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Design of a production control system for a diffusion department

J. W. M. BERTRAND†

A learning approach is presented to the design of comprehensive production control systems for complex situations. The approach essentially starts from the assumption that defining the production control problem and solving the problem are interdependent processes. Furthermore, the approach explicitly takes into account the fact that in complex situations, *a priori* knowledge about the problem situation is severely limited especially with respect to organizational circumstances.

As a test, the approach has been applied to the problem of designing a production control system for a diffusion department of a semi-conductor plant. The different phases of the design process in practice are described and the results of each design phase are presented. A rough survey is given of the growth of the control system together with an account of the performance of the final control system.

Introduction

This paper is concerned with production control system design and the experience gained from applying a specific approach to an actual design situation in practice. A complete report on the design project of course should cover a detailed account of control procedures, decision rules, etc. With respect to control procedures and decision rules, quite interesting results were obtained from the project. These results are discussed in detail in Bertrand and Wortmann (1981). In this paper, we focus attention on those aspects of the project which may elucidate our design approach and the results of applying it in practice.

The design approach

Our approach is based on the observation that in designing control systems for complex production control situations, relevant information is found to be distributed between two, mostly entirely disjoint, groups of people. The first we shall call the expert team, whose members know a lot about production control theory and, at best, have gained valuable insights from experience with earlier design projects. The second is the client system, whose members know a lot about relevant aspects of the actual design situation but have only some knowledge of production control theory.

The usual procedure in such a situation is to set up a design team consisting of members of both groups. The design team has to define the production control problem and to find an economic solution which can be implemented. Essentially, this is a straightforward process; defining a problem and finding a solution are viewed as separate activities. In its most extreme form, the approach assumes that an initial definition of the problem is possible and that a solution can subsequently be found without the need to reconsider the definition of the problem. It furthermore assumes

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that communication of facts and values (from the client system to the expert team) and of production control knowledge (from the expert team to the client system) never constitutes a problem in the design process. Communication of very specific information however may first require development of a common language, which may take quite some time.

We advocate a design approach which explicitly takes into account the possibility that one or more of these assumptions do not hold; it reflects our view that in complex production control situations, *a priori* formal definition of the problem is unlikely to be possible and that communication may be a tedious process. In consequence, defining the problem and designing the solution are being viewed as interacting, evolving processes.

In our design approach, which is illustrated in Fig. 1, four phases are distinguished. The first phase is the *conceptual design* of the production control system (PCS) and the production control information system (PCIS). The conceptual design consists of determining the basic concepts and the basic relationships needed for defining and discussing the production control problem and its

Figure 1. The design approach.

solution. It is a crucial phase because educating the client (transfer of production control theory) and gathering production control information (transfer of data to the expert team) start from the validity of these concepts and relations. Once they have been introduced into the organization and into the information system, it is very difficult to change them. The conceptual design should, therefore, only contain concepts and relations expected to remain valid during quite some time as a basis for a control system.

The second phase is the design of an experimental PCS and of an experimental PCIS (definition and creation of data bases, storage and retrieval procedures, organizational procedures, training programmes, decision meetings, decision-aid procedures, algorithms, etc.).

In the third phase, the experimental system is tried in practice. We expect that during this phase a lot of information will be gained by the experts about the actual production control problem and that a lot of specific production control knowledge will be transferred to the client system, apart from being a possible solution to the practical control problem itself.

Four effects of applying the experimental system can be distinguished:

- (1) The definition of the situation to be controlled may change. This is a point which is mostly overlooked in production control system design. It means that information gained during experimentation reveals that one or more of the assumptions underlying the experimental design is invalid, or that, due to new insights produced by the experimental results, management wishes to change the definition of the problem.
- (2) Some theory may turn out to be very difficult or even impossible to transfer to the client. This will interfere with good interpretation of decision-aid output based on these concepts.
- (3) The level of detail of the models used and of the definition of variables may turn out to be inadequate; for example, measuring the workload in terms of the number of remaining operations may yield the same control performance as measuring it in terms of operation time required.
- (4) Technical deficiencies of the solutions of the production control problem may be revealed; for example one workload control rule is able to control the average workload level quite well, but the resulting workload variance may be too high.

