A Batch Sequencing Model for a Semiconductor Packaging Company

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***Abstract*— The objective of this work is to reduce the machine downtime due to setup times during the electrical test in a semiconductor packaging company, whose products has high volume–high mixture characteristics. The group technology is adapted for the plant production workflow modeling. Based on the real data of the production floor, a taxonomy of setup times was developed. The compatibility of different package geometries was validated to build product families. As a result, a flexible batch sequencing model is obtained. The model is implemented in the plant showing an increment of 25.93% of the installed capacity in a pilot test and of 12% under real conditions. The proposed batch sequencing model is exportable to any discrete manufacturing business, which has to sequence production orders.**

***Index Terms*— group scheduling, sequence-dependent setup time, product family, batching, part number.**

I. Introduction

A semiconductor packaging company realizes some assembly operations and an electrical test of products with high volume–high mixture characteristics. This process is time-consuming and requires hundreds of machines, which occupy big areas of the plant. There are two machine platforms (types M1 and M2), each one with a number of identical machines working in parallel. Due to the nature of the electrical test on the electronic components, there is a difference in the performance of this operation on different microcircuits, which implicates preferences in allocating a product to a predetermined platform for processing to avoid additional adjustments. An individual machine adjustment to process a production lot may take from a few minutes to some hours depending on the similitude of the adjacent products in the workflow. Consecutively, the lot changeover time on a machine is strictly dependent on the sequence of the lots. Given the diversity and the frequent changes of the product nomenclature at the plant, the minimization of the machine setup break times implies a reduction of the flowtime, as well as a decrease of the flowtime, the penalties, the number of involved machines, the facilitation of rescheduling, an improvement of the machine loading, and consecutively, a decrease of the production costs.

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There are several practical approaches used to reduce the overall setup time as well as the sequence-dependent setup time (SDST). These approaches are mainly described in earlier publications. Afentakis et al [1] proposed to enlarge the lot sizes. Nevertheless, this method leads to an accumulation of the work-in-process (WIP), and it may also be impossible to create larger lot sizes. A second method proposed by Boyle [2] consists in reducing the setup frequency, and is essentially based on the group technology (GT) concept, which was initially proposed for a single machine environment. A similar method, which is referred to as sequence-dependent scheduling (SDS), was proposed by Kusiak et al. [3]. The products requiring the same limited resources (jigs, fixtures, etc.) are scheduled separately from each other to reduce the waiting period of these resources. Carmon et al. [4] formulated the group set-up scheduling (GSU) approach for a multi-machine environment. Ovacik and Uzoy [5] presented some dispatching rules to decompose the general complex job shop problem of testing facilities into a number of work centers, and then to simplify the management of setups with the goal to reduce the WIP. Leon and Petters [6] suggested a partial setup strategy for replanning purposes on a single-placement multiproduct machine in a Printed Circuit Board (PCB) assembly system. The partial setup proposed is a combination of a unique setup for each product and a group setup for a group or family of similar products. Lambert et al. [7] considered both approaches, SDS and GSU, combined with the family shortest processing time (FSPT) first scheduling rule for a surface mount technology (SMT) production line.

The mentioned strategies are widely recognized in the semiconductor industry, and various models that allow a better utilization of the installed capacity were developed. In this paper, the workflow on the electrical test planning area is analyzed in order to minimize SDST on the equipment. A paradigm shift is proposed, with which planning is done at the product family level instead of at the level of the part number, always starting with priority products required by the market.

The rest of the paper is organized as follows. After presenting a state-of-art review for the parallel machine SDST problem in Section 2, a batch sequencing model is exposed in Section 3, where the GT was adapted to the work flow characteristics. The pilot test implementation is described in Section 4. Some conclusions and future work conclude the paper in Section 5. This paper is an extended version of [8].

