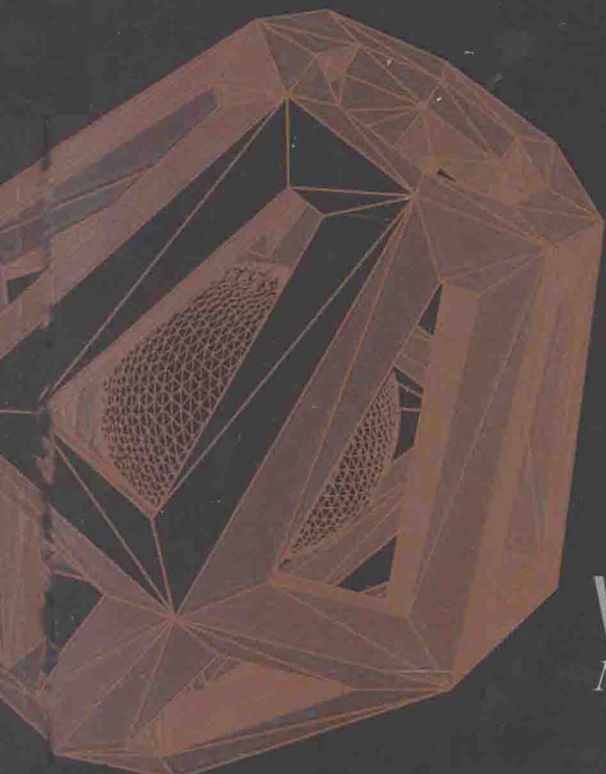

Vol. 5
Manufacturing Processes

Computer Aided and Integrated Manufacturing System

A 5-Volume Set

Cornelius T Leondes

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University of California, Los Angeles, USA

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Preface

Computer Technology

This 5 volume MRW (Major Reference Work) is entitled "Computer Aided and Integrated Manufacturing Systems". A brief summary description of each of the 5 volumes will be noted in their respective PREFACES. An MRW is normally on a broad subject of major importance on the international scene. Because of the breadth of a major subject area, an MRW will normally consist of an integrated set of distinctly titled and well-integrated volumes each of which occupies a major role in the broad subject of the MRW. MRWs are normally required when a given major subject cannot be adequately treated in a single volume or, for that matter, by a single author or coauthors.

Normally, the individual chapter authors for the respective volumes of an MRW will be among the leading contributors on the international scene in the subject area of their chapter. The great breadth and significance of the subject of this MRW evidently calls for treatment by means of an MRW.

As will be noted later in this preface, the technology and techniques utilized in the methods of computer aided and integrated manufacturing systems have produced and will, no doubt, continue to produce significant annual improvement in productivity — the goods and services produced from each hour of work. In addition, as will be noted later in this preface, the positive economic implications of constant annual improvements in productivity have very positive implications for national economies as, in fact, might be expected.

Before getting into these matters, it is perhaps interesting to briefly touch on Moore's Law for integrated circuits because, while Moore's Law is in an entirely different area, some significant and somewhat interesting parallels can be seen. In 1965, Gordon Moore, cofounder of INTEL made the observation that the number of transistors per square inch on integrated circuits could be expected to double every year for the foreseeable future. In subsequent years, the pace slowed down a bit, but density has doubled approximately every 18 months, and this is the current definition of Moore's Law. Currently, experts, including Moore himself, expect Moore's Law to hold for at least another decade and a half. This is impressive with many significant implications in technology and economies on the international scene. With these observations in mind, we now turn our attention to the greatly significant and broad subject area of this MRW.

"The Magic Elixir of Productivity" is the title of a significant editorial which appeared in the *Wall Street Journal.* While the focus in this editorial was on productivity trends in the United States and the significant positive implications for the economy in the United States, the issues addressed apply, in general, to developed economies on the international scene.

