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ISSUES IN LOADING AND SCHEDULING OF SMT LINES*

Summary. Surface Mount Technology (SMT) has been widely used for the last decade in the manufacture of printed wiring boards. A typical SMT line consists of several assembly stations in series and/or parallel, separated by finite intermediate buffers. This paper discusses some significant issues in the loading and scheduling of SMT lines. Various configurations of SMT lines encountered in the electronics industry are described and compared. A new integer programming approach to scheduling SMT lines with blocking due to full buffers is introduced and applied to determine optimal schedules for a numerical example with a dual-conveyor line. The influence of process time variability and machine breakdowns on an SMT line's performance is discussed.

PROBLEMY RÓWNOWAŻENIA OBCIĄŻEŃ MASZYN I SZEREGOWANIA ZADAŃ W LINIACH MONTAŻU ELEKTRONICZNEGO

Streszczenie. W pracy przedstawiono problem równoważenia obciążeń maszyn i szeregowania operacji w liniach SMT (ang. Surface Mount Technology) montażu powierzchniowego kart elektronicznych. Omówiono i porównano różne konfiguracje linii spotykanych w przemyśle elektronicznym. Przedstawiono koncepcję modelowania problemu szeregowania linii SMT z blokowaniem maszyn jako zadania programowania całkowitoliczbowego. Zamieszczono przykładowe harmonogramy montażu kart elektronicznych wyznaczone na podstawie takiego modelu dla linii SMT z podwójnym transporterem. Na koniec przedyskutowano wpływ typowych zakłóceń losowych na funkcjonowanie linii SMT.

1. Introduction

Surface Mount Technology (SMT) has been widely used for the last decade in the manufacture of printed wiring boards. SMT assembly involves the following basic processes: screen printing of solder paste on the bare board, automated placement of components, robotic or manual placement of large components, and solder reflow. A typical SMT line consists of several assembly stations in series and/or parallel, separated by finite intermediate buffers and connected by a conveyor system transferring the boards between the stations [7, 8].

The two major short-term planning problems in electronics assembly are loading and scheduling. Given a mix of boards to be produced, the loading objective is to allocate assembly tasks and component feeders among the placement stations with limited working

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space, so as to balance the station workloads, e.g. [9]. An important issue in printed wiring board assembly is dynamic balancing of SMT lines that accounts for the intermittent availability of machines and variability of processing times, which are caused by machine breakdowns and part pick-up failures. In contrast, the scheduling objective is to determine the detailed sequencing and timing of all assembly tasks for each individual board, so as to maximize the line's productivity, which may be defined in terms of the assembly schedule length (makespan) for a mix of board types. The limited intermediate buffers between stations result in a „blocking scheduling" problem, where a completed board may remain on a machine and block it until a downstream machine becomes available. Blocking scheduling has received surprisingly little attention in the literature from either a theoretical or computational perspective [1].

It has recently been demonstrated that loading and scheduling can be successfully solved with mathematical programming techniques, thanks to advances in computer hardware and software. While integer programming formulations have been widely used to express the assembly line balancing problems (e.g. [4]), there are only a few papers that have applied this technique to scheduling flexible flow lines, such as SMT lines. In practice, both the loading and scheduling decisions are often made based on various heuristic approaches (e.g. [7, 9]) which cannot guarantee the best utilization of SMT line capabilities.

This paper provides a modeling approach (cf. [6]) that uses mixed integer programming for scheduling flexible flow lines with finite capacity buffers. The approach can be applied to construct optimal blocking schedules by using commercially available software for mixed integer programming. This has been illustrated in the paper with a numerical example. The optimal schedules for the example problem have been found using an advanced algebraic modeling language AMPL with the CPLEX solver that runs on Windows platform.

This paper focuses primarily on the scheduling problem for SMT lines and is organized as follows. In the next section various configurations of SMT lines encountered in the electronics industry are described, and their basic characteristics are compared. In section 3 a new integer programming approach to blocking scheduling of SMT lines is introduced and applied to determine optimal schedules for a numerical example with a dual-conveyor line. The influence of process time variability and machine breakdowns on an SMT line's performance is discussed in section 4, followed by some concluding remarks in the last section.

