The use of mathematical methods in production management

EINDHOVEN UNIVERSITY OF TECHNOLOGY
Department of Mathematics and Computing Science

Memorandum COSOR 88-30

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Eindhoven, November 1988
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Abstract

In this report, the use of mathematical models and mathematical techniques for solving design and planning problems in industrial production systems is discussed. We describe several projects carried out in different Philips factories. Topics include design problems in an (automated) manufacturing system, production planning and inventory management in a Telecommunication company, and shopfloor scheduling problems in a cable factory. In addition, we briefly list a number of research activities, motivated by these projects, which take place at the Eindhoven University of Technology.

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1. Introduction

The development of new industrial products and of advanced technologies requires an ever increasing application of, often complex, mathematical techniques. As an example, one may think of the use of combinatorial methods for the design of integrated circuits (IC's), the use of discrete mathematics for the development of coding systems, the finite element method as a building stone in certain CAD (Computer Aided Design) systems, applications of systems theory in audio and video signal processing, developments in fluid dynamics, etc. To quote David[1984]: "When we entered the era of high technology, we entered the era of mathematical technology."

Apart from their use in approaching purely technical problems, there is a growing tendency to apply mathematical techniques for designing, planning and controlling complex industrial processes, with the aim to increase their performance. In particular, Industrial Statistics and Operational Research have provided useful tools that can be applied in this area. Mathematical statistics, arosen initially from an attempt to describe certain processes in demography (Malthus) an biogenetics (Pearson, Fisher) became popular in industry by the work of Walter Shewhart on statistical quality control at Bell Laboratories. Other pioneers in this field are e.g. Wald, Deming, Juran and Crosby.

The term "Operations Research" or "Operational Research" stems from the second world war, when scientific methods were developed to solve complex logistics problems. However, industrial mathematics that can be classified as Operational Research avant la lettre, can be traced back to the preceding century. In 1832, Charles Babbage, who later became famous as the father of the first digital computer, wrote "On the Economy of Machinery and Manufactures" in which he followed and extended Adam Smith's idea's on labour division. Another pioneer was the Danish mathematician Erlang; in his studies on the expected performance of telephone exchanges he developed the roots of modern queueing theory. Stochastic networks were proposed by Jackson in the early sixties to study the behavior of Job Shop production systems (cf. Jackson[1963]). In the field of production control, the book of Holt, Modigliani, Muth and Simon "Planning Production, Inventories and Work Force" marked an important step ahead (see Holt et. al.[1960]). Forrester's "Industrial Dynamics" is now recognized as a pathbreaking study on the cyclical variation of stocks in large production/distribution chains (cf. Forrester[1961]).

Despite of all this, the acceptance of mathematics as an important tool to solve complex industrial problems is certainly not as widespread as seems to be desirable. Industrial mathematicians are working mainly within large companies, and quite often in a research function, developing mathematical methods for the design of advanced products and complex technologies. The use of mathematics on a routine basis as a tool for planning and controlling complex production processes is still limited, despite the undeniable successes that have been reached. Only large multinational organisations (e.g. IBM, AT&T, Philips) seem to employ groups of mathematicians who direct their efforts primarily to the solution of problems arising in the field of production management and logistics control.

Philips' Centre for Quantitative Methods is a group of mainly mathematically skilled consultants working on projects in the latter field: industrial production management, industrial process control (including quality control), logistics issues, design and control of flexible manufacturing systems, forecasting and project management, etc. In this report, we describe some projects carried out in different Philips factories by the author, as a member of the Operations Research Group of the Centre for Quantitative Methods. The examples each highlight a specific type of problem. Production planning and inventory management is the key element in the analysis of the production of telephone exchanges in a Telecommunication company. Certain design problems had to be solved when developing a completely automated production line for transformers (to be built in in TV sets). Shopfloor scheduling techniques were proposed for a mains leads department in one of Philips' cable factories.

In describing the examples, we omit all mathematical details, these fall beyond the scope of this report. Several projects have motivated more theoretical research activities; these are carried out at the Eindhoven University of Technology, under the supervision of the author. A brief description of some of these research interests will be given in section 3.

2. Projects in production management

In this section, we briefly describe a number of studies carried out in the field of production management in several Philips organizations. Mathematical details are omitted.