At the end of the experimental phase, information all these aspects becomes available. Thereupon the fourth design phase can be started, involving a comprehensive redesign of the PCS and of the PCIS, followed by application of the final system.

The actual production control situation

The diffusion department in this case study manufactures integrated circuits employing a diffusion technique. Thin silicon slices are fed through a number of manufacturing phases (each phase being a variant of a *basic phase route*) through different types of equipment. The basic phase route consists of a cleaning operation followed by a furnace operation, followed by a set of 'yellow room' operations, followed by an etching operation. A basic phase route results in slices with altered electrical properties in specific areas. The production of an integrated circuit is made

up of a number of such phases. Some phases include one or more special types of operation for which special equipment is available. At various places, measuring operations are embodied in the route. Figure 2 gives an example of an entire process route, which may consist of 80 to 150 operations. The number of operation types is about 300. According to the state of technology, the manufacturing process cannot

Figure 2. An example of a typical manufacturing process route.

be stringently controlled, resulting in yield variations. The mean yield depends upon the mean flow time of the batches; a short mean flow time results in a high mean yield.

The slices are processed in batches, each batch mostly consisting of about 70 slices. Each slice contains a certain number of potential products, depending on the product type. Integrated circuit manufacturing is still a rapidly developing field. Changes in design of the circuits, in size of the slices, in the number of slices per batch, in manufacturing technology, and in equipment, occur very frequently when compared with more conventional areas of manufacturing.

The manufacturing equipment is grouped functionally into work centres; each equipment type belongs to only one work centre while a work centre may contain a number of equipment types; in general each operator works in a specific work centre on a specific equipment type. However, due to training, most operators can work at other equipment types than their own, and some operators can even work in work centres other than their own.

Because the manufacturing process consists of a number of similar phases, the functional grouping leads to a cyclic routine, an example of which has been shown in Fig. 2. Generally each operation requires a specific type of equipment and a specific type of operator. The required amount of equipment capacity is not always equal to the required amount of operator capacity. Furthermore the operation-time (the duration of the operation) may differ from the time the equipment is needed or from the time the operator is needed, or from both.

The diffusion department receives its raw materials both from manufacturing departments within the same plant and from other suppliers. The coordination of the material flow between several production departments within the plant, the suppliers, and the customers of the plant, is performed by the *Materials Management Department*. In its arrangements with Materials Management, the production department does *not* commit itself to certain *product deliveries*. Instead, the department is responsible only for the *average level* of the yield over a certain period and for delivering the released *batches* on time. Reactions to the actual yield per batch per produce type are made by Materials Management, which is able to increase or decrease the number of batches per product type in the next order release schedule.

A normative framework

The first step is to make a conceptual design on the basis of available production control theory (e.g. Buffa 1968, Greene 1970) and of a broad assessment of the actual production control situation. The normative control framework is developed for production situations where available capacities and/or arriving orders can only be described as dynamic stochastic variables. For this type of production situation, the mean flow time of an order and the utilization of the capacities cannot be controlled independently. In general, a conflict exists between increasing utilization and decreasing mean flow time. It is crucial to guard against the choice of a combination of mean flow time norm and utilization norm which cannot be realized in practice. Thus, a valid model is required of the realizable combinations of mean flow times and utilizations; this model will be called the Flow Time-Utilization model (FTU-model). To specify the FTU-model as well as to check the chosen combination with respect to its realizability, and if necessary to reject it, one considered to be tasks of a production control system.