2. SMT Line Configurations

Printed wiring board (PWB) assembly is typically is performed on an automated SMT line which includes three different processes in the following sequence: solder printing, component placement and solder reflow. For the process of solder printing and reflow soldering, one machine per line is needed. The number of machines for the placement process can vary and depends on the number and type of components on the boards to be assembled. Basically, these electronic components can be divided into two major groups: small chip parts and fine pitch parts. It is assumed that an SMT line contains at least one machine capable of placing each component group. The components can be assembled on one or both sides of a

PWB. The manufacturing line can be single- or double-sided, which means that the board may travel once or twice through the same line. In addition, each PWB can be transported and assembled as a set of boards in a panel.

The following are the basic SMT line configurations found in electronics assembly factories:

1. SMT lines for single-sided boards
    - 1.1 SMT line with single stations
    - 1.2 SMT line with parallel stations
    - 1.3 SMT line with dual-conveyor
2. SMT lines for double-sided boards
    - 2.1 Single-pass SMT line
    - 2.2. Double- pass SMT line

SMT lines for single-sided boards

A simple *SMT line with single stations* is shown in Fig. 1. In this basic configuration, all machines in the SMT line are connected in series. The line consists of a PWB loader, a solder printer, a reflow oven and two placement machines (one for small and one for fine pitch components). The placement machines have to be adjusted to the product running by controlling the conveyor width, installing the proper feeders for components, as well as selecting the nozzle configuration to pick up the required components. Machines are separated by buffers and connected with conveyors. The assembly process is as follows: A tote of bare (pre-assembly) PWBs is brought to the beginning of the line, and a material loader loads each PWB separately on the conveyor. Each PWB is transported by the conveyor system through each machine in the line and then is stored again in a tote box. The loader and the tote box are used as the input and output buffers of the line. There are external buffers in front of and behind each placement machine, except the last one. In addition, every placement machine has its own internal input and output buffers of a fixed capacity. The internal and external buffers are shown in Fig. 1 in gray.

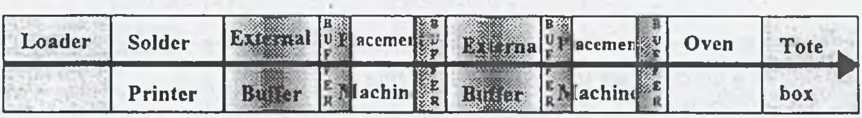

Fig.1. A simple SMT line with single stations
Rys.1. Linia SMT z pojedynczymi stacjami

The *SMT line with parallel stations* in Fig. 2 consists of two parallel placement machines for small components and two additional shuttles routing the PWB to the next available placement machine. The "placement density effect" tends to increase throughput in this line configuration. A parallel station in Fig. 2 would assemble twice as many parts as a single station in Fig.1.

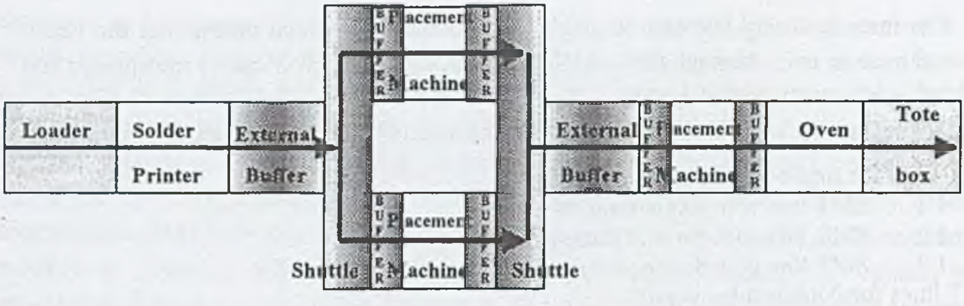

Fig.2. SMT line with parallel stations
Rys.2. Linia SMT z równoległymi stacjami

Therefore, the non-productive operations of board loading-unloading would represent a smaller fraction of the total assembly time at the station, and the average time per placement would decrease.

To further reduce the effects of load-unload times and achieve higher throughput at each station, *a dual-conveyor SMT line* (Fig.3) has been introduced. Each placement machine is equipped with a dual conveyor system that can operate in either synchronous or asynchronous mode. In synchronous mode, two panels are loaded at the same time. Thus, the loading time per panel is halved, and the number of placements in the assembly program is doubled. In asynchronous mode, a second panel can be loaded or unloaded while the first panel is being assembled.