Economists split productivity growth into two components: Capital Deepening which refers to expenditures in capital equipment, particularly IT (Information Technology) equipment: and what is called Multifactor Productivity Growth, in which existing resources of capital and labor are utilized more effectively. It is observed by economists that Multifactor Productivity Growth is a better gauge of true productivity. In fact, computer aided and integrated manufacturing systems are, in essence, Multifactor Productivity Growth in the hugely important manufacturing sector of global economies. Finally, in the United States, although there are various estimates by economists on what the annual growth in productivity might be, Chairman of the Federal Reserve Board, Alan Greenspan — the one economist whose opinions actually count, remains an optimist that actual annual productivity gains can be expected to be close to 3% for the next 5 to 10 years. Further, the Treasure Secretary in the President's Cabinet is of the view that the potential for productivity gains in the US economy is higher than we realize. He observes that the penetration of good ideas suggests that we are still at the 20 to 30% level of what is possible.

The economic implications of significant annual growth in productivity are huge. A half-percentage point rise in annual productivity adds $1.2 trillion to the federal budget revenues over a period of ten years. This means, of course, that an annual growth rate of 2.5 to 3% in productivity over 10 years would generate anywhere from $6 to $7 trillion in federal budget revenues over that time period and, of course, that is hugely significant. Further, the faster productivity rises, the faster wages climb. That is obviously good for workers, but it also means more taxes flowing into social security. This, of course, strengthens the social security program. Further, the annual productivity growth rate is a significant factor in controlling the growth rate of inflation. This continuing annual growth in productivity can be compared with Moore's Law, both with huge implications for the economy.

The respective volumes of this MRW "Computer Aided and Integrated Manufacturing Systems" are entitled:

Volume 1: Computer Techniques
Volume 2: Intelligent Systems Technology
Volume 3: Optimization Methods
Volume 4: Computer Aided Design/Computer Aided Manufacturing (CAD/CAM)
Volume 5: Manufacturing Process

A description of the contents of each of the volumes is included in the PREFACE for that respective volume.

Henceforth, Manufacturing Processes will be continually improved and updated with a view towards enhancing productivity significantly, and this is the subject of Volume 5. Production planning will become increasingly effective and will greatly enhance the production process in major areas such as electronics manufacturing systems. Mold design is a complicated process and powerful computer techniques are presented for manufacturing systems in this area. Computer modelling for the determination of optimum manufacturing strategy will increasingly become a way of life in manufacturing systems, and this greatly significant topic is discussed in this volume. Machining operators are one of the most prevalent methods utilized in manufacturing systems, and economic optimization methods in CAM (Computer Aided Manufacturing) systems as they relate to machining operations are treated comprehensively in this volume. An absolutely essential process in manufacturing processes is the construction of solid models in CAD (Computer Aided Design), and highly powerful computer techniques for accomplishing this are presented. Manufacturing systems are generally sophisticated Mechatronic Systems, i.e. the optimal integration of electronic and electromechanic systems, and the computer techniques and applications required in such Mechatronic Systems are discussed in detail. These and numerous other significant techniques are treated rather comprehensively in this volume.

As noted earlier, this MRW (Major Reference Work) on "Computer Aided and Integrated Manufacturing Systems" consists of 5 distinctly titled and well-integrated volumes. It is appropriate to mention that each of the volumes can be utilized individually. The significance and the potential pervasiveness of the very broad subject of this MRW certainly suggests the clear requirement of an MRW for a comprehensive treatment. All the contributors to this MRW are to be highly commended for their splendid contributions that will provide a significant and unique reference source for students, research workers, practitioners, computer scientists and others, as well as institutional libraries on the international scene for years to come.

Contents

CHAPTER 1

TECHNIQUES AND APPLICATIONS OF PRODUCTION PLANNING IN ELECTRONICS MANUFACTURING SYSTEMS

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The electronics industry is a major part of modern manufacturing, and electronic systems play an increasingly important role in the majority of today's products. Electronic systems are usually implemented with printed circuit boards (PCBs), and, consequently, PCB assembly has become an important sector of the electronics manufacturing industry overall. However, operating effectively in this industry is becoming more difficult as the companies must compete with high quality standards, rapidly changing technologies, short production cycles, and increasing product variety and complexity. In addition, the capital equipment cost of electronics assembly industry facilities are high in comparison to the usual turnover of a company. As a result, production planning decisions need to made more and more frequently due to continuous changes in the production conditions.