II. State-of-art of parallel machine SDST scheduling

It is known that even the single machine the scheduling problem involving arbitrary sequence-dependent setup times is strongly NP-hard, see Pinedo [9]. The recent literature shows the whole diversity of scheduling technics, which were applied to the variants of the problem. So, recently, various publications appeared, which consider SDST in parallel machine environments. Logendran et al. [10] proposed six different search algorithms based on tabu search. Vallada and Ruiz [11] presented a genetic algorithm with a fast local search and a local search enhanced crossover operator. Two versions of the algorithm were obtained after calibrations using the Design of Experiments (DOE) approach. Two heuristics were presented by Gamberini et al. [12] for a job pre-allocation to parallel unrelated machines when the batch size is not known a-priori to minimize the average idle residual capacity during the planning horizon. A mathematical model was also given. Zeidi and Hosseini [13] considered the problem under due-date constraints to minimize the total cost of tardiness and earliness. A new mathematical model was presented due to the complexity of the problem and an integrated metaheuristic algorithm, which consists of a genetic algorithm as the basic algorithm and a simulated annealing method as a local search procedure to improve the quality of the solutions. Wang et al. [14] proposed a hybrid estimation of distribution algorithm (EDA) with iterated greedy (IG) search (EDA-IG). Numerical tests and comparisons with 1640 benchmark instances show that the EDA-IG outperforms the existing GAs.

It can be noted that several approaches use the GT for the solution of practical problems involving SDST. It is based on the principle "similar things should be done similarly". This philosophy was formulated first by Mitrofanov [15], and then popularized by Gombinski [16]. The GT is dedicated to increase the production efficiency through a simplification and standardization in the organization of all participants of the production. The main idea consists in the formation of the part families exploiting technical similarities of the machine tools, processing facilities, and people. Similar parts are sorted out and put together into groups, according to predetermined design attributes, such as shape, size, geometry, material used, similar components, or manufacturing attributes, such as processing time, lot size, sequence of the operations. The parts of the same family do not require a considerable setup in-between, therefore the setup times are eliminated or reduced.

The reader can find details of the flexible planning with GT in earlier publications. The basic concepts were described in Askin and Standridge [17]. In the paper by Burbidge [18], the first step in the GT planning was explained. Cyr at all. [19] studied the influence of the new SMT on the manufacturing flexibility. They paid attention on the effect of different strategies of the product family formation based on four different GT policies. Liaee and Emmons [20] presented a general model and notations for single and parallel machine environments. The authors classified problems according to the complexity for both group and non-group technology assumptions. Cheng et al. [21] proposed heuristic batching rules for clustering the machines into the cells, which process the part families. Foulds and Neumann [22] proposed a GT Network Flow Model, which permitted to solve simultaneously two problems that before were solved separately: i) assigning parts to individual machines, and ii) forming matches into cells. The paper by Andrés et al. [23] addressed the problem of grouping the products with common features in a tile plant, with the goal to minimize SDST. The "coefficient of similarity" between the products was first defined and used as a parameter, allowing products to be grouped when the setup in-between is small or simple. There are three criteria to define whether two products belong to the same family and their interpretation for the tile industry. The authors reported about positive results of the implementation of this model in a tile plant. An exploratory study of computational challenges in industrial grouping problems is presented in [24].

There are several publications dedicated directly to the implementation of GT in semiconductor plants. The most close one to our research is the work by Sinma and Tharmmaphornphilas [25], which explored the effect of the product and machine grouping on the performance of a final test process. The attributes used to classify a product include package sizes, lead types and the hardware required including machine, handlers, load boards and tools. So, 545 types of products were grouped into 65 families, generally two types: 1) with unshared resource, and 2) with shared resource. Moreover, 216 handlers, 330 load boards, and 327 tools were grouped into 840 combination sets were generated that belong to 6 types of machines. The result obtained was very significant: a capacity reduction of 12.8% compared with the current capacity planning of the company and a setup time reduction of 7.8%