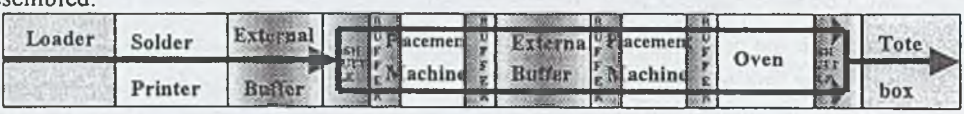

Fig.3. Dual-conveyor SMT line
Rys.3. Linia SMT z dwoma transporterami

SMT lines for double-sided boards

Generally there are two ways to produce double-sided boards, i.e., using a single-pass (continuous) line or a double-pass (re-entrant) SMT line.

A single-pass SMT line (Fig.4) consists of two lines linked together by a board flipping station. Each PWB is transported by the conveyor system through the complete line.

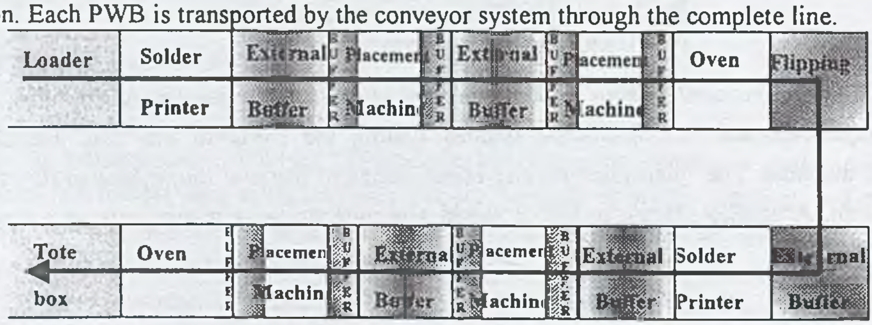

Fig.4. Single-pass SMT line
Rys.4. Jednoprzejściowa linia SMT

After the first side of the PWB is completed in a *double-pass (re-entrant) SMT line* (Fig.5), the individual panels return to the front of the line, or panels get collected in a cassette and

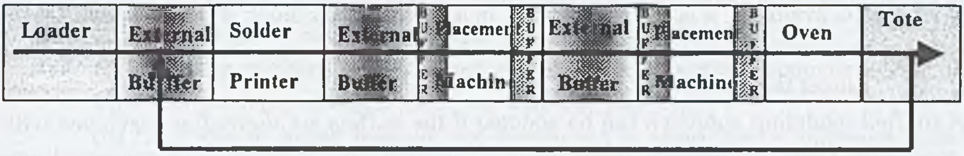

Fig.5. Double- pass SMT line
Rys.5. Dwuprzejściowa linia SMT

then return as a batch to the front. At the beginning of the line, the PWB is flipped and inserted in the production flow again. During the second pass, the second side of the PWB is populated with components, and the finished products are collected in a tote and leave the line. Table 1 gives an overview and comparison of the different SMT line configurations.

Table 1

Characteristics of various SMT line configurations

Type of SMT line	Functional characteristics	Relia-bility	Cycle time	Work in process	Typical applications
1.1) SMT line with single stations	Standard configuration	-	-	-	For production of any type of PWB
1.2) SMT line with parallel stations	Placement machines have a parallel configuration	Higher than 1.1	Lower than 1.1 due to placement density effect	Higher than 1.1	For medium volume production (24 hours a day, 7 days a week), with high replenishment and setup times
1.3) SMT line with dual-conveyor	Placement machines are equipped with a dual conveyor system	-	Lower than 1.1 due to elimina-tion of the non-productive transport time	Higher than 1.1	For high volume production (24 hours a day, 7 days a week)
2.1) Double-pass SMT line	PWB has to re-enter the line	-	-	-	For medium volume and high mix production
2.2) Single-pass SMT line	A manufactu-ring line for each side of the PWB	Lower than 2.1	Lower than 2.1	Higher than 2.1	For high volume production (24 hours a day, 7 days a week)

3. Scheduling for SMT Lines

An SMT line is a practical example of a flexible flow line with limited intermediate buffers and parallel machines.[5]. The line produces several different board types. Each board is processed by at most one machine in each stage. A board which has completed processing on a machine in some stage is transferred either directly to an available machine in the next stage or to a buffer immediately preceding that stage. A typical scheduling objective is to determine the shortest production schedule for a mix of boards, so as to complete all the boards in a minimum time and by this to maximize throughput and machine utilization. In SMT lines blocking scheduling problems may often arise, e.g., [1]. When no intermediate buffer storage is available, a board may remain in a machine and block it until a downstream machine becomes available. This prevents another board from being processed on the blocked machine and causes the machine to be idle.