In this work we discuss production planning in electronics assembly—and in particular, in PCB assembly. Our intention is to identify the typical problems arising from production planning and to give a survey of the solution methods suggested in the literature. In addition to this theoretical perspective, we will briefly review applications designed for production planning in PCB assembly.

This work is organized as follows. We begin with an introduction to flexible manufacturing systems in general and present a framework for production planning systems in Sec. 1. Next, we study the fundamentals of PCB assembly process in Sec. 2 and survey the relevant literature in Sec. 3. In Sec. 4 we review existing commercial applications for production planning, and in Sec. 5 study more closely one of these systems. Finally, in Sec. 6 we sum up the discussion and outline few important topics for the future research.

Keywords: Production planning; electronics manufacturing systems; flexible manufacturing systems; automated manufacturing.

1. Introduction

Let us begin our discussion by recalling some basic concepts of industrial production. Five basic types of production operations can be classified according to the degree repetitiveness involved[20]: project, jobbing, batch, flow, and process. The *project form* includes large-scale complex products, and it involves the allocation and coordination of large-scale input to achieve a unique product. *Jobbing* describes a situation where the manufacturing of a whole product is considered as one operation and the work must be completed on each product before starting on the next. In the *batch form*, the volume of products to be manufactured is larger than in jobbing. A regular and consistent demand for a product such that the item can be produced for stock identifies the *flow production*. Lastly, the *process production* requires that the material is involved in a continuous process.

The type of production affects also the plant layout. There are three basic forms of layout[20]: process, product, and group. The *process layout*, in which all the plants associated with a particular type of process are grouped together, is typical in jobbing and batch production. In the *product layout*, which occurs in flow and process forms of production, the plant is laid out according to the sequence of processes required by the product. A *group* (or cellular) *layout* is typical in batch production, and it involves the recognition that many of the products have similarities in their makeup and they can thus be grouped into (product) families.

There are two basic principles for decomposing a manufacturing facility into subsystems: decomposition based on processes and decomposition based on products.[42] *Process based facility decomposition* leads to equipment being arranged into functional machining areas (*work centers*) dedicated to general manufacturing processes (i.e. *job shop*). *Process planning* is the systematic determination of the detailed methods by which parts can be manufactured from raw material to finished products. *Computer-aided process planning* (CAPP) *determines a set of instructions and machining parameters required to manufacture a part and prepares data for production planning and scheduling activities.*[85] As Zijm and van Harten[120] observe, CAPP bridges the gap between *computer-aided design* (CAD) and *computer-aided manufacturing* (CAM), and thus CAPP represents the "/" in CAD/CAM. *Process control* refers to the automatic monitoring and control of a process by an instrument or system configured or programmed to respond appropriately to process feedback.[102]

Product based decomposition utilizes the principle of group technology by dedicating machines to cells in order to produce the associated families of parts (i.e. *cellular manufacturing*). *Production planning* refers to the *process of establishing strategies for producing finished products so that manufacturing resources are used efficiently.* When there is a large number of production variables and a long planning horizon, the problem can be approached by breaking it hierarchically into a series of decision levels.[109] *Production control* is the *systematic planning, coordination and direction of all manufacturing activities to ensure that products (of adequate quality) are made on time and at reasonable cost.*[102] To summarize, in production planning we first *make a plan* anticipating the future events and after that *follow the plan*, whereas in production control we simply *react to the events* as they occur during the production.

In the remainder of this section we discuss flexible manufacturing systems (FMSs) in Sec. 1.1, and develop a common methodology for building practical production planning systems in FMSs in Sec. 1.2.

1.1. *Flexible manufacturing systems*

In the late 1950s, several ideas for improving manufacturing began to surface. One of the earliest was the idea of group technology for manufacturers who had to make a variety of different but similar parts. In some types of industry—for example, chemical and oil-refining industries—*automated manufacturing* has a long history, but in the batch-manufacturing industries—like the metalworking industry and the electronics industry—the concept of automated manufacturing was introduced in the early 1970s. By then, a number of technological developments, in particular flexible manufacturing systems, offered solutions to the problems of job shop environments.