Some reviews on group scheduling can be found since 2000. Potts and Kovalyov [26] considered scheduling with batching. Logendran et al. [27] surveyed papers about group scheduling in flexible flow shops. Zhu and Wilhelm [28] reviewed the literature on sequence-dependent setups for scheduling and lot sizing problems. Optimization and hybrid methods as well as heuristics were summarized for different circuit card assembly line configurations. Pickardt and Branke [29] surveyed setup-oriented dispatching rules, which were categorized into purely setup-oriented, composite and family-based rules. The performance of the most promising rules were compared empirically. Allahverdi [30] presented the third comprehensive survey on scheduling problems with setup times/costs, where static, dynamic, deterministic, and stochastic problems with family and non-family setups for different shops were considered. The most recent review by Neufeld et al. [31] is the most exhaustive one. It is dedicated directly to group scheduling, particularly, in flow shop environments. A classification, the problem specification and complexity for basic group scheduling problems as well as for their extensions were presented in the survey. The authors characterized group scheduling by sequencing tasks on two levels: 1) a sequence of the part families has to be determined considering major family setup times while, 2) a job sequence has to be found within each part family. Some open problems and promising fields for future research in the area of flow shop group scheduling were pointed out. A description of basic concepts on SDST and GT can be found in [32].

The state-of-art analysis shows that there are numerous algorithms to schedule jobs in parallel machine environments with SDST, for both group and non-group technology assumptions. Usually they are time-consuming and therefore, their use for the application in a high tech semiconductor packaging company with high volume–high mixture product characteristics is restricted. In addition, it can be concluded that group scheduling is a convenient approach to improve the machine loads and increase the plant productivity. The majority of publications use families as part of the input data for the experiments, but there are a few, which are dedicated to the formation of the families of products and the effect of grouping based on the plant planning model.

III. Batch sequence modelling

A study of the workshop setup information was performed to set the relation ´product geometry– setup time´, which was used to model a batch sequence. As a preliminary step, the products were grouped into three categories. Then the setup activities, which are required when a lot change occurs, were fixed. With this information the products were grouped forming the families, the lots were grouped into the batches, and a general model for batch sequencing was built.

A. Grouping the Products into Families

In the case considered, a family includes all those products (part numbers) that share the same geometry of the microcircuit and therefore do not require a major adjustment between production lots. The geometry stands as the microcircuit device surface size (Package Size) and the height (Package Height).

To extract all geometries declared in the business plan and to group the products into the families, the company catalog and the portfolio were considered. Table I shows the number of geometric variations in the portfolio. As it can be seen from this table, approximately 67% of the geometries are active and constitute the main part in the product categorization for the planning according to the demands.

TABLE I
Product portfolio characteristics

Products	Quantity	Geometries	Heights
Active	556	70	11
Inactive	533	34	5
Total	1089	104	16

The three product groups were established according to the A-B-C categories of inventories, where category A denotes the highest priority, and C denotes the lowest one, as a function of the volumes required by every geometry. The mentioned categories are referred to in the classification of inventories established by American Production and Inventory Control Society (APICS) [33]. Table II shows that different geometries are confronted with the volumes required and the product mix within the period, resulting in 65.9% of the demands, which are concentrated in 35 part numbers (high volume and high frequency for the priority type A).

As it was noted before, a product family includes all those products with identical package geometry. However, some part numbers that belong to the same family can present a variation in the number or positions of the contactors (tool offset) because of different product characteristics. It causes the tooling changes even if the products of the same family are processed.

Based on these data, three policies are proposed for the planning according to the following priorities that consider grouping the products into the families:

1) Load the equipment capacity assigned to a family with products of type A priority first (confirmed orders by the customers).

2) Once a product of the priority type A completed its allocation, pass to assign the capacity with a family of the priority type B of the same family (to buffer demand peaks).

3) Once products of the priority type B complete their allocation, pass to assign the capacity with a family of the priority type C (to forecast the future demands).

B. Setup Time Analysis

The setup types were sorted out according to their length from low to high as follows:

1) A lot setup is performed when the next lot in the sequence has the same part number (is the same product). This adjustment consists of the next activities: the purge of the equipment, the blower cleaning, the feeding of a new lot, and lot change related activities.

2) A recipe setup is performed when the next lot in the sequence has a different part number and the symmetry of the contactors is the same as for the previous lot. This minor setup consists of the next activities: the recipe loading, the correlation of variables, and lot change related activities.

3) A tool setup is performed when the next lot has a different part number and the symmetry of contactors is not compatible with the current test tools. This changeover consists of the next activities: the tool installation, the handler fine tuning, the recipe setup, and lot change related activities.