A unified modeling approach can be adopted if the buffers are viewed as machines with zero processing times. In this way, the scheduling problem with buffers can be converted into one with no buffers but with blocking, e.g., [3, 6]. The blocking time of a machine with zero processing time denotes the time a board waits in the buffer represented by that machine. It is assumed that each board must be processed in all stages, including the buffer stages. However, zero blocking time in a buffer stage indicates that the corresponding board does not need to wait in the buffer. Buffers and machines can be jointly called processors.
Blocking scheduling of a flexible flow line with limited intermediate buffers can be formulated as a mixed integer program that addresses the two basic questions:

- What should be the sequence of boards entering the line?
- What should be the assignment of boards to parallel stations and buffers?

The generic scheduling model has the following structure [6]:

Minimize **Maximum completion time**
subject to

1. **Assignment constraints for stages with parallel processors** to ensure that each board is assigned to exactly one processor and to equalize the workload assigned to each parallel processor.
2. **Assignment constraints for stages with dual conveyors** to ensure that each board is assigned to exactly one conveyor and does not change the conveyor until completion.
3. **Board completion constraints** to ensure that each board is processed at all stages.
4. **Board non-interference constraints** to ensure that no two boards are processed by the same processor simultaneously.
5. **No-store constraints** to ensure that processing of each board at every stage starts immediately after its departure from the previous stage.
6. **Completion time constraints** to ensure that each board leaves the line as soon as it is completed at the last stage. These constraints are also used to calculate the maximum completion time, i.e., the makespan of a given production schedule.

The high complexity of an SMT line scheduling problem is mainly caused by:

- limited buffers that result in machine blocking and require separate board completion and board release time variables to be introduced for each board, machine, and buffer,
- parallel processors that require additional binary assignment variables to be introduced for each board, machine, and buffer,
- simultaneous assembly of different board types, and
- medium to high volume production that contributes to the size of scheduling problem.

In order to reduce the complexity of a **general scheduling** problem, where any sequence of boards is allowed, the following scheduling modes can also be considered:

- **Cyclic scheduling**, where different board types are scheduled alternately in a cyclic order of board types, where in addition:
  (a) the cycle of board types is fixed and equal to the optimal sequence determined for a minimum set of boards (e.g., one board of each type) or
  (b) the cycle of board types is not determined a priori, but is obtained with the optimal schedule for all boards.
- **Batch scheduling**, where boards of a given type are scheduled consecutively, where in addition:
  (a) the sequence of board types is fixed and equal to the optimal sequence determined for a minimum set of boards (e.g., one board of each type) or
  (b) the sequence of board types is not determined a priori, but is obtained with the optimal schedule for all boards.

In order to test the four proposed methods for reducing computational complexity, optimal assembly schedules were determined for a double conveyor line (see, Fig. 3) with a screen printer, two placement machines and an oven. Schedules for 30 boards of 3 types (10 boards of each type) were found by solving mixed integer programs representing some typical electronics assembly line scenarios. The assembly times (in seconds) required for each type of board at each processing stage are shown in Table 2.

Table 2

Assembly Times

Board type	1	2	3
Screen printer:	20	20	20
Placement machine #1:	112	117	147
Placement machine #2:	120	102	113
Oven:	40	40	40

Characteristics of the mixed integer programs for the example problem and the solution results are summarized in Table 3. The size of the mixed integer programs is represented by the total number of variables, *Var.*, number of binary variables, *Bin.*, number of constraints, *Cons.*, and number of nonzero coefficients, *Nonz.*, in the constraint matrix. The last two columns of Table 3 give the number of nodes in the branch-and-bound tree and CPU computation time in seconds required to find a proven optimal solution.