Automated manufacturing has a wide variety of potential benefits to offer. One of the most important advantages is the increased ability to respond to changes in demand and changes in the products, which is essential in the today's view of short production cycles. Other advantages include shorter lead times, reduction in the work-in-process levels and improved machine utilization. At the same time it is not an easy task to fully attain these possibilities, because the reality of the shop floor rarely coincides with the theoretical models (as we shall see in Sec. 1.2.1).

A *flexible manufacturing system* (FMS) aims at achieving a similar level of effiency for manufacturing several different product types as in the mass production of a single product type. An FMS comprises a *group of programmable production machines integrated with automated material handling equipment which are under the direction of a central controller to produce a variety of parts at non-uniform production rates, batch sizes and quantities.*[53] The machines or work stations are used to perform operations on parts, and each operation requires a number of tools that can be stored in the limited capacity tool magazine of the machines. An automatic tool interchanging device switches the tools during production. Because this interchange is relatively quick, the machine can perform several operations with *virtually no setup time* between the operations, if the required tool is present in the tool magazine.

Electronics assembly (especially printed circuit board assembly) plants are usually FMSs. However, the terminology associated with FMS, which originates from the metal industry, can be somewhat confusing when applied to electronics assembly. For example, the concept of "tool" refers to a *feeder*, which contains the electronic component to be mounted, rather than the actual tool (or *nozzle*) which does the printing operation. We discuss the technical aspects of electronics assembly at greater length in Sec. 2.

The most prevalent analytical approach to real-time FMS control attempts to hierarchically decompose the problem into a number of more easily manageable subproblems, which relate to a variety of decisions concerning *long-term*, *medium-term* or *short-term planning*. One of the main reasons for decomposing the general planning problem is that this problem is 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.

A typical hierarchical classification scheme of FMS[28] discerns:

(1) *Strategic level* or *long-range planning* which 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* which determines the allocation patterns of the system production capacity to various products so that external demands are satisfied (e.g. by solving *batching* and *loading problems*).
(3) *Operational level* or *short-range planning* which coordinates the shop floor production activities so that the higher level tactical decisions are observed (e.g. by solving *release* and *dispatching problems*).

Maimon and Shtub[82] and Johnsson[54] relate these objectives to electronics assembly: 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 equipments and what kind of machines should be purchased[35]). These decisions are usually made on an economical basis, and they are revised over long operational periods, typically measured in several months.[34,66] 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). *The tactical and operational problems have to be solved frequently, and consequently, the existing production planning systems concentrate on these levels.*

Notwithstanding the similarities, there are also differences between PCB assembly and FMSs. Klegka and Driels[66] study four cases of PCB assembly and conclude that FMS analysis is inappropriate for PCB assembly system analysis: FMS analysis chooses among multiple paths through manufacturing systems, and the best path depends on the state of the system that is changing as the workload changes. In PCB assembly, however, the production cycle is fixed (e.g. receiving inspection, panel preparation, screen paste, paste volume inspection, component placement, solder joint reflow, visual inspection, and X-ray inspection) and that results a single, sequential, and somewhat deterministic manufacturing process. Hence, a linear cost model may be adequate to evaluate and identify the cost elements of a PCB manufacturing system.

Zhou and Leu[119] list three features of PCB assembly distinct from conventional systems for automated assembly of mechanical parts:

(1) Each PCB requires numerous insertions, and the activities for each board are highly repetitive.

(2) There is no strict sequence which has to be followed, and the components can be inserted (almost) in any order (i.e. they have no or just a few precedence constraints).
(3) Only a single manipulator can operate at the time on the board even if the machine has multiple manipulators (e.g. see Ref. 46).

Jain *et al.*[52] discuss setup problems in FMSs and PCB assembly. They translate the tool setup problem of FMSs into PCB assembly system and show that the FMS formulation is a relaxed version of PCB component setup problem: in PCB assembly the tooling is more constrained due to the restrictions on the width of the component reels.