TABLE II
Volume-priority relation considering the group and geometry of the products

Priority	A	B	C
Characteristics	High volume, High frequency	Middle volume, Middle frequency	Low volume, Low frequency
Quantity	65.90%	24.75%	9.35%
Part numbers	35	114	407
Geometries	8	12	50

TABLE III
STANDARD OF CHANGEOVER TIMES ´MACHINE TYPE – GEOMETRY RANGE´

Geometric range	Changeover type	M1 (minutes)	M2 (minutes)
M1 1 to 3.9 M2 1.6 to 2.8	Lot setup	10 ± 2.5	8 ± 2
	Recipe setup	30 ± 5.5	45 ± 12.3
	Tool setup	90 ±3.2	135 ± 51.4
	Family setup	290 ±62.3	430 ± 93.2
M1 4 to 6.9 M2 2.9 to 4.5	Lot setup	10 ± 2.5	8 ± 2
	Recipe setup	30 ± 4.8	45 ± 7.9
	Tool setup	90 ± 7.8	98.2 ± 35.4
	Family setup	210 ± 42.1	340 ± 38.4
M1 7 to 11 M2 4.6 to 5.5	Lot setup	10 ± 2.5	8 ± 2
	Recipe setup	30 ± 3.2	45 ± 5.4
	Tool setup	90 ± 6.2	89 ± 22.1
	Family setup	170 ± 33.5	± 25.1

4) A family setup is performed when the next batch has a different geometry, so that both handler and tester machine adjustments are required. This major setup consists of the next activities: the handler kit installation, the tool installation, the handler fine tuning, the recipe setup, and batch change related activities.

After this sorting, a taxonomy for each setup type is proceeded.

A timing of core setup elements is performed to identify the main components:

1) 443 lot setups: 360 on machine type M1 and 83 on machine type M2.

2) 168 recipe setups: 116 on machine type M1 and 52 on machine type M2.

3) 120 tool setups: 84 on machine type M1 and 36 on machine type M2.

4) 54 family setups: 37 on machine type M1 and 17 on machine type M2.

With this, the machine setup activities were grouped by sorting the times from a minor setup, which is a lot change, to the major one, which is a family (batch) change. The time measurements show that the setup times follow the ranges of the geometries, according to Table III.

A. Compatibility of Family Setups

A matrix of the changeovers on a machine according to the setup types was prepared for the products of every family (Fig. 1). It was assumed that a minor setup always corresponds to a lot change. If the next product in the sequence shares the same installed tool, then a recipe change is performed. If the next product in the sequence is not compatible with the installed tools, then a tool setup is done.

The individual family matrices were consolidated into a single matrix that includes all families, which were extracted from the product catalog, as it is stated in Fig. 2, taking into account that in the case when the next product geometry is different, a family setup is required. Since each family has different adjustment times, three standard ranges of the geometry combining with the type of the assigned test machine were created, this is mentioned in Table III. It is assumed that, to move from one family to another one, the family changeover time must be taken to make the corresponding activities: setting the handler, adjustment of tool, recipe, lot, and cleaning. If a change is related to products, which belong to the same family, these times are minimal. Currently, there are 83 product families included into the matrix.

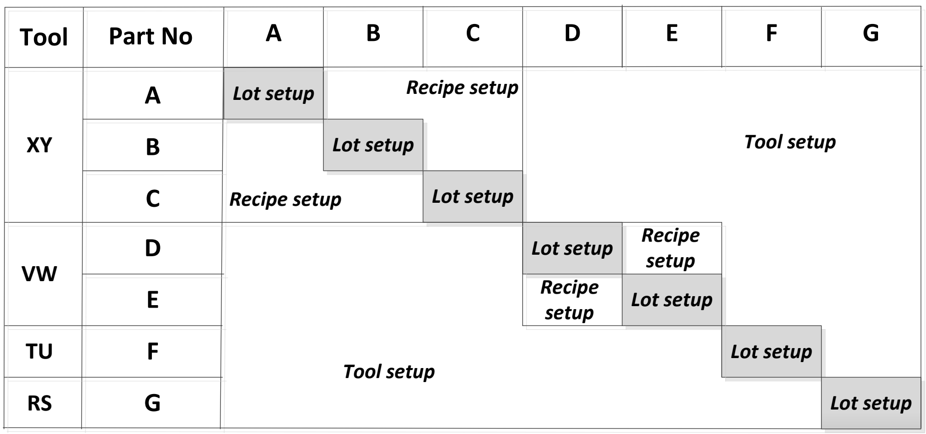

Fig. 1. Morphology matrix of adjustments between products of the same family.