Table 3

Mixed Integer Program Characteristics and Solution Results

Mode	*Var.*	*Bin.*	*Cons.*	*Nonz.*	C_{max} [s]	*Nodes*	*CPU* [s]
General	1501	660	20354	74550	3922	20	36
Batch	1501	660	20651	75144	3922	60	19
Cyclic	1447	606	20381	72336	3922	0	28

The examples were solved on a Compaq Presario 1830 laptop with a Pentium III, 450 MHz processor using AMPL and the CPLEX v.6.5.2 solver.

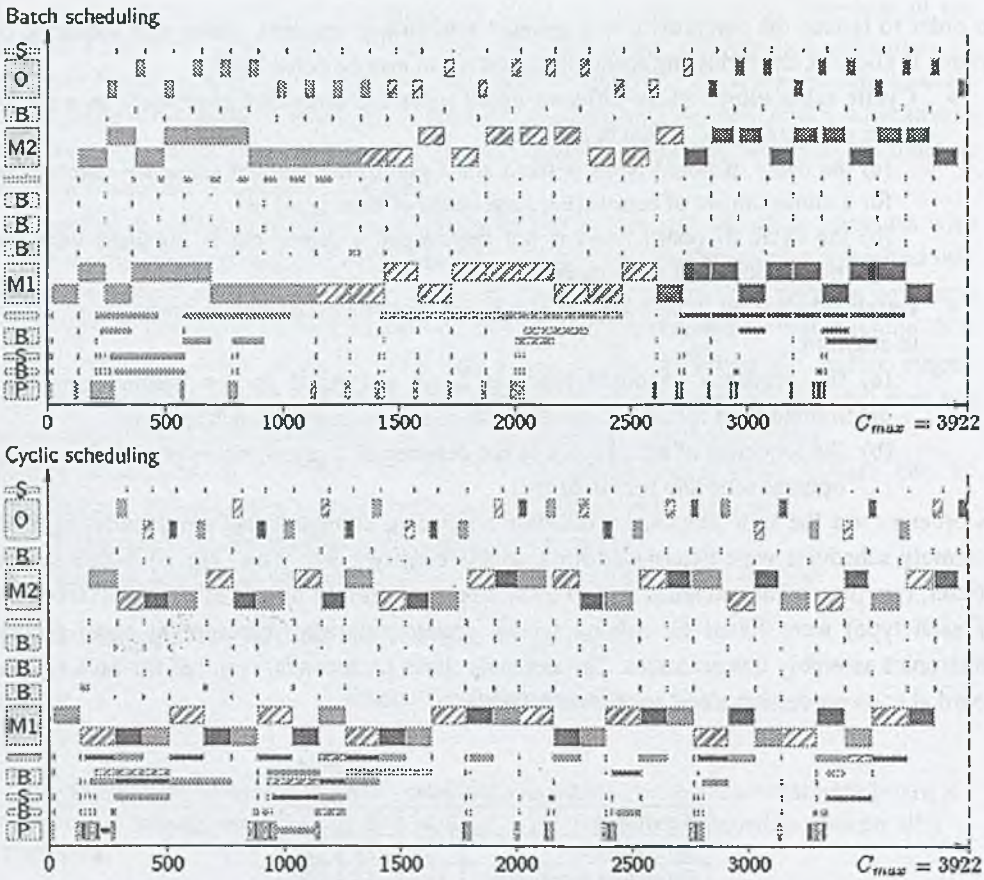

Fig.6. Optimal schedules for batch and cyclic scheduling modes
Rys.6. Optymalne harmonogramy: seryjny i cykliczny

The optimal schedules obtained for batch and cyclic scheduling are shown in Fig. 6, where letters B, M, O, P and S stand for Buffer, Machine, Oven, Printer and Shuttle, respectively. Boards of types 1 and 2 are indicated with different shading and boards type 3 with cross hatching. The sequence of board types was not fixed a priori. The optimal sequence of board types for batch scheduling is 1,3,2 and is the same as the optimal cycle of board types for cyclic scheduling. For the example problem, the same optimal makespan C_{max} = 3922 [s] was achieved for all scheduling modes.

4. Effects of Randomness on SMT Line Performance

One of the sources of randomness in an SMT line is the natural variability caused by differences in vision inspection times and loading and unloading times. These times are determined by the motors that run the conveyors. There is also some variability from machine breakdowns, which can require additional machine operations and/or actions by human operators. An example of the first type of breakdown is the picking of components from feeders. If a pickup is not successful, the mis-picked part has to be dropped into a trash box, and the complete pickup process will be repeated. Depending on how many of these mis-picks occur during a machine cycle, the process time can increase by 5 sec. or more. This results in a randomized actual process time with a minimum raw process time for all SMT placement machines.