1.2. *Production planning in FMSs*

Despite the differences mentioned earlier, we will, for the remainder of this section, regard PCB assembly as an FMS. In Sec. 1.2.1, we begin with a discussion of the common problems apparent in the theoretic approaches to construct a practical production planning system. After that, in Sec. 1.2.2, we suggest a methodology for overcoming these problems and describe a general framework for modeling production planning problems.

1.2.1. *Problems in constructing a practical production planning system*

According to Ammons *et al.*[9] the control of an FMS requires a complex interaction of two components:

(1) Computers to perform automated control and routing activities.
(2) Humans to supervise the automation, to monitor system flows and output, to intervene in the unexpected operation of the system, and to compensate the effect of unanticipated events.

Especially in dynamic production environments (i.e. in FMSs which are subject to limited resources, random machine failures or multiple optimization criteria) the problem of controlling and scheduling the production process is best tackled by a synergy of the computer's scheduling algorithms and the human's effective internal heuristics. In this "interactive scheduling" the production planner remains in control and is able to affect the scheduling process by using his experience and intuition via computer support. In other words, the production planning system should act as a decision support for the production planner.

However, literature references to practical systems where this interaction has been realized are rare, and the models—even if based on reality—tend to be oversimplified. According to Saygin *et al.*[96] the existing software tools are typically (1) too slow and cannot react to changing dynamic shop floor conditions; (2) based on simplistic formulations of the reality that ignore important constraints; (3) based on a single objective function or simplistic trade-offs; and (4) difficult to install and integrate into preexisting commercial shop floor systems. In general, the gap between theory and practice can usually be attributed to the following factors:

(1) Researchers fail to address the right problems.
(2) The given solutions are too complex to use.
(3) Findings are presented in terms that are foreign to the practitioners.
(4) Researchers focus on certain problems and omit other, often more important issues.
(5) The realities of the shop floor are ignored.

As Johnsson notes,[54] these observations are valid in electronics assembly, where problems are usually tackled by first modeling an existing problem, then finding a solution method to the problem, and after that validating both the solution method and the model by solving some randomly generated artificial test cases. However, this approach does not shed much light on the *practicality* of the method.

In addition to interactivity, real-world scheduling problems usually differ (and often quite radically) from the mathematical models presented in literature. Pinedo lists twelve differences[91]:

(1) Theoretical models assume that the scheduling problem is static, whereas in the real world new jobs to be scheduled can emerge at any time and the schedule is constructed without a perfect knowledge of the near future. The *production environment is dynamic* by nature (e.g. jobs may arrive unexpectedly, urgent prototype series may cut in the predefined sequence, machines may break down or have a temporary reduction in the production rate, or the required components may not be available at the present time).
(2) Resequencing problem is rarely addressed in literature even though it is present in most of the actual problems. Production planning is based on a *rolling horizon*, which leads to *rescheduling* or *reactive scheduling*, where the schedule is constantly updated and revised to meet events occurring randomly.
(3) In the real world, *production environments are more complicated than the models presented in literature*, which often disregard machine, job and time dependent processing restrictions and constraints.
(4) The mathematical models assume that the weights or priorities of the jobs are fixed and do not change over time; in practice, the *weight of a job often fluctuates over time* (e.g. a low-priority job may become suddenly a high-priority job).
(5) *Preferences* are usually not taken into account in mathematical models. In reality, even if a job can be scheduled on a given machine, there may be a preference to schedule it on another one.
(6) Most theoretical models overlook the *machine availability constraints* and assume that machines are available at all times, whereas the real-world production plants have deterministic and random processes which prevent machines

from operating (e.g. shift patterns, preventive maintenance, breakdowns and repairs).

(7) Most penalty functions considered in the literature are piecewise linear (e.g. the tardiness of a job or the unit penalty), whereas, in practice, there usually exists a committed *duedate.*

(8) Theoretical research tends to focus on models with a single objective. In the real world, there are usually *a number of objectives*, whose weights may vary over time and may even depend on the subjective preferences of the production planner in charge.