The actual mean flow time as well as the actual equipment and operator utilization are determined, among other factors, by the number of orders present on the shop floor. A large number of orders on the floor enables a high utilization but causes high mean flow times. From a chosen realizable combination of flow time norms and utilization norms, a norm must be derived for the workload of the production system. The workload is defined as the amount of work which is still to be done on the remaining operations of accepted workorders. Thus, a decision point should exist which controls the workload on the basis of measurements of the actual workload and of the workload norm. Control is exercised by varying the number of orders to be released over time. This control system is called the Workload Control System.

An order to be processed by the production system should be provided with a progress schedule, namely a set of dates associated with the set of operations of the workorder. These dates function as norms for the production progress of the order. Progress schedules are required in order to allow such an allocation of capacities to workorders that large flow time variances per order type are avoided.

Moreover, progress schedules are required in order to calculate production progress deviations. The due date of the last operation of an order is the internal order due date. The difference between internal order due date and the actual delivery time is called the *order due date deviation*. The external order due date, which is communicated to the customer of the department, is determined by adding to the internal due date, the mean due date deviation plus a safety margin related to the variance. The control system performing these tasks is called the Scheduling System.

If available capacity is scarce and demand for capacity is not evenly distributed over time, orders generally will compete for available capacity. Given the actual level of work in process, which is controlled by the Workload Control System, capacity should be allocated to the orders so that a certain balance is maintained between minimizing the mean flow time and minimizing the variance of the due date deviations; this function is performed by the Sequencing System.

The actual performance of the production control system should be observed over time, and if necessary, control parameters should be updated. Furthermore, it is necessary to register the actual due date deviations.

Two adaptive processes are distinguished here:

- recording the actual combinations of mean flow time and utilization, if necessary adapting the FTU-model accordingly, and communicating the new model to the FTU-Control System, and

- recording the mean and variance of the due date deviations and communicating them to the Scheduling System.

The relations between the various control subsystems are depicted in Fig. 3. Because of their strong interdependence, the loading and scheduling activity are represented as being a single function. The picture clearly reveals the hierarchical character of the control system. Besides, the role of the actual remaining workload as the main state variable of the production system is shown. In principle, each direct control subsystem (i.e. the Workload Control, the Scheduling and Sequencing system) bases its action on information derived from the actual remaining workload.

The information streams of the process modelling and adaptation system are indicated by dotted lines.

Figure 3. The composite normative framework.

The conceptual production control system

In close cooperation with the client system, the normative framework was applied to the actual production control situation. Figure 4 shows the conceptual decision system which eventually was agreed upon by the researchers and the client. The main differences with the actually existing control system and with the *a priori* normative frame work are discussed below.

At the start of the project no FTU-controlling system existed. The department could be convinced of the necessity of having such a system. It therefore was incorporated into the conceptual control structure.

Figure 4. The conceptual production control system for the diffusion department.

Control activities affecting the workload take place at three levels.

- (1) Production, inventory levels and deliveries throughout the entire organization (to which the plant belongs) are coordinated by means of a planning system which periodically produces a moving period plan.
- (2) In the short term the production level is subject to coordination activities by the materials management department.

These two activities require the department to make promises regarding future production levels in the long and the short term. Thus, it was decided to incorporate

into the experimental control structure a decision point which evaluates and, if possible, approves production levels by means of detailed capacity models (on the basis of the utilization norms specified by the FTU-Control System).

- (3) On a weekly base, the production department negotiates with Materials Management about the specific set of batches to be started each day during the next week. For each type of production process, agreements with Materials Management exist regarding mean flow time norms, which depend upon the length of routing of the batch. In its coordination activity, Materials Management uses these norms as production lead times. Except for extreme situations, at the start of the project the actual progress of production on the floor was not taken into account, when negotiating with Materials Management. The department only checked the proposed batch release schemes for availability of raw materials, such as silicon slices. The absence of feedback on production progress was considered to be a serious deficiency.