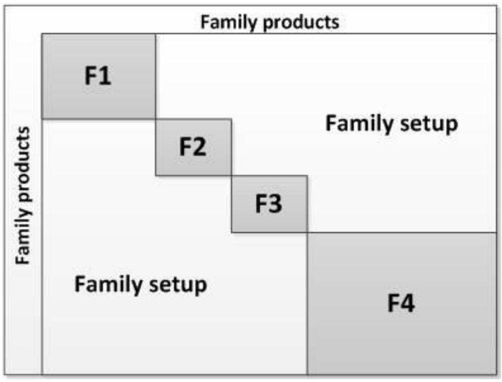

Fig. 2. Morphology matrix of the adjustments between four families of different volumes.

Integrating the obtained standards of the changeover times for both machine types (platform) and the geometry ranges (Table 3), with the setup types taken in the morphology matrixes (Fig. 1 and 2), and taking into account the preferences in the assignment of a product to a platform (machine), two matrices of the machine time setups were created, where the information about the setup times was grouped first by the machine and then by the package geometry range (family). Fig. 3 shows the machine setup times for the family change, considering 24 families.

By mapping the setup times on the machines, the cycle times for the activities corresponding to each setup type were validated.

A. Flexible Planning Model

The general model of the lot sequencing procedure using product group families is presented in Fig. 4.

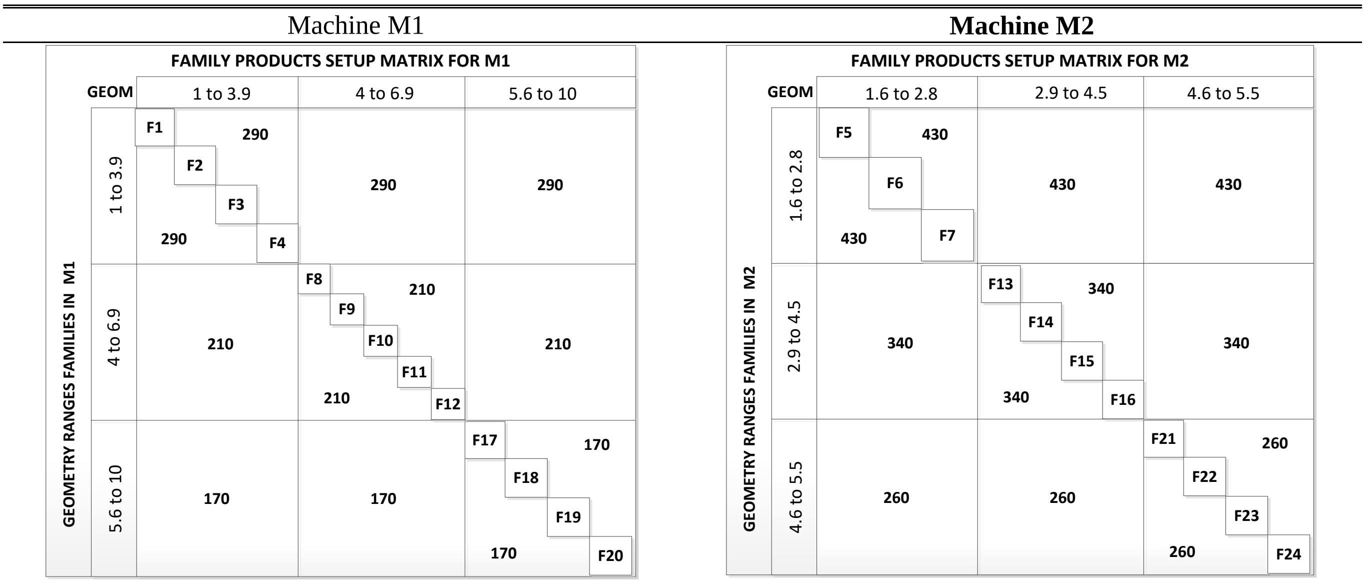

Fig. 3. Matrices of the setup times on the test machines of type M1 and M2.