(9) In practice, whenever the workload appears to be excessive and the due dates appear to be too tight, the problem can be tackled by assigning *extra shifts* and *scheduling overtime.*

(10) The stochastic models studied in the literature usually assume special *processing time distributions* (e.g. exponential distribution). In automated assembly, the processing time is fixed with a very high probability, and with a very low probability there is an additional random time that is exponentially distributed with a very large mean (i.e. if a robot performs a task, the processing time is fixed, and if, by accident, something goes wrong, the processing time immediately becomes significantly larger).

(11) *Successive processing times* on the same machine tend to be highly positively correlated in practice, whereas theoretical models usually assume that all processing times are independently drawn from given distributions.

(12) In practice, the *processing time distribution* may be subject to change due to learning or deterioration.

In spite of the differences between the real-world and the mathematical models, Pinedo notes that the general consensus is that the theoretical research done in the past has not been in vain, but it has provided valuable insights into many scheduling problems. These insights have proven to be useful in the development of the algorithmic framework for a large number of real-world production planning systems.

1.2.2. *Structure of a production planning system*

The methodology for solving the production planning problems can be divided into four stages:

(1) Familiarization with the problem environment.
(2) Modeling the problem.
(3) Designing and implementing algorithms to solve the modeled problem.
(4) Integrating the algorithm to an existing system or including it in a new system.

The far-reaching decisions made in the initial stages influence the overall usability of the system. For example, if the model fails to represent the important aspects of the real-world problem, no algorithm (no matter how cleverly designed and effectively implemented it is) can give results which would satisfy the production planner. In our experience, this modeling process cannot be overlooked nor its importance underestimated: a poor algorithm solving an accurately modeled problem gives better real-world results than an accurate algorithm solving poorly modeled problem.

After the initial familiarization stage, the construction of a production planning system begins with building a model which represents the production environment. At the same time one must bear in mind that this model is always an idealization of the actual problem: a coarse model may be easier to understand but it may lack some important aspects, whereas a detailed model may be a more accurate representation but much harder to understand. Because of this duality there are two approaches for using the model: if there is uncertainty about the accuracy of the model, we may want to grant the final decision to a human user, and in this case the model is used to point out the important aspects of the actual problem and possibly for suggesting some solutions. An alternative approach is to solve the problem by using an algorithm which utilizes an objective function based on the model for evaluating the solutions.

Figure 1 illustrates the role of the model in this scheme. A system based on visualization allows the production planner to interact and analyze the schedule, whereas an algorithm driven system solves the given problem efficiently and is independent from the user. Although both approaches have their benefits, extremes should be avoided when designing a production planning system. An algorithm is capable of solving a combinatorial problem inexhaustibly, whereas a human tends to try only few possible solutions before choosing one. Instead, a human usually has some "outside" knowledge about the reality concerning the problem, whereas the algorithm "sees" nothing but the model. Therefore, the usability of a production planning system, in essence, depends on the balance between these two points of view: the computer should provide the user with sufficient support for making the actual decision (e.g. generate a number of good schedules from which the

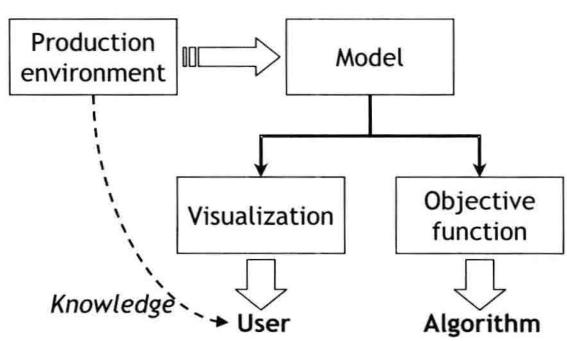

Fig. 1. A model of the production environment can be used as a basis for visualization or for calculating an objective function.

user chooses—and possibly refines—one for the production). Saygin *et al.*[96] conclude that the human scheduler should remain in control and be able to affect the scheduling process, because the model is an abstraction of the reality and, therefore, cannot capture all the characteristics of a problem, and because it is hard to transcribe the entire knowledge of the human scheduler in a computable form. Ammons *et al.*[9] express a similar view: "an 'optimal' real-time scheduling system is one that effectively combines computer scheduling algorithms and artificial intelligence methodologies within the context of the versatile capabilities of the human supervisor". Also, Martin-Vega[86] lists the integration of human and technical resources to enhance workforce performance and satisfaction as one of the six grand challenges for future research.