The solder printing process is a typical example of the second type of breakdown. The solder stencil has to be cleaned by a human operator (or automatically in newer machines) after approximately every 20 to 30 panels. This results in frequent breaks in the output of the machine itself. Another example is the replenishment of components on the SMT machine by the operator to keep the machine running. There are also frequent short stops in the SMT line which can be described by the Mean Time To Assist (MTTA) and Mean Time Between Assists (MTBA). Likewise, all machines have a characteristic breakdown behavior known as Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR). The MTBF is assumed to be significantly longer than the makespan of a typical production schedule. Random disturbances that may occur in an SMT line and their influence on the line performance are described in Table 4.

Table 4

Random disturbances in SMT lines

Random Effects	Natural randomness	Randomness caused by breakdowns			Randomness caused by changeovers
		Pickup errors	Operator required breakdowns	Machine breakdowns	
Variability	Frequent	Frequent	Frequent (MTBA)	Infrequent (MTBF)	Infrequent
	Very small	Small	Medium (MTTA)	Large (MTTR)	Very large
Impact on Throughput	Not measurable	Cycle time increases on the bottleneck machine	Higher variability of the line flow	Complete stop of the production	Planned, organized stop of the complete line
Statistical Distribution	Normal	Pearson 6	Gamma	Gamma	-
Examples	Vision time, loading / unloading time	Vacuum leakage, bent nozzles	Stencil cleaning, component replenishment	Broken part	Maintenance, feeder changeover

5. Concluding Remarks

This paper has proposed the use of mixed integer programming for scheduling SMT lines. It is a general approach which can be applied to a variety of different assembly line configurations with only small modifications to the constraint formulations and/or input data definitions. The most important scheduling decisions for PWB assembly include the input sequence of boards entering an SMT line and the assignment of boards to parallel machines or conveyors. The detailed timing of start and finish events for each station is of secondary importance. The computational effort to find optimal schedules for realistic problems, e.g., for the electronics industry, can be reduced by introducing specific scheduling modes, such as batching or cyclic.

Batch sizes and cyclic schedules are two types of "environmental controls" than can be imposed on a production system to improve its performance and reduce the complexity of the associated optimization problems. Work-in-process (WIP) limits, e.g., kanban, have been proposed as effective countermeasures against variability in process times [2]. Future work should include an investigation of other environmental factors, such as the buffer sizes and locations. Future work should also focus on the application of large-scale mixed integer programs for simultaneous (e.g. [5]) loading and scheduling of SMT lines. This technique might be very useful both for off-line decision making as well as for developing fast heuristics for real-time re-balancing and re-scheduling, which is necessary when the different types of randomness discussed in this paper cause disruptions in the line.

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Streszczenie

W pracy przedstawiono problem równoważenia obciążeń maszyn i szeregowania operacji w liniach SMT (ang. Surface Mount Technology) montażu powierzchniowego kart elektronicznych. Linia SMT zbudowana jest z szeregowo połączonych stacji montażowych, rozdzielonych buforami międzyoperacyjnymi i powiązanych jednokierunkowym systemem transportu paneli z montowanymi kartami. Omówiono różne konfiguracje linii spotykanych w przemyśle elektronicznym: linie z pojedynczymi i/lub równoległymi maszynami, linie z pojedynczym lub podwójnym transporterem oraz linie jedno- lub dwuprzejściowe dla montażu dwustronnych kart elektronicznych. Przedstawiono nową metodę modelowania problemu szeregowania linii SMT z blokowaniem maszyn jako zadania programowania całkowitoliczbowego. Dla produkcji średnio- lub wysokoseryjnej rozważono możliwość zastosowania w praktyce harmonogramowania seryjnego lub cyklicznego. W pracy zamieszczono przykładowe harmonogramy montażu kart elektronicznych wyznaczone na podstawie modelu programowania całkowitoliczbowego dla rzeczywistej linii SMT z podwójnym transporterem. Na koniec przedyskutowano wpływ typowych zakłóceń losowych na funkcjonowanie linii SMT w praktyce.