Thus, applying the normative framework to the actual production situation revealed that in fact control of the production level should be performed at two levels. For the long term, agreements should be made with respect to the production level, based on expected available capacity and on utilization norms; this is done by the *Production Level Controlling System*. For the short term, agreements should be made about the specific number and types of batches to be started the next week, based on remaining workload and on workload norms derived from expected available capacity, utilization norms and from mean flow time norms. The system performing this task is called the *Batch Release Scheme Controlling System*.

The scheduling of batches was very soon recognized to be an important, though yet absent, part of the production control system. It was therefore incorporated into the conceptual design.

Operator-capacity is of a multi-task type. For each operation, operator capacity as well as technical capacity are required. *In principle*, for the execution of most operations, a selection from among a rather large number of operators can be made. However, allocating operator capacity to operations was severely restricted because, due to organizational circumstances, switching operators between operation types during a shift was not possible. Thus, the sequencing problem had to be split into two problems, the first concerning the daily allocation of operator capacity to operation types, the second concerning the selection of operations from the queue(s) by the allocated operators. Thus, two separate sequencing decision subsystems were introduced, the *Operator Allocating System* and the *Batch Selecting System*.

Functioning of the experimental production control system

At first no adequate information regarding the relation between utilization and mean flow times was available; the operator capacity was known to be the bottleneck. Thus, for a start, it was decided to set the operator utilization norm equal to its realized value over the last year; the norm for the maximum equipment utilization was set equal to 100%.

A detailed model was built of the equipment capacity and the multi-task operator capacity of the department. For each operation type the required capacity was estimated. A computer routine was designed to produce on the basis of these

data, the capacity utilizations implied by a set of proposed production levels per product type. Evaluation of these data eventually led to agreements on production levels.

It was then decided that the mean flow norm should dominate the utilization norm (because of the effects of the mean flow time on the mean yields and on Materials Management control). A computer routine was designed to compare the cumulative future available capacity with the cumulative capacity required by the remaining workload and the proposed batch release scheme, assuming that future operation flow times would be equal to their norms. A proposed batch release scheme was accepted when required capacity did not exceed available capacity. In accordance with the mean flow time norms, time schedules were assigned to the accepted batches.

From the simulation experiments of Fryer (1973), it can be concluded that using the multi-task capability of operators may substantially improve the relation between mean flow times and capacity utilization. In our situation, however, fast switching of operators on the basis of actual queue-length was not possible. Thus a procedure was designed to produce each day a proposal for a good allocation based on the daily amount of work *expected* per work centre and based on the *actual* available capacity.

Because processing times per equipment type did not vary greatly, basing sequencing decisions on processing times would not be of much use. Taking into account work in next queue could only be moderately beneficial (Conway 1967, Jones 1973), so that reducing flow time variance remained the main sequencing goal. All batches on the floor were provided with schedules: thus for each operation it is known on which day the operation should be performed. In order to minimize flow time variance, it was proposed to select a batch from among the batches with the nearest operation due date: further selection was based on other considerations.

The variables for measuring process behaviour were defined and procedures for measuring, storing and analysing these data were designed.

Experience from the application of the experimental design

For a number of decision points and for the FTU-modelling activity, capacity models were used. Because most operations are of a multi-task type, the operator capacity per operation type cannot be expressed in a single figure. A capacity model was, therefore, derived consisting of constraints on a number of different combinations of operation types. For most decision points the interpretation of output was too difficult, and this required modification of our solution for two decision points and reconsideration of the FTU-modelling procedures.

It was found that the operators were more less flexible than indicated by their past training. This was due to a number of organizational circumstances. We concluded that either the organizational circumstances should be changed or that our solution for operator allocation should be reconsidered.

The level of detail for a number of variables turned out to be too high; about the same quality of control or prediction could be achieved with more aggregated variables or with models containing fewer variables. This especially pertained to the capacity models used for the production level decision aid output and for the FTU-modelling procedures.

After several months of operating with parts of the experimental control system, management took the position that the decision regarding future operator capacity

and operator training should be incorporated into the control system. This widened the situation to be controlled, but other control procedures could be simplified.