Figure 2 gives a more detailed view of the structure of a general production planning system. There are two ways, which correspond to the division shown in Fig. 1, to interact with the system: either directly by altering the production plan or indirectly by controlling the algorithm with the objective function and parameter settings. In the former case, the user makes alterations in the graphical representation of the production plan; the system updates the production plan accordingly or informs the user if the suggested change violates some hard constraint of the model. In the latter case, the user adjusts the objective function by setting weights for different criteria. The objective function is then used by an optimization algorithm, which generates a new production plan. After that, the new plan is simulated in order to discern predefined characteristics (e.g. lateness, earliness, workload, line balance, buffer sizes; see Refs. 35, 51, 71 and 97), which are used in the next iteration of the objective function and can be visualized to the user.

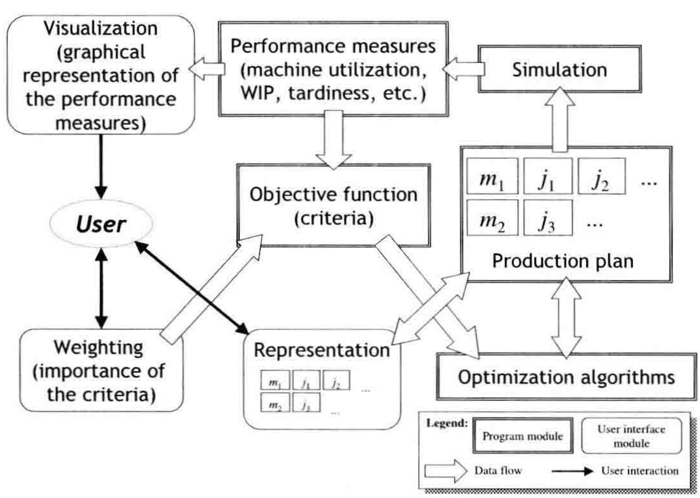

Fig. 2. The interaction between the components of a general production planning system.

Essentially, the modules represented in Fig. 2 are self-contained and connected by well-defined interfaces. For example, the optimization algorithm alters the production plan, which gives feedback whether the alteration violates any of the hard constraints, and receives an evaluation of the new plan from the objective function. Apart from these definements, the algorithm can be designed and implemented independently from the rest of the system.

Smith and Peters[101] present a more general framework for production planning and control systems. They observe that the development of FMS control systems is still implementation-specific and no tools exist to automate this development process. As a result, changes to the systems are often difficult to make, which has lead to many instances where FMS installations have failed to live up to expectations due to the inflexibility of the underlying control software. As a solution, Smith and Peters present an FMS control system concept, which comprises three components: a resource model instance (which combines the system configuration and the production requirements), a decision maker module, and an execution module. The *resource model instance* provides structural information required for constructing the other two modules, as well as the operational information required to run the system. The *decision-making module* decomposes the production requirements into specific instructions for the *execution module*, which interacts with the physical equipment and personnel on the shop floor to implement the given tasks. Within this general framework, the model of Fig. 2 corresponds to the decision-making module and clarifies the interaction between the system and the user.

2. Printed Circuit Board Assembly

A common characteristic in the printed circuit board (PCB) assembly industry is that customers demand more functions and flexibility each year in the products they buy. In addition, consumers expect reliable and cheap products, and thus a common goal in the PCB assembly industry is to put more functions into a board with the same size and cost.[108]

PCB assembly requires complete agility and reliability, which are only achievable with the use of robotics.[49] 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 board assemblies. 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 longer.

A recent development in PCB assembly is the growing role of *contract manufacturing*. Many original equipment manufacturers (OEMs) have abandoned the