2.1. Production and inventory management in a Telecommunication industry

Fig. 1 shows the logistics diagram of the production process of our first example, i.e. the assembly of large office exchanges for voice- and data-transmission. The production process of these exchanges (starting with the supply of components and ending with the installation of the exchange) can be divided in three important phases, separated by physical stock points. In the first phase, components and raw materials (electrical components, integrated circuits, cables, wood, etc.) are delivered by external suppliers. In the second phase the production of subassemblies takes place (cables prepared for connection, shelves and, in particular, printed circuit boards). In the third phase we find the final assembly, the functional tests, the packing and the expedition. Often, also transport and installation are included in this phase. Two warehouses exist: the component store (components and raw materials) and the commercial store (for all subassemblies). Finally, we note that some subassemblies are also delivered directly

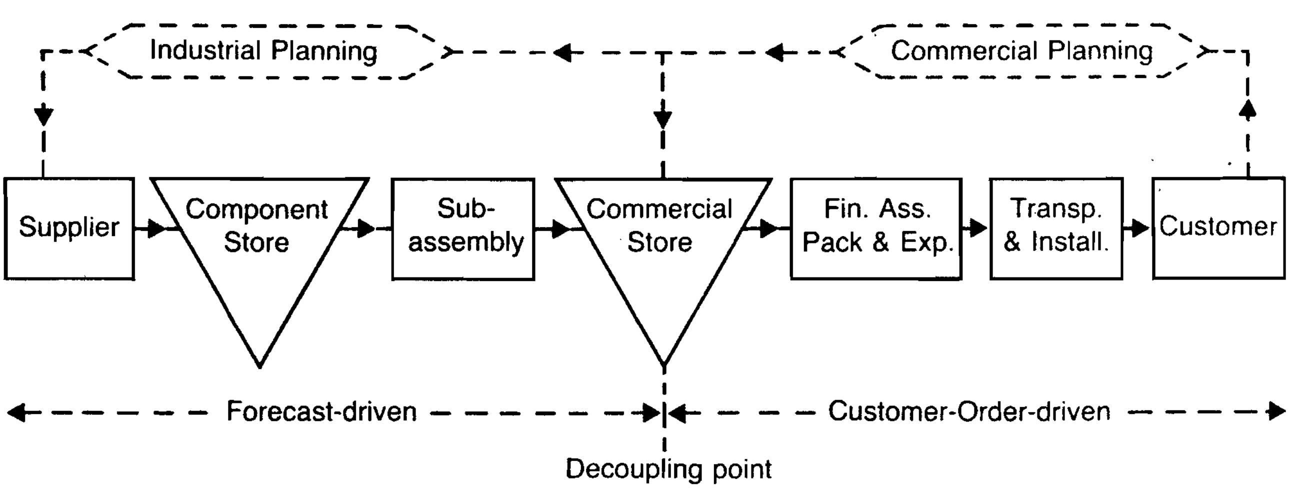

Fig. 1. Logistics diagram of the exchange production process.

from outside suppliers.

The production planning department of the company works according to the following rule. Upon arival of an order, a commercial delivery time is agreed upon with the customer which is sufficient to incorporate the time needed to complete the third phase of the production process (i.e. final assembly, tests, packing, expedition and sometimes transport and installation). In our example, the total leadtime needed to complete this third phase varied from 2 to 4 months, depending on the size and the complexity of the exchange. Hence, upon arrival of a completely specified order, the necessary amount of all types of subassemblies (specified by the Equipment Survey) must be available, to make sure that the final assembly of the exchange can be started almost immediately.

It follows that purchase orders for components and production orders for subassemblies have to be released before customer orders that need the subassemblies have arrived (or before all details of a customer order, such as size, special features, etc. are completely specified). Therefore, production of subassemblies will be driven by inventory control rules, based on forecasts of the demand. The logistic performance of the production process depends heavily on the choice of these rules and in particular on the value of the parameters which determine the size of production orders, safety stock levels, etc. The third phase (final assembly, etc) is then completely order-driven. We also say that the decoupling point in the logistics chain is located between the subassembly and the final assembly phase, at the commercial store.

We have developed a so-called Master Production Scheduling (MPS) rule for the production of subassemblies, which served as the basis for a computer-based Materials Requirements Planning (MRP) program (for concepts like MPS and MRP, see Orlicky[1975]). This MPS was based on the concept of the Economic Inventory Position (see e.g. Silver and Peterson[1985]) of all subassemblies. This Inventory Position is formally defined as

Economic Inventory Position (subassemblies) = Inventory in commercial store
+ released production orders for subassemblies
- subassemblies, committed to customer orders.