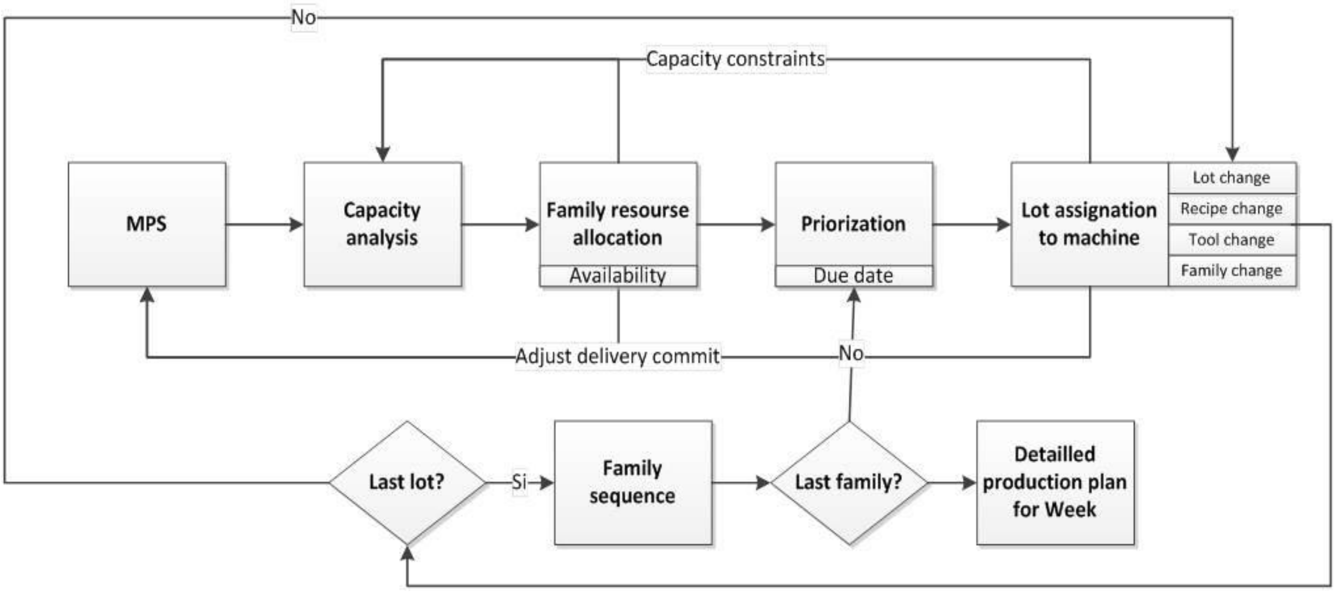

Fig. 4. General lot sequencing algorithm.

TABLE IV
CONTRAST OF THE CURRENT PLANNING ACTIVITIES VS. THE PROPOSED ONES

Current planning model	Proposed planning model
Develop a general plan according to the demand volume.	Develop a detailed product and volume plan with families, matching capacity requirements in advance.
Try to match the next product with a similar geometry whenever it is possible.	Minimize the family setups by an allocation of the products, which belong to the same family, to get minor setups (lot, recipe and tool ones).
Reactive response to request for tooling when a setup is required.	Anticipate the tooling requirements, breaking any constraint in advance (tooling inventory for handler and tester).
Limit the amount of setups to a number, which is already established by the maintenance area.	The realized setups are mostly minor, so the maintenance area focuses its efforts on the prevention of failures.

