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INTEGRATION OF PULPMILL CONTROL WITH THE PRODUCTION PLANNING OF A PAPERMILL

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Synopsis In an integrated pulp and papermill, all subprocesses are interrelated. This means that they cannot always be run at the optimum production level, since the result as a whole is decisive. The production managers have for many years successfully carried out the difficult scheduling of an entire mill. With increasing complexity of a modern mill, it is desirable to help production managers more systematically to utilise existing storage capacities. Thus, a production control system has been developed for the Gruvön mill. The mathematical formulation and solution of the scheduling problem is based upon optimum control theory.

In order to perform unavoidable production changes with the minimum of disturbances, the process control must not only produce uniform quality during steady state conditions, but whenever possible carry out production changes without introducing disturbances in the quality of the product.

In order to implement computerised production and process control systems, good human relations must exist between computer staff and production personnel. This, together with good technical solutions, including the man/machine interface, will guarantee success.

Introduction

THE technical evolution and the ever-increasing manpower cost have made it possible and necessary for the pulp and paper producing companies to centralise in big production units in order to improve company efficiency. This has led to a greater interest for advanced optimisation techniques on both company and mill levels. In many cases, it has also meant more complex production units, where again optimum co-ordination techniques are of great interest.

The computer work of Billerud's started with an administrative computer system in the early sixties, followed shortly after by a process control computer. The major effort of the administrative side has been put in the mechanisation

Under the chairmanship of Dr S. A. Rydholm of manual routines plus the organisation of an extensive recording system for different costs throughout the company.

The process computer work at Gruvön mill has been carried out in parallel with the work of administrative routines.

No advanced control system can be designed without considering the environment. Thus the first process computer system (IBM 1710) covered the entire papermaking process from incoming order to quality control and reporting.[(1)] Our second system (IBM 1800) covers not only papermaking, but also pulping and chemical recovery areas.[(2)] Given the incoming orders, the basic objective is to utilise the production units at Gruvön in the most economical way while producing uniform qualities.

To control a large integrated pulp and paper producing unit such as Gruvön efficiently, it is necessary to include planning and scheduling routines, as well as control of the different subprocesses of the mill. This paper describes the integrated control system being implemented. As an example from the process control part, digester control strategy is reported. Finally, some views on the man/machine interface are discussed.

Production planning and production control

IN APPLYING computer control to the papermaking process, Billerud has used the systems approach. This means that we are not only interested in process control of different control loops in the processes, but that we have also included some of the surrounding systems. Production planning, for example, was included as a grade change on a papermachine is initiated by the fact that there is an order for producing another grade.

The production planning part of our first computer system was designed to help the production planning department at Gruvön to optimise the utilisation of the papermaking facilities, given the orders from the sales department. A specially developed program, TRIM 67[(3)] presents trim losses on alternative machines for the ordered quality. From this, the manual planner can assign the order to a machine. Given this information the computer calculates the best production sequence on the different machines in order to minimise the grade change time. The sequencing problem has been solved according to the 'branch and bound' algorithm[(4)]; unfortunately, the speed of the 1710 system (which was the most powerful computer at Billerud at that time) is too slow to obtain more than a semi-optimum solution. This, together with the fact that the five papermachines of the kraft mill have been rebuilt and specialised, has meant that the production planning system is due for a thorough revision.

Our next step was to develop a system to schedule all departments of the mill. This production control application was developed in conjunction with the enlargement of Gruvön mill, including a production line for fluting paper, in June 1968.

Gruvön mill consists of kraft pulpmill, a bleaching plant, a kraft papermill with five papermachines producing 160 000 tons/year, an NSSC pulpmill and a papermachine for fluting paper producing 130 000 tons/year. Approximately 8 per cent kraft fibre is used in the fluting paper. Red and black liquors from the pulping plants are cross-recovered in a chemical recovery system containing one evaporating plant, two Tomlinson recovery boilers, two parallel causticising lines and one lime kiln. The cooking liquor for the NSSC digester is prepared in a special plant using some green liquor from the chemical recovery system. The necessary additional steam is produced in one combined bark and oil fired boiler and all steam passes through two power generating back-pressure turbines (and one condensating turbine when necessary) before distribution to the different processes of the plant.

With the rather complex interconnection between the kraft and fluting production lines (Fig. 1), it was envisaged by the Billerud technical management that a systematic computerised scheduling would be of great interest.

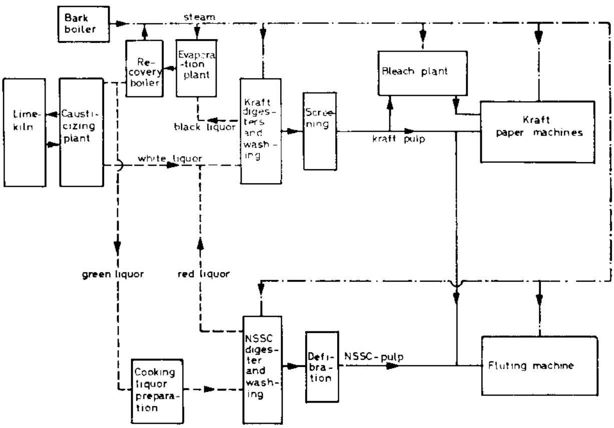

Fig. 1—Simplified process flow chart of Gruvön mill

Thus, a model of Gruvön mill was constructed consisting of 3 model papermachines (in reality corresponding to six machines), 9 process units and 10 buffer tanks (Fig. 2). The model is described further elsewhere.[5]

Given planned paper production and planned stop periods for the papermachines, the system calculates the production levels for the different process units with the objective of making as few changes in the production rates as possible. Furthermore, the system tries to store steam indirectly, as Gruvön mill has a somewhat low steam capacity. We will start with planning periods of 2–3 days divided into 10–15 periods, not necessarily of equal length.

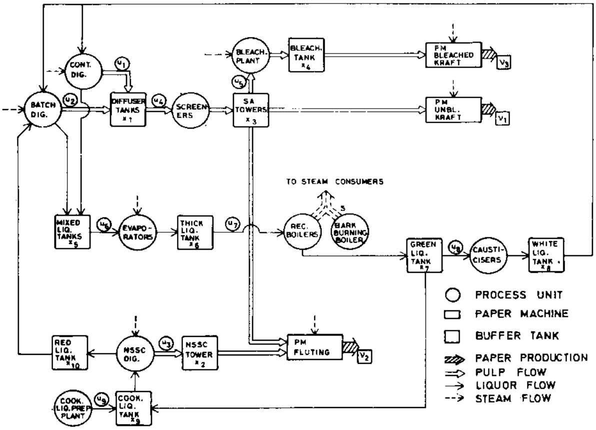

Fig. 2—Model of Gruvön mill

To solve the scheduling problem, an optimising algorithm has been developed. It can be characterised as a successive solution of a number of linear programming problems, defined and linked together by means of the Pontryagin maximum principle.[7–9] The mathematical formulation and solution of the scheduling problem as an optimum control problem is given in Appendix 1.

Our work so far has proved that the model is describing the mill with necessary accuracy and that the number of production rate changes can be lowered.[6] The system is planned to be in operation by the end of 1969.

Execution of the planning

FROM THE production planning and the production control system, we will arrive at a more optimum production schedule of the entire mill. The more uniform a separate process can be run, the better are the chances that the process itself produces a uniform product. On the other hand, the optimum schedule requires changes in the production rates of different departments. Here we have had to rely on the process operators to make these production changes without introducing severe disturbances into the system. Such disturbances could, because of the long dead times in the chemical recovery area, remain several days before being damped out.

To overcome the problems with production changes in different departments, the process control system must not only produce uniform quality during steady state conditions, but whenever possible carry out production changes without introducing disturbances in the quality of the product.

As has been pointed out, all processes in an integrated pulp and paper mill are closely interrelated. The paper quality and the productivity of the paper-machines depend, of course, on the pulp characteristics. The pulp quality, too depends on the uniformity of the cooking chemicals. Thus, we have implemented closed loop computer control of the entire production line—

> NSSC cooking liquor preparation plant—NSSC digester—defibration—refining—fluting paper machine

with our second process computer.

Process control

MOST OF our computer control loops include feedforward and feedback control. Irrespective of whether the final control is direct digital (DDC) or digital directed analog control (DDA), the computer controls the process according to a set of reference values, one set for each grade. Based on these reference values, a number of equations, which make up the static model of the plant, is used to calculate the 'highest' (that is, the less frequent loop in a multiple cascade system) set points for the periodic control.

By using multiple cascaded control loops at steady state, one can take care of disturbances of different frequencies. Fig. 3 shows a typical example already employed with our first process computer, basis weight control. The flow loop (R_1) could be either DDC or DDA and eliminates fast flow disturbances.

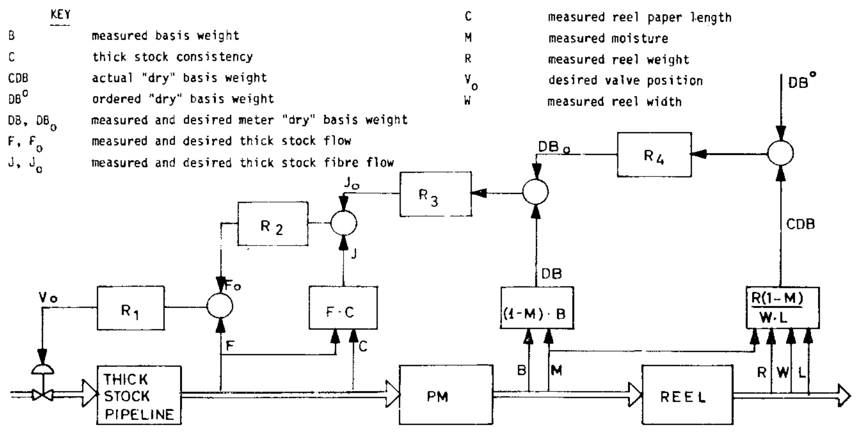

Fig. 3—Multiple cascade system exemplified by a basis weight control system

The rest is all digital. The fibre flow control (R_2) takes care of the second fastest control and compensates for consistency disturbances. The next loop (R_3) measures the basis weight at the dry end and the control eliminates drift in the flow and consistency measurements. Sometimes a basis weight meter can have a slow drift, which can be handled either by feeding manual samples to the computer or by a reel weighting system (R_4).

Grade and production changes are mainly performed in a feedforward manner, but often a feedback checking to control the change rate is included. Grade changes, of course, must be carried out as fast as possible, whereas the production must be changed with a minimum of disturbances in the product quality. Such a production change in the NSSC digester takes about 1 h.

Digester control

AS PART of a joint development effort between Billerud and Kamyr at the Billerud experimental plant in Jössefors, an NSSC digester has been developed using the main continuous kraft digester machinery. The first full-sized NSSC digester was started up at Gruvön in late May 1968. Having no previous experience in computer control of continuous pulping, we considered the somewhat simpler NSSC process a good starting point.

The basic analog instrumentation is supervised by the computer in order to produce uniform pulp during steady state conditions as well as during production changes. The computer system controls, for instance, such ratios as chemical-to-wood and liquor-to-wood, taking into account the moisture content of ingoing chips and the composition of the cooking liquor. By controlling all flows to and from the digester body, including the steam flow, the important conditions in the cooking zone, the washing zone and digester bottom can be efficiently supervised. This means, for example, that the computer can sense a tendency for plug development in the blow line and by preventive action avoid disturbances in production.

The chip moisture content is a very important variable. Nevertheless there is no accurate moisture measuring method that can easily be employed in a climate with severe winters. We considered calculating the chip moisture from heat and material balances around the steaming vessel or the digester top, but our error estimation indicated a rather low accuracy. Thus, the chip bin was equipped with load cells in order to allow weighing of the ingoing chips. The chip bin is filled periodically, so allowing calculation of the moisture content based on chip weight and speed, volumetric packing coefficient and volume of the chip metering wheel. The calculating moisture content has proved to be more accurate than expected. Probably the accuracy can be increased by periodic updating of the volumetric packing coefficient of the chip metering wheel.

Our calculation method has been of great importance for the successful control of the NSSC digester.

During a production change, the computer schedules the temperature change in the cooking zone, so that each single chip is cooked at a temperature corresponding to its resident time in the cooking zone. This means that production of off-grade pulp is avoided. In an emergency, an immediate production change can be performed at the expense of the pulp quality.

From the digester, the chips are blown to a buffer (Fig. 4). The computer controls the output from this intermediate storage and the feed to three parallel difibrating double disc refiners. A strategy to control the refiners via a kWh/ton set point, where this set point is updated in a feedback strategy from manual samples after the refiners, is being tested.

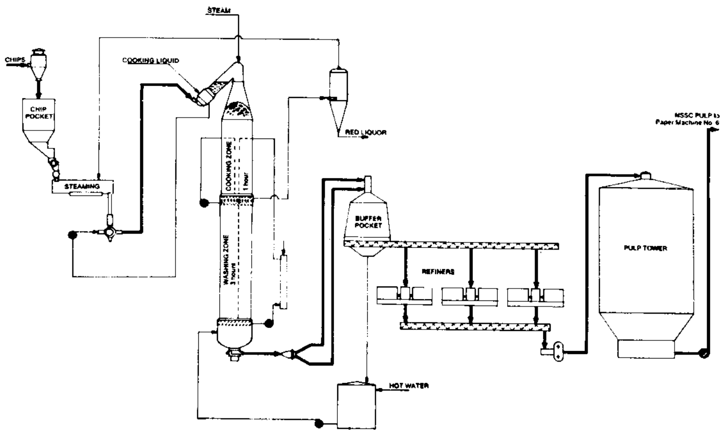

Fig. 4—NSSC pulping plant at Gruvön

The major variables of interest characterising the NSSC pulp are yield and defibration. If the defibration is controlled successfully, it should be possible to estimate the yield very accurately, as we have found a close relationship between yield and energy consumption (Fig. 5).

Man/machine interrelations

THE WORLD is getting smaller every day with the new facilities for communication. Still, there are two aspects in this field that may be of greatest importance for the development of computer control. The first considers human relations between systems engineering and production people; the second is the man/machine interface.

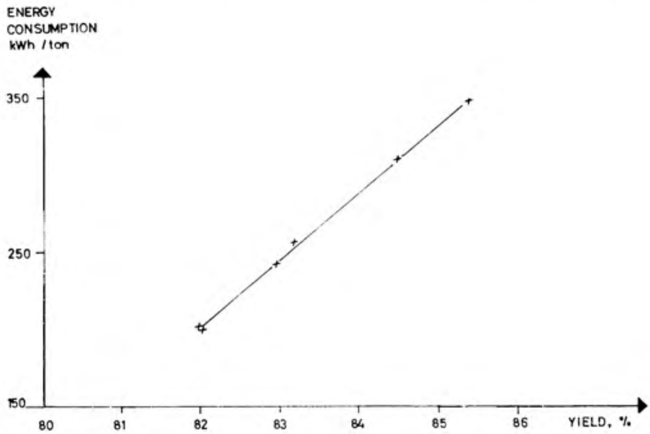

Fig. 5—Energy consumption plotted against yield for defibration

Fig. 6—Manual entry unit test laboratory

It is our experience that quite simple man/machine communication equipment will suffice. The interrelation between the computer implementing staff and the production personnel is more vital. Thus, it is most important that the objectives for the installation are clearly defined for production management and machine crews. It is also important that some of the applications work quite quickly in order to prove the computer capability. The 'salvation work' to be done is just as important as a technical solution. On the other hand, good technical solutions, including the man/machine interface, will simplify the salvation work.

At Billerud's, we have so far been considering three major fields for man/machine communication—(*1*) process personnel, (*2*) production management and (*3*) computer staff. The process operator console for our first application consisted of a manual entry unit and a typewriter. Today, we have a series of different consoles starting with very small units for entering one or two data without any feedback to the operator, except for a lamp to indicate that the computer finds something wrong with the data. In the test laboratory, a more advanced input console is necessary for fast data entering (Fig. 6). For standardisation reasons, we have also used this laboratory console in conjunction

Fig. 7—Process operator console developed at Billerud

with a typewriter for operator guide applications by using the same philosophy as for our first system. For process parts in which to a large extent we use closed loop computer control, we have designed our own process operator console (Fig. 7).

On-line communication with the production management has not so far been included in our process computer system. On the other hand, we have kept communications links open by locating the computers close to production management offices. For efficient use of the production control system, production management need for on-line communication will be greater. This, together with the fact that CRT displays are becoming feasible in price, means that we are planning to have a closer contact between the computers and production management.

The price of direct access storage on computers is high, thus programming in this part of a computer system must be as effective as possible. On the other hand, programming in a machine-oriented language is very cumbersome. Such considerations led to the development of new programming package, which means that we can program the entire periodic control by filling in a form (Fig. 8). Then the non-periodic part can be programmed in a problem-oriented language such as FORTRAN.

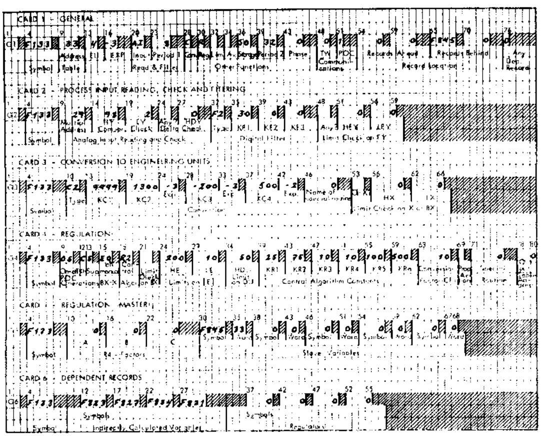

Fig. 8—Programming form for periodic control

The design of our process operator console was integrated with the new programming package, allowing control or process engineers to trim control loops directly from the console.

Future plans

We are now planning our third step in computer control. Nothing has so far given us any reason to diverge from our basic philosophy in the first two projects—integrated control. Moreover, we will not only include new processes on the process control level and make the entire planning of the Gruvön mill more efficient, but also tie in the process computers in a company information system that furnishes, for example, the sales department with the costs of a produced order.

Appendix 1—Mathematical formulation and solution of the Gruvön scheduling problem

Introduction

In this appendix, the mathematical formulation and solution of the Gruvön scheduling problem is derived.

The scheduling problem has been formulated in the following manner[5, 6]: given the planned paper production during a planning period of 2–3 days and the levels of all significant storage tanks at the beginning of the period, calculate a 'good' production scheme for all processes of the mill during the period. In order to attack this problem, a model of Gruvön mill has been developed. The model is illustrated in Fig. 2 and is further described elsewhere.[5, 6]

With the model as a basis, the scheduling problem is formulated as an optimum control problem for a multi-variable deterministic system and the Pontryagin maximum principle[7–9] is applied (next section). The scheduling objectives, stated in this section, are further discussed.[b] In the third section, the numerical solution of the optimisation problem is derived. The solution method is illustrated using a simple two-dimensional model. The results are then applied to the model of Gruvön and the final formulation and solution of the problem is given (fourth section).

If interested in only a brief description of the formulation and solution of the problem, the introductory parts of the second and fourth sections are recommended.

Application of the maximum principle to the scheduling problem

In this section, the scheduling problem is formulated as an optimum control problem for a multi-variable deterministic system, consisting of 10 state variables (storage tank levels) and 9 control variables (production of processes). The state variables as well as the control variables are constrained. The system is looked upon during a fixed time T, the planning period. The objectives of the scheduling are[5, 6]—

1. Few changes in the production rates of the processes.
2. Indirect storage of steam.
3. Acceptable final tank levels.

The first objective is expressed by the performance functional, the other two by fixing the final state of the system. We have found that the functional—

$$J(u) = \int_O^T \|u(t)-a(t)\|dt$$

will give schedules with few production rate changes, provided the vector $a(t)$ is suitably chosen. This $a(t)$ can be physically interpreted as a desired mean value of the production vector $u(t)$. $\|y\|$ is the norm,

$$\|y\| = \sum_i |y_i|$$

The optimum control problem has been given a formulation based upon the Pontryagin maximum principle. It is shown that the adjoint vector $p(t)$ of the maximum principle will be piecewise constant. The discontinuities appear when a tank reaches a limit. Only a finite number of p values influences the optimum solution. There is no direct way to solve the optimisation problem. Thus, some iterative technique must be used. It is shown that an iteration over p will lead to excessive computations.

The system, illustrated in Fig. 2, is described by—

$$\frac{dx(t)}{dx} = B.u(t)+C.v(t) \qquad . \quad . \quad . \quad . \quad . \quad (2.1)$$

where $x(t)$is an n vector of state variables ($n = 10$),
$u(t)$ is an m vector of control variables ($m = 9$),
$v(t)$ is a given vector function (the planned paper production),
t is the time,
B and C are time-independent matrices.

The control space as well as the state space are constrained—

$$u(t)\epsilon\Omega_u cE^m, \; x(t)\epsilon\Omega_x cE^n$$

where Ω_u is a convex hyperpolyhedron, described by—

$$u_i^{min} \leq u_i(t) \leq u_i^{max} \quad i = 1,\ldots,m$$

$$S^{min} \leq D.u(t)+E.v(t) \leq S^{max}$$

where D and E are time-independent row vectors.

The term Ω_x is a hyperparallelepiped, described by—

$$x_i^{min} \leq x_i(t) \leq x_i^{max} \quad i = 1,\ldots,n$$

The initial state $x(0)$ is known. Consider the system during a fixed time $0 \leq t \leq T$ and assume that $x(T)$ is fixed.

The problem is to find control strategy $u(t)$, $0 \leq t \leq T$, $u(t)\epsilon\Omega_u$, minimising the performance functional—

$$J(u) = \int_O^T \|u(t)-a(t)\|dt \qquad . \quad . \quad . \quad . \quad . \quad (2.2)$$

where $\|y\|$is the norm—

$$\|y\| = \sum_i |y_i|$$

and $a(t)$ is a given vector function. Thus, $a(t)$ can be physically interpreted as a desired average of the production vector $u(t)$.

The solution is to introduce the Hamiltonian function—

$$H(x,u,p,t) = \|u(t)-a(t)\| + \langle p(t), B.u(t)+C.v(t)\rangle \quad . \quad . \quad (2.3)$$

where $\langle a,b \rangle$ denotes the scalar product of the vectors a and b and $p(t)$, the adjoint vector, is a new vector function, not identically zero and satisfying the ordinary differential equation—

$$\frac{dp(t)}{dt} = -\frac{\partial H(x,u,p,t)}{\partial x} \quad . \quad . \quad . \quad . \quad . \quad . \quad (2.4)$$

if the optimum trajectory of the system lies in the interior of Ω_x and the ordinary differential equation—

$$\frac{dp(t)}{dt} = -\frac{\partial H(x,u,p,t)}{\partial x} + \lambda(t).\frac{\partial \varphi(x,u)}{\partial x} \quad . \quad . \quad . \quad (2.5)$$

if the optimum trajectory lies on the boundary of Ω_x.

$$x(T) \text{ given} \quad . \quad . \quad . \quad . \quad . \quad (2.6)$$

is the boundary condition on the differential equations (*2.4*) and (*2.5*).

In equation (*2.5*), $\lambda(t)$ are certain Lagrange multipliers.[9] Then φ is defined by—

$$\varphi(x,u) = \langle \text{grad } g(x), B.u(t)+C.v(t)\rangle \quad . \quad . \quad . \quad (2.7)$$

$$\text{where } g(x) = 0 \quad . \quad . \quad . \quad . \quad . \quad (2.8)$$

describes the boundary of Ω_x. So g (x) must have continuous second partial derivatives.[9] This condition is not fulfilled on the edges and the corners of the box Ω_x, but this difficulty can be avoided by smoothing the edges and the corners.

When the optimum trajectory reaches a boundary of Ω_x, the vector $p(t)$ makes a jump.[9] Assume that the optimum trajectory of the system during the time $t < t_o$ lies in the interior of Ω_x and during $t > t_o$ on the boundary of Ω_x. Introduce—

$$p^-(t) = p \text{ vector for } t < t_o$$

$$p^+(t) = p \text{ vector for } t > t_o$$

The following relation between p^- and p^+ is valid (the jump condition)—

$$p^+(t_o) = p^-(t_o) + \mu.\text{grad } g[x(t_o)] \quad . \quad . \quad . \quad (2.9)$$

where μ is real and not identically zero.

Since Ω_x is a hyperparallelepiped with edges parallel to the co-ordinate axes, the gradient of g is parallel to the unit vector e_i if x_i is the state variable that has reached its upper or lower limits—

$$\text{grad } g[x(t_o)] \sim (0,\ldots,0,\underset{\substack{\uparrow \\ \text{component No. i}}}{1},0,\ldots,0) \quad . \quad . \quad . \quad (2.10)$$

$$\text{Hence } p_j^+(t_o) = p_j^-(t_o) \text{ if } j \neq i \quad . \quad . \quad . \quad . \quad (2.11)$$

$$p_i^+(t_o) = p_i^-(t_o) + \mu \text{ if } \mu \neq 0 \quad . \quad . \quad . \quad (2.12)$$

This means that, when a storage tank has reached a limit, the corresponding element of p makes a jump to a new value while the other components remain unchanged. Physically, this implies that an input or output flow of the tank must be changed.

From equations (*2.7*) and (*2.10*), we find that $\varphi(x,u)$ is a piecewise constant function of x. Hence—

$$\frac{\partial\varphi}{\partial x} = 0 \qquad (2.13)$$

Equation (*2.5*) together with (*2.13*) now give that the relation (*2.4*) remains unchanged, that is—

$$\frac{dp(t)}{dt} = -\frac{\partial H}{\partial x} \qquad (2.14)$$

is valid also on the boundary of Ω_x.

Thus, we find from (*2.3*) and (*2,14*) that—

$$\frac{dp(t)}{dt} = 0 \qquad (2.15)$$

in every point where it is defined. Equation (*2.15*) together with (*2.11*) and (*2.12*) now imply—

$$p(t) = \text{piecewise constant} \qquad (2.16)$$

during the planning period $0 \leqq t \leqq T$. The discontinuities appear when a tank level reaches a limit.

The Pontryagin maximum principle states that a necessary condition for minimum of the performance functional $J(u)$ is that $H(x,u,p,t)$ is minimised as a function of u.

The maximum principle is valid if the system is controllable and if certain regularity conditions (continuity, derivability)[8] are fulfilled. Except for the conditions on $g(x)$ discussed above, the regularity conditions are fulfilled here, but our system as described by (*2.1*) is not controllable. The reason for this is that we will introduce as few variables as possible, thus reducing the complexity of the model.

Since $v(t)$, $0 \leqq t \leqq T$, is given, the maximum principle now gives that a necessary condition for minimum of the performance functional (*2.2*) is that—

$$||u(t)-a(t)|| + \langle p(t), B.u(t)\rangle \qquad (2.17)$$

is minimised as a function of u. The vector $p(t)$ is a piecewise constant function of t, satisfying the boundary condition $x(T)$ given.

Thus, it follows from the maximum principle that the function—

$$||u(t)-a(t)|| + p_o{}^*.B.u(t) \qquad (2.18)$$

is to be minimised; $p_o{}^*$ is the transpose of the piecewise constant adjoint vector p_o.

There is no direct way to solve the optimisation problem, therefore some iterative technique must be used. An immediate way is the following. Guess the p vector, solve the optimisation problem and iterate until the desired boundary value is reached. We will now show that this method leads to excessive computations.

Introduce a vector A, defined by—

$$A = p_o{}^*.B \qquad (2.19)$$

It can be shown that only a finite number of A vectors influence the optimum solutions. These values are—

$|A_i| < 1$ implying that the production of process u_i is kept at the level a_i
$A_i < -1$ implying that the production of process u_i is increased
$A_i > 1$ implying that the production of process u_i is reduced

Then u_j, $j \neq i$, is not affected.

Hence, if the number of processes is m, only 3^m distinct values of A influence the optimum solution, if the state space constraints are neglected. Each time a tank reaches a limit, however, the adjoint vector makes a jump to a new constant value and 3^m new A values must be considered. Since $3^m