Note that the work in process inventory in the subassembly phase is included in the economic inventory position, since also released production orders are counted.

It is important to realize that, in our example, the inventory positions of hundreds of different types of subassemblies have to be recorded. Since this requires a lot of data processing capacity and time, the inventory positions are updated only once in a fixed review period (instead of continuously). As a result, production orders for subassemblies are also released only once per review period.

The Master Production Scheduling rule for period t is based on the forecasted demand in the period [t,t+R+L], where R denotes the length of the review period and L the subassembly leadtime. It takes into account a <u>safety stock</u> factor, based on forecast errors of the demand, as well as <u>lotsize</u> considerations. Also, commonality of subassemblies was considered. We speak of a high <u>degree of commonality</u> if the same subassembly can be applied in a large variety of final exchanges; such a high degree of commonality requires a highly <u>modular product structure</u>, based on standardized subassemblies, of these final exchanges. The final MPS rule orders subassemblies such that the Economic Inventory Position of these subassemblies is returned to an order-up-to level S_t (based on the above mentioned forecasts) at the beginning of every review period. This rule is known to perform well in the case of nonstationary demand (see e.g. Silver and Peterson[1985]). A detailed description of the MPS rule can be found in De Kok and Zijm[1988].

Since the production planning procedure for subassemblies highly influences average commercial stocks and work in process inventory levels, we next built a simulation model to investigate the effects on these inventories of various actions, including

- reduction of the subassembly leadtime L,
- better pre-information from the Sales Department to Production Management in order to reduce forecast errors and therebye safety stocks,
- standardization of subassemblies, resulting in a higher commonality degree and hence again lower safety stocks in the commercial store,
- reduction of both subassembly and final assembly leadtime, without changing the commercially agreed delivery time of exchanges. This may ultimately enable Production Management to shift the decoupling point to the component store, thus making the production of subassemblies customer order-driven. The absence of uncertainty, together with the leadtime reductions, cause a dramatic reduction in inventory levels.

The model enables decision makers to evaluate the effects of these actions in quantitative terms of FAV (Factory Accounting Value) and Turnover (the rate of annual sales divided by the average inventory levels, both expressed in terms of money). Hence, the model serves as a Decision Support System, helping Production Management to choose the proper mix of actions to be taken to improve the competitive position of the Telecommunication company by a severe cost reduction.

2.2. Design of an automated manufacturing system for transformers.

For the production of certain new types of transformers, which perform several important functions in a TV set, one of Philips' factories has installed a number of highly productive and flexible manufacturing lines. An automated conveyor system moves products (one by one) on coded product carriers between different locations, except for some oven processes where transport is in batches. All production steps, handling and tests are mechanized or automated. Also, the transport of the products is under rigid computer control.

Before building such a system of production lines, it seems desirable to gain insight into the performance of a proposed design, to predict the effects of a large number of variations, or even to evaluate completely alternative designs. Performance must be understood in terms of productivity, throughput and waiting times, sensitivity of a line with respect to machine breakdowns (reliability), flexibility with respect to product mix and variability in demand, etc.

Let us highlight one design issue in more detail. In order to cope with uncertainty in the production process caused by machine breakdowns, buffers have to be situated at crucial points in order to achieve a satisfactory production rate. Absence of buffers would cause the whole line to stop each time a machine breaks down. However, since all transport functions are completely automated and all products in the system are coded, any buffer system must be integrated with the automatic conveyors. Spacial and financial considerations place a severe constraint on the size of buffers. The question now is how the effective productivity of a line depends on the location and the size of these, necessarily limited, buffers.

A simple example may illustrate what happens. Fig. 2 depicts a line, consisting of only two machines and one finite buffer (of size K) in between. Both machines are unreliable. Fig. 3 shows a sample path of the stochastic process representing the behavior of the buffer contents as a function of the machine conditions. Note that machine 1 may continue production, even if machine 2 fails, as long as the buffer is not completely filled; in the other case we say machine 1 is <u>blocked</u>. Also, machine 2 may continue production, even if machine 1 has failed, as long as the buffer is not empty; in the other case we say machine 2 is <u>starved</u>. If machine 2 is the faster one, then it can only work at a rate equal to the production rate of machine 1 in the case of both machines working and an empty buffer in between; we say that machine 2 is <u>slowed down</u>. It will be clear that the <u>effective capacity</u> of the line is severely influenced by the size of the buffer.

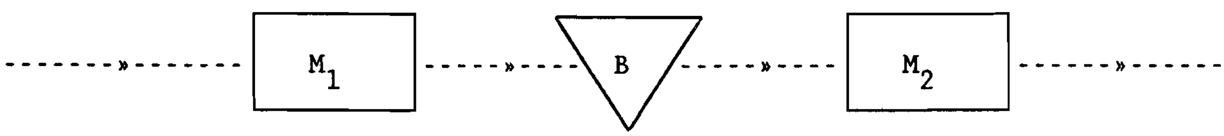

Fig. 2. Two serial unreliable machines with a finite buffer.

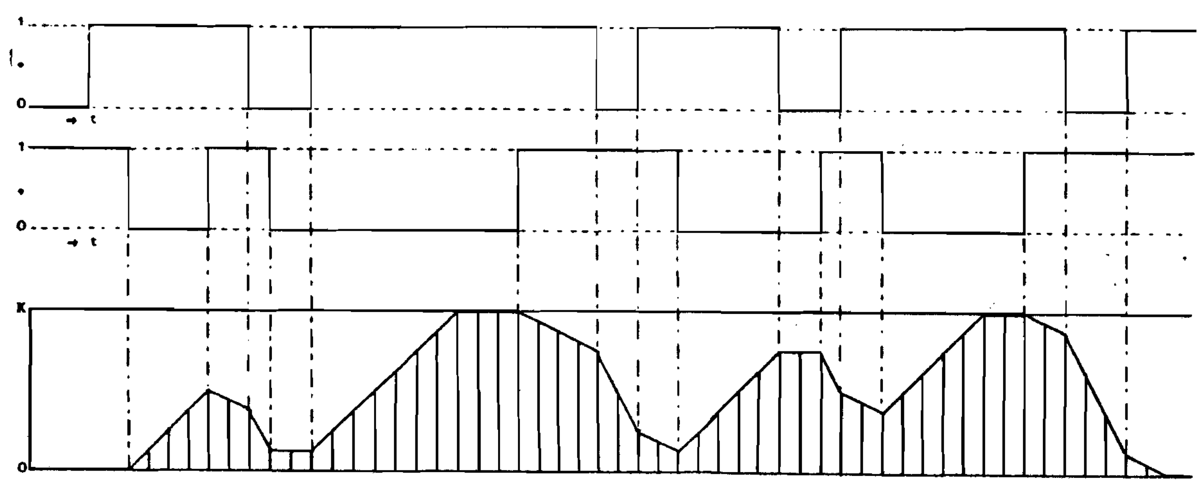

Fig. 3. Buffer behavior corresponding to alterations in machine states. When both working, machine 2 is the faster one.

When lifetimes (times between breakdowns) and repair times are specified by probability functions of phase type (see e.g. Neuts[1981]), it is possible to calculate the effective capacity of such a line by solving a system of differential equations (using a fluid model approach) or by analyzing a specially structured Markov Chain (using a queueing-theoretical approach). See e.g. Wijngaard[1979] or Neuts[1981], ch. 5. Approximations for longer lines have been studied by several authors; a fluid model approach for this particular Philips case has been described by Wessels, Hontelez and Zijm[1986].

Returning to the transformer manufacturing lines, a natural decomposition appears to be possible. First, demand characteristics allows the allocation of each line to one particular family of products, within these families products can be manufactured alternately, without changeover times of machines. Hence, flexibility with respect to product mix is assured. Furthermore, from an aggregate point of view, each line can be divided into three parts. In parts 1 and 3, products are moved one by one on unit product carriers, running through a set of small cycle time operations and tests; in the middle part where several oven processes take place, transport is in large batches (on multiple product carriers). Product handling between the unit product carriers and the multiple product carriers is performed by specially designed robots. Machines in part 1 and 3 are not completely reliable, the middle part is almost perfect. Between machines in part 1 only very small buffers (of two or three products at most) are allowed. The same holds for part 3. Between the three parts, hence in front of and immediately behind the oven processes, larger buffers are allowed, because of storage possibilities on multiple product carriers.

Using a fluid model approach, in combination with a simulation study, we evaluated a number of alternative designs and we developed a control rule for dispatching products to the line. In particular, the following results were obtained.

- The optimal sizes and locations of the buffers were determined. On the one hand these buffers had to be as small as possible, on the other hand they had to be large enough to gaurantee a desired minimum throughput.
- The best performance of the line was achieved by giving it a "push-pull" character. Recall that, from an aggregate point of view, the line could be divided in three main parts. The first part had to <u>push</u> products into a buffer in front of the middle part, thereby guaranteeing input for the

(expensive) ovens, even when, due to breakdowns, that first part is blocked temporarily. The latter part pulls products from the middle part- even when taking into account its disturbance rates - therebye preventing overflow or an excessive amount of work in process.

- For capacity balancing reasons, some operations should be located at a point parallel to the line.
- At the beginning of the line, a number of parallel machine units were situated along the conveyor system. Each machine unit has its own cycle time. Products visit only one of the parallel machine units. In order to avoid blocking on the conveyor system, caused by products operated at one machine (in line), a control rule has been developed for dispatching products to these machines.

Valuable insight with respect to the performance of the different alternatives has thus been obtained. The proposed model and the subsequent analysis appeared to be powerful instruments to support the design process of these type of production lines. These types of models are now frequently used, also after the realization of production lines, to assist management in making the right decisions when product or process changes need to be introduced. So it may properly be thought of as a management tool.

2.3. Shopfloor scheduling in a cable factory

Our third example concerns the production of mains leads, with attached plugs, in a cable factory. These leads are then distributed to other product divisions such as the Consumer Electronics Division (audio and video equipment), Domestic Appliances, etc. The leads are supplied on reels by another department (one reel may contain several kilometers of lead). The processing of leads with plugs takes place in three phases. In the first phase, the leads are cut to the right lenght (between 1.5 and 3 meters), stripped at the end, the end points are soldered, etc. In the second phase, the plastic plugs are attached by an injection moulding machine. In the third phase finally, certain specified leads are tested (only those leads for which a test certificate is required by the customer) and all leads are packed in boxes.

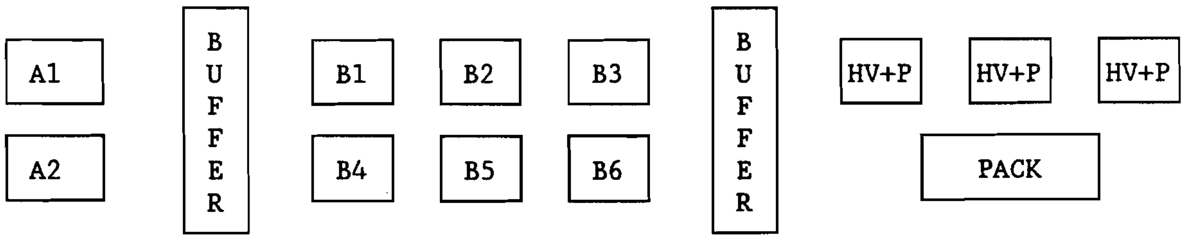

Fig. 4. Production layout for mains leads manufacturing.

For the first phase, two identical machines are available, for the second phase six identical machines. In the third phase, three high-voltage test machines are available, leads that pass through one of these three machines are packed immediately after testing. Another part of the daily production is packed directly.

Between each two phases buffers are available to store products temporarily, on the floor (in case no machine in the next phase is directly available for processsing that particular kind of product). Buffers however have only limited capacity.

Weekly production plans are made for this mains leads department, taking into account due-dates (delivery dates which may be even within that week), the availability of material and in particular changeover times. Both the machines in the first and in the second phase are characterised by <u>sequence-dependent changeover times</u>, i.e. the changeover time depends both on the type of product just produced and the type of product to be produced. Since there exist about 200 different type numbers, a <u>matrix of changeover times</u> would require 40,000 entries (200*200). It appeared to be possible however to considerably reduce the number of space required by taking a closer look at the changeover times.

For the two machines in the first phase, the changeover times are built up as the sum of the times needed to perform changes in a number of tool settings. For each tool setting, there are only a few choices possible (at most four in our case). Each type number is characterized by a specified tool setting for each tool needed. Hence, a database which specifies the tool settings for all 200 product types, together with a small database which contains the times needed to perform changes in the tool settings, is sufficient to <u>calculate</u> for each group of part types, to be produced in the next week, say, the changeover time matrix when needed. The total changeover times are relatively large when compared with the time needed to produce 1000 leads (which is about half an hour, whereas the changeover times may vary from 8 minutes to at most one and a half hour). In the second phase, something similar happens. The only difference is in fact that, instead of the sum, the maximum of a number of times has to be taken. In the third phase, changeover times are negligable and can be ignored.

A Master Production Plan specifies the group of orders to be produced in the next week. Next, the shopfloor scheduler has to determine a schedule which specifies for each machine when precisely to produce a particular order. Orders vary in size from 2000 to 25000 leads. In one week, 40 to 50 orders have to be produced. Orders may be split over several machines in each phase. We were asked to develop a scheduling methodology that could be implemented on a small personal computer, to assist the shopfloor scheduler in evaluating different alternatives (under slightly different constraints) quickly and to enable him to quickly <u>reschedule</u> part of the set of orders in case of serious interruptions (e.g. rush orders or machine breakdowns). Before our involvement, the scheduling was done manually on a large planning board (actually a Gantt chart was constructed).

A brief outline of the way we approached the problem is given below. First, we determined in which phase the capacity limitations were most severe. In our case, the two machines in phase one constituted the bottleneck, partly caused by the fact that these machines suffered from more or less serious breakdowns. The next important observation was that the planning problem for one group of machines (in one phase) closely resembles a so-called <u>multiple traveling salesmen problem</u> with <u>time constraints</u> (cf. Lawler et. al.[1985]). In this problem, a group of salesmen (machines in our case) have to visit a set of cities (to process a set of orders), where the distance between city i and city j is given by c_{ij} (the changeover time from order i to order j is given by c_{ij}). For each city, earliest entry times s_i, visit durations p_i and latest departure times t_i are specified. In our scheduling problem, where cities are replaced by orders, these variables denote material avaibility dates (from a preceding phase or a preceding department), processing times and due-dates (or dates at which material must be available for a subsequent phase), respectively. The problem is then to minimize the total time needed to visit all cities exactly once (to process all orders), taking into account the time windows (material availability and due-dates), by specifying for each salesman (each machine) a particular sequence of cities (orders), to be visited (processed) in that order. Although the original problem setting was slightly different, the main question was to produce as efficiently as possible hence to minimize the time lost to changeovers, which in a natural way constitutes the multiple traveling salesmen problem with time constraints for each phase. The only, not unimportant, difference with the usual traveling salesmen problem is that our scheduling problem is essentially asymmetric (i.e. a changeover time c_{ij} from type i to type j is in general not equal to c_{ji}). Since all known (heuristic) algorithms for traveling salesmen problems with time constraints are developed for the symmetric case, we had to develop new heuristics.

We developed a heuristic (based on local search techniques) for scheduling the two machines in the first phase (since this phase appeared to be the bottleneck). We omit mathematical details again. If not absolutely necessary (because of due-dates) orders are not split and processed on two machines in parallel, in order to avoid additional changeovers. In planning the first two machines, we loosely take into account the main changeover times in the second phase, in order to prevent arriving at sequences which would cause a very unsatisfying changeover pattern in the second phase.

The resulting schedules appeared to be a very serious improvement over the manually prepared schedules (an improvement of 20% was the rule rather than the exception). Even more important however was the fact that the runtime needed to arrive at a good schedule on a micro-computer was only a matter of seconds, thus enabling the shopfloor scheduler to use the method as an instrument in what-if simulations. All kind of unforeseen events could be handled easily now by proposing new schedules, starting from the situation at which the event occurred (this constituted another constraint on our traveling salesmen problem formulation which however could be easily handled). In this way, a practical and easy to handle instrument was made available to the shopfloor controller, to enable him to develop production schedules within a few minutes, to evaluate whether a proposed Master Production Plan is feasible indeed and, if not, to evaluate alternatives, and to reschedule quickly in case of breakdowns or rush orders, a situation which could not be handled in a satisfactory way when planning manually.

3. Research activities in production management

The first responsibility when carrying out projects in factories, is to respond properly to the problems posed by management, within a reasonable time. Problems in factories or logistics organizations have to be solved adequately, but a reasonable trade-off has to be made between the efforts needed to replace a good solution by an optimal one (if possible) and the benefits that can be expected from a very minor improvement of an already good solution to for example a production planning problem. Besides that, optimality is not always clearly defined in the often turbulent environments we are working in.

On the other hand, one often feels the need for a more basic theoretical understanding of certain problems, for instance because their appearance in many different places in many different forms justifies such a serious research investment, or simply because the importance of the area is recognized by top management. Another (very good) reason may be the personal interest of a researcher in the field. In our case, many projects led to research activities which are carried out at both Philips and the University of Technology in Eindhoven. In this section, we briefly indicate some of these activities, carried out at the Mathematical Department of the EUT, under the supervision of the author.

3.1. Global performance analysis of automated transport systems in factories

This problem area was motivated by several projects, among which the case described in section 2.2 and a study concerning the redesign of the transport system in a vacuum cleaner factory in the Netherlands. One may think of automated conveyor belts but also on so-called AGVS's (Automatic Guided Vehicle Systems) or railcart systems which both are often applied in Flexible Manufacturing Systems (see e.g. Ranky[1983] or Zijm[1987]). Queueing network models have provided valuable insights into the behavior of these systems (cf. Stecke and Suri[1986]). In our research, we concentrate on approximative network models, and in particular on issues such as traffic priority rules, integration with local or centralized buffer systems, etc. A comprehensive description of the queueing analysis of the vacuum cleaner case can be found in Repkes and Zijm[1988].

3.2. Machine scheduling problems

Many machine scheduling problems can be classified as so-called generalized flowshop scheduling problems. All products have to pass through a sequence of machine banks, where each bank consists of one or a number of parallel machines. Products visit at most one machine in each bank (products may skip a bank). Machines in each bank may suffer from changeover times or breakdowns. Orders may be subject to release and due-dates, they may or may not be split in smaller lots, etc. Certain orders may have a higher priority than others. With respect to the product structure a certain family structure may be apparent.

Combinatorial optimization methods can be exploited to solve only rather small problems in manufacturing environments which are a very special case of the above sketched general situation (e.g. a single parallel machine system or a simple flowshop with only one machine in each phase and no changeover times at all). In our research, we concentrate on approximation methods for more complex environments such as the generalized flowshop described above. The approach is based on decomposition methods, using combinatorial procedures for the smaller problems as our building blocks, and exploiting a rather sophisticated iterative aggregation procedure recently proposed by Adams et. al.[1988]. A first attempt to solve a generalized flowshop scheduling problem without changeover times is described in Zijm and Nelissen[1988].

Another important research topic is the analysis of these scheduling procedures in a rolling planning environment (where the set of orders may change frequently) and the development of order acceptance procedures based on feasibility of the eventually resulting schedules.

3.3. Multi-echelon production/inventory control systems

Consider a logistic chain, consisting of a number of suppliers, a components warehouse, a factory (possibly to be split into a subassembly and a final assembly department), a central warehouse for final products, several local warehouses and finally retailers and market. To develop models which adequately describe the many complex interactions in such a chain still appears to be extremely difficult, despite the many attempts that have been made in the past. We first devoted our attention to a description of these interactions, both in terms of the physical materials flow and in terms of the flow of information in such a system (including the role of a central planning department). Next, we concentrate on a comparison between a Base Stock Control System and a Manufacturing Resources Planning System (compare e.g. Vollmann et. al.[1984]). In the near future, we wish to include concepts such as Hierarchical Production Planning, commonality of components, size and location of safety stocks, flexibility in capacity and the like.

A central role in our models and analysis methods is played by the concept of echelon stock, developed by Clark and Scarf[1960] and, in our view, highly underestimated by both researchers and practitioners. The decomposion approach, proposed by Clark and Scarf, has been generalized to more complex environments, compared with the simple line system studied by these authors. A first review article will appear in the beginning of the next year (Langenhoff and Zijm[1989]).

3.4. Design and control of flexible assembly systems

About 90 % of the literature in the field of Flexible Manufacturing Systems concerns Machining Centres, more in particular in a Metal Cutting Environment. We have planned to study assembly systems and, as an example, we have taken the mounting of printed circuit boards, being one of the most widespread processes in electronics manufacturing. Problems we study include

- Machine control problems. How to load components on a particular insertion machine? How to control so-called pick-and-place devices?

- How to spread a total amount of work over a number of parallel machines?
- What are preferrable production configurations? Line structures or assembly cells?
- What MHS (Material Handling System) should be chosen?
- How to estimate overall performance of different assembly configurations?

Right now, we concentrate on the last issue. We try to develop approximation methods, based on queueing theory, for difficult assembly structures. In particular, we study job-dependent parallel structures, i.e. a system of basically parallel machines, visited by jobs belonging to several different classes (types of printed circuit boards), where each job type can only visit a subset of the group of parallel machines. The subsets however may overlap which causes essential difficulties. Moreover, jobs may choose a queue according to a shortest queue principle, a very common control rule in practice which unfortunately leads to known hard problems in a queueing-theoretical sense. First results have been obtained, see Adan et. al.[1988].

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List of COSOR-memoranda - 1988

Number	Month	Author	Title
M 88-01	January	F.W. Steutel, B.G. Hansen	Haight's distribution and busy periods.
M 88-02	January	J. ten Vregelaar	On estimating the parameters of a dynamics model from noisy input and output measurement.
M 88-03	January	B.G. Hansen, E. Willekens	The generalized logarithmic series distribution.
M 88-04	January	J. van Geldrop, C. Withagen	A general equilibrium model of international trade with exhaustible natural resource commodities.
M 88-05	February	A.H.W. Geerts	A note on "Families of linear-quadratic problems": continuity properties.
M 88-06	February	Siquan, Zhu	A continuity property of a parametric projection and an iterative process for solving linear variational inequalities.
M 88-07	February	J. Beirlant, E.K.E. Willekens	Rapid variation with remainder and rates of convergence.
M 88-08	April	Jan v. Doremalen, J. Wessels	A recursive aggregation-disaggregation method to approximate large-scale closed queuing networks with multiple job types.

Number	Month	Author	Title
M 88-09	April	J. Hoogendoorn, R.C. Marcelis, A.P. de Grient Dreux, J. v.d. Wal, R.J. Wijbrands	The Vax/VMS Analysis and measurement packet (VAMP): a case study.
M 88-10	April	E. Omey, E. Willekens	Abelian and Tauberian theorems for the Laplace transform of functions in several variables.
M 88-11	April	E. Willekens, S.I. Resnick	Quantifying closeness of distributions of sums and maxima when tails are fat.
M 88-12	May	E.E.M. v. Berkum	Exact paired comparison designs for quadratic models.
M 88-13	May	J. ten Vregelaar	Parameter estimation from noisy observations of inputs and outputs.
M 88-14	May	L. Frijters, T. de Kok, J. Wessels	Lot-sizing and flow production in an MRP-environment.
M 88-15	June	J.M. Soethoudt, H.L. Trentelman	The regular indefinite linear quadratic problem with linear endpoint constraints.
M 88-16	July	J.C. Engwerda	Stabilizability and detectability of discrete-time time-varying systems.
M 88-17	August	A.H.W. Geerts	Continuity properties of one-parameter families of linear-quadratic problems without stability.
M 88-18	September	W.E.J.M. Bens	Design and implementation of a push-pull algorithm for manpower planning.
M 88-19	September	A.J.M. Driessens	Ontwikkeling van een informatie systeem voor het werken met Markov-modellen.
M 88-20	September	W.Z. Venema	Automatic generation of standard operations on data structures.

Number	Month	Author	Title
M 88-21	October	A. Dekkers E. Aarts	Global optimization and simulated annealing.
M 88-22	October	J. Hoogendoorn	Towards a DSS for performance evaluation of VAX/VMS-clusters.
M 88-23	October	R. de Veth	PET, a performance evaluation tool for flexible modeling and analysis of computer systems.
M 88-24	October	J. Thiemann	Stopping a peat-moor fire.
M 88-25	October	H.L. Trentelman J.M. Soethoudt	Convergence properties of indefinite linear quadratic problems with receding horizon.
M 88-26	October	J. van Geldrop Shou Jilin C. Withagen	Existence of general equilibria in economies with natural enhaustible resources and an infinite horizon.
M 88-27	October	A. Geerts M. Hautus	On the output-stabilizable subspace.
M 88-28	October	C. Withagen	Topics in resource economics.
M 88-29	October	P. Schuur	The cellular approach: a new method to speed up simulated annealing for macro placement.
M 88-30	November	W.H.M. Zijm	The use of mathematical methods in production management.