When the planning is focused on a product family rather than on a part number (product) level, the planner's flexibility is enhanced by the information about the families and the compatibility of the products. This is more than enough to ensure the execution and the fulfillment of the production plan when a product in the scheduled lot sequence is replaced by another one, which is available for processing. A comparative table of the current practices versus the proposed ones was developed to contrast the differences in the planning activities (Table IV).

IV. IMPLEMENTATION OF THE PILOT TEST

In order to verify the general batch sequencing model (Fig. 4), a one-month test period and one family were selected. The information used was related to the part numbers that belong to that family and the installed dedicated capacity. Next, the realized steps to develop the pilot test are described in detail.

A. Family Selection

To simulate the model, a family type A, corresponding to the geometry 8.15x5.6 with the three part numbers, and a single tool type were selected (Table V). This family represents a product volume that fills a capacity equivalent to 80 machines M1 of 410 machines dedicated to perform the electrical test of the microcircuits in the whole area.

TABLE V.
SETUP TIME MATRIX FOR A FAMILY OF 8.15X5.6 GEOMETRY WITH A SINGLE TOOL

Part No	Setup time (minutes)		
	X-1	X-2	W-1
X-1	10	30	30
X-2	30	10	30
W-1	30	30	10

B. Analysis of the Lot Processing Time

The production volumes for each manufactured part number were obtained and the processed lots were filtered with the goal to correspond only to the geometry 8.15x5.6. Table VI shows a sample section of lots with the corresponding part numbers, which were processed during the selected month.

TABLE VI
PROCESSING DATA FOR THE LOTS OF THE FAMILY GEOMETRY 8.15X5.6.

Part No	Tracking Qty	Start Process Time	End Process Time	Trackout Qty
X-2	7113	2016-01-01 00:13:18	2016-01-01 14:28:24	6836
X-2	5486	2016-01-01 14:39:24	2016-02-01 01:59:17	4891
X-2	6043	2016-01-02 02:09:06	2016-02-01 11:31:02	5971
X-2	6769	2016-01-02 11:40:51	2016-03-01 23:32:21	6463

There are given Tracking Qty, which is the number of pieces in the lot when it arrives to a machine; Starting Process Time denotes the time of the lot loading on the machine; End Process Time denotes the lot unloading time; and Trackout Qty is the number of good devices in the lot when it gets out from the machine, while a quantity of pieces was lost due the natural process of segregation.

The information about the time standards at the product level was obtained according to the information partially displayed in Table VII. This serves to calculate the time, which each lot spent testing on the machine. The components of the time (electric test, index and withdrawal) in the standard processing time of each piece are shown. The Product No column is dedicated to the part number; Pkg Size shows the package geometry; Test Time denotes the electrical test time; Index Time is the machine device feeding time; Withdrawal is the time, which corresponds to the retirement of the tested pieces from the fixture; and Cycle Time is the complete test time per piece. The times are given in seconds. The information displayed in the Cycle Time column was used as the part number standard time.

TABLE VII
COMPONENTS OF THE TEST STANDARD TIME

Product No	Pkg. Size	Test Time	Index Time	Withdrawal	Cycle Time
X-1	8.15x5.6	1.10	0.14	0.14	1.24
X-2	8.15x5.6	1.40	0.14	0.15	1.54
W-1	8.15x5.6	1.15	0.14	0.15	1.29

A. *Batch Sequencing*

Batch sequencing starts by calculating the duration of each lot processed (Processed parts volume x Part number standard time). A setup time is directly related to the change of a lot, recipe, tool or family; it depends on the sequence and the similarity of the lots on every machine. To note this, four Boolean variables are introduced. Every variable multiplies the corresponding setup time; it takes the value 1 in the case to be present; if absent, takes the value 0. The variables are defined as follows:

Same PartNo – the next part number in the sequence is the same;

Same ContactMask – the symmetry of the contactors in the next lot is the same;

Different ContactMask – the symmetry of the contactors in the next lot is different;

Different Geometry – the product geometry in the next lot is different.