After some time it became clear to the department that the operator allocation problem would become easier to solve if specific changes in the organization of the department could be made. Furthermore, it became clear that a good solution to this problem would result in significant savings, and action in this respect was subsequently taken.

Functioning of the final production control system

At the end of the experimentation period a lot of additional information was available regarding the various aspects of the control sub-problems. As a next step a comprehensive redesign took place to take advantage of this information. It should be mentioned that all the required changes could be easily instituted, mainly due to the flexibility built into the information system (Wortmann 1981).

On the basis of data regarding the required capacity per operation type, calculations are now made of the net equipment capacity and the net aggregate operator capacity required by expected future production levels. The real capacity required is obtained by taking into account utilization norms. The resulting figures are expected to lead to actions regarding capacity adjustments (hiring and firing, training, ordering technical equipment, etc.).

Detailed operator capacity constraints and capacity utilizations are no longer presented to the decision makers; instead, a restricted number of aggregate operator capacity constraints and utilizations are shown.

The workload norm is now broadly determined as the sum of:

- (1) the remaining workload due to the agreed production levels, if all past batch releases would have taken place according to these levels and if all batches flow according to their flow time norms, and
- (2) the workload implied by a further batch release according to the agreed production levels during the next week.

The workload norm is compared with the sum of the actual remaining workload and the workload implied by the proposed batch release scheme, which is being accepted only if the workload norm is not exceeded.

In connection with the organizational changes, the information system was redesigned so that, instead of rather complex allocation proposals, each day the following information is presented to each work centre: production progress deviations, mean amount of operator capacity required, work inventory. It was hoped that, within the new organizational structure, this information, combined with the short-term information regarding disturbances, would lead to an improved operator capacity allocation.

Control performance

Figures 5 to 10 give an account of some aspects of the control performance of the system over time. Application of the experimental control system started with the introduction of the batch selecting system in period 4. Introduction of the final control system was started in period 13 and, except for the production level decision point, was completed in period 18.

Figure 5 shows for a typical manufacturing process the periodic standard deviation of the batch flow times as a function of time; a period is equal to one month.

Figure 5. Standard deviation of batch flow times.

The effect of introduction of the batch flow time schedules in period 4 is clear; with only one exception in period 13 the standard deviation of the batch flow times decreased from about 5 days to about 2.5 days.

The periodic mean flow times are shown in Fig. 6. No improvements occurred after the introduction of the experimental control system. This was due to the fact that, because of its deficiencies, the experimental batch releasing procedure was never used in practice. Only after the introduction of the final control system in

Figure 6. Mean of the batch flow times.

period 18, the mean batch flow time decreased substantially to a value near to the mean flow time norm.

Figures 7 to 10 show the period mean operation flow times and operators utilization for the four most important work centres. It should be noticed that during the experimentation phase a relationship existed between operator utilization and mean operation flow time. It is remarkable that, except for the furnaces, a substantial improvement of this relationship was achieved after period 17, while the final operation allocation procedure had been already introduced in period 13. This phenomenon is explained by the fact that using high operator flexibility is only possible if the number of batches on the floor is not too large. With a large number of batches on the floor there is no need for operator reallocation. If the number of batches is small, operator idleness can only be prevented by frequent reallocation; in this way, a high operator utilization can be achieved with a relatively low mean operation flow time. In our case, the improvement occurred only after the introduction of the Batch Release Scheme decision procedures, after which the number of batches on the floor decreased substantially. The absence of an improvement in the furnace work centre was due to the fact that at that work centre, waiting times were already very low. This result supports the conjecture that production control system design should be comprehensive. The performance of the decision points may strongly depend upon each other.

It should also be noticed that with the final control system, the relationship between mean operation flow times and operator utilization is much weaker than before: statistically the relationship hardly exists. This means that in this control

Figure 7. Mean operation flow times and operator utilization for the 'yellow room'.
+, Observations from period 8 to 19; O, observations from period 20 to 30.