The start date of the electrical test was defined as 01.01.2016 at 12:00 a.m., and the processed lots were sequenced on machines. The flowtime for the total quantity of lots (C) in this period was calculated using the next formula:

$$C = \sum_{f=1}^{F} \sum_{Pri=1}^{3} \sum_{m=1}^{M} \sum_{Prod=1}^{P} (Q_{f,Pri,m,Prod} \times St_{f,Pri,Prod} + \\ Lot\ setup_{f,Pri,m,Prod} \times Same\ PartNo + \\ Recipe\ setup_{f,Pri,m,Prod} \times Different\ ContactMask + \\ Tool\ setup_{f,Pri,m,Prod} \times Same\ ContactMask + \\ Family\ setup_{f,Pri,m,Prod} \times Different\ geomerty) \rightarrow \min,$$

Same PartNo, Same ContactMask, Different ContactMask, Different Geometry $\in \{0,1\}$.

The notations used are:

Q – Quantity of pieces,
St – Standard processing time,
f – Family,
Pri – Priority,
m – Assigned machine,
Prod – Product or Part Number.

B. *Results*

To check the efficiency of the general sequencing model, three scenarios of the test run were defined as follows:

1) Best Case - Only machines dedicated per part number are considered; the idle time caused by the lot change is only taken.
2) Worst Case – The machines are shared among the families; every processed lot is taken with the family change idle time.
3) Proposed Case - Minimal changes are considered to process the volumes ordered by the customer according to their priority and the part number.

The processing and setup times for each lot were considered in the pilot test, and only a family change with a duration of approximately 210 minutes was applied at the beginning of a monthly period. Table VIII presents the lot processing time for the family 8.15x5.6 per scenario; the lead time is expressed in days.

This time consists of the production processing time plus the idle time due to the changeovers (lot, recipe, tool and family).

TABLE VIII
ANALYSIS OF TIME PER SCENARIO

	Start	Finish	Lead time (days)
Best	2016-01-01 00:00:00	2016-01-23 02:07:00	22.09
Worst	2016-01-01 00:00:00	2016-01-31 06:47:00	30.28
Proposed	2016-01-01 00:00:00	2016-01-23 12:07:00	22.50

In order to measure the efficiency of the batch sequencing model and to compare the time gained or lost with moving from one scenario to another, a matrix was developed with the demonstration of the time deviation expressed in Delta days, where Delta days represent the difference in days to move from the current scenario to another one. The information in Table IX shows that, in the case of moving from the proposed scenario to the best one, the difference is 0.42 days. The worst case scenario represents a family change for each lot processed in the factory. This means that the model, even though it is heuristic, is quite efficient as it is very close to the best result.

TABLE IX
COMPARISON OF THE SCENARIOS EXPRESSED IN DELTA DAYS

Scenario	Best	Worst	Proposed
Best	0.00	-8.19	-0.42
Worst	8.19	0.00	-7.78
Proposed	0.42	7.78	0.00

In the same table, it can be observed that the data present an additional improvement of 7.78 days per month, which means an increment of 25.93 % of the installed capacity in the factory. Currently, the planner team has recognized an increment of 12% in the installed capacity, using the general sequencing model under real conditions. When this planning practice at a family level will be spread to all families in the catalog, surely, better results will be achieved.

V. Conclusions

In a high tech semiconductor company, with characteristics of high volume – high mix, it is important to understand the product similarities. Planning without taking advantage of this fact leads to a myopia that complicates the efficient use of the installed capacity and excessive setups resulting in a high downtime when machines are not productive. This work has presented a foundation and structure for a planner to make a detailed short-term plan at the family level, including an assignment of the required machines, an attention to the product grouping into the families, and a quick action when a part number does not arrive as planned. In this case, it is clearly observed that there are major advantages of planning at the family level. As it was demonstrated, a gain of 25.93 % in the additional capacity was rescued from the operation, and it helps to reduce the discrepancies in the sequenced plan to enhance the utilization of the installed capacity. Rescuing a quarter of the capacity implies a more efficient use of the production area and definitely reduces the operating cost, since machine depreciation is amortized in a greater volume of products, and this enhances the profitability of this semiconductor company. It has also been observed that the proposed model is exportable to any discrete manufacturing business, which has to sequence production orders. The best productivity in the plant can be reached by combining the optimal planning model with an optimal batch scheduling, which will be done in future work.

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