Figure 8. Mean operation flow times and operator utilization for 'etching and cleaning'.
 +, Observations from period 8 to 19; O, observations from period 20 to 30.

Figure 9. Mean operation flow times and operator utilization for 'furnacing'.
 +, Observations from period 8 to 19; O, observations from period 20 to 30.

Figure 10. Mean operation flow times and operator utilization for 'measuring'.
 +, Observations from period 8 to 19; O, observations from period 20 to 30.

situation, it is possible to remove or counteract almost all the variations to which the production system is being exposed.

Conclusion

A learning approach to the design of production control systems in complex situations has been formulated and has been used in one situation in practice. The design process was successful in two respects: first, it eventually led to an actual functioning control system, and secondly it improved substantially the performance of the production system. Both facts support the design approach adopted, and this is encouraging. However, further testing of the approach in other situations and by other researchers should be undertaken.

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Présente une approche type apprentissage de la conception de systèmes de contrôle de production complets pour des situations complexes. Cette approche part essentiellement de l'hypothèse que la définition du problème de contrôle de production et la résolution de ce problème sont des processus interdépendants. De plus, l'approche tient compte explicitement du fait que dans des situations complexes, la connaissance à priori de la situation afférente au problème est gravement limitée, en particulier en ce qui concerne les circonstances organisationnelles.

En guise de test, cette approche a été appliquée au problème de la conception d'un système de contrôle de production pour un service de diffusion pour la

fabrication de semiconducteurs. Les différentes phases du processus d'étude pratique sont décrites et les résultats de chaque phase d'étude sont présentés. L'article donne un bref résumé de la croissance du système de contrôle des performances du système final retenu.

Die Gestaltung eines umfassenden Fertigungssteuerungssystems für schwierige Situationen wird vom Gesichtspunkt des Lernens aus in Angriff genommen. Dabei wird im wesentlichen von der Annahme ausgegangen, daß die Definition des Fertigungssteuerungsproblems und seine Lösung eng ineinandergreifende Prozesse darstellen. Der Lösungsweg berücksichtigt außerdem ausdrücklich die Tatsache, daß in schwierigen Situationen a priori-Kenntnisse des Problems, insbesondere was organisatorische Verhältnisse betrifft, äußerst beschränkt sind.

Der Lösungsweg wurde versuchsweise auf das Problem der Ausarbeitung eines Fertigungssteuerungssystems für die Diffusionsabteilung einer Halbleiterfabrik bezogen. Die verschiedenen Phasen des Gestaltungsprozesses in der Praxis werden beschrieben und die Ergebnisse jeder Gestaltungsphase dargelegt. Die Entwicklung des Steuerungssystems wird kurz behandelt und die Leistung seiner endgültigen Ausführung beurteilt.

References

- BERTRAND, J. W. M., and WORTMANN, J. C., 1981, *Production Control and Information Systems for Component Manufacturing Shops* (Amsterdam: Elsevier Scientific Publishing Co.) (to appear).
- BUFFA, E. S., 1968, *Production-Inventory Systems. Planning and Control* (Homewood, Ill.: Richard D. Irwin, Inc.).
- CONWAY, R. W., MAXWELL, W. L., and MILLER, L. W., 1967, *Theory of Scheduling* (Reading, Mass.: Addison-Wesley Publishing Co.).
- FRYER, J. S., 1973, Operating policies in multi-echelon dual constraint job shops, *Mgmt Sci.*, **19**, 1001.
- GREENE, J. H., 1970, *Production and Inventory Control Handbook* (New York: McGraw-Hill Book Co.).
- JONES, C. H., 1973, An economic evaluation of job shop dispatching rules, *Mgmt Sci.*, **20**, 293.
- WORTMANN, J. C., 1981, An information system for production control in a diffusion department, to appear in *Int. J. Prod. Res.*, **19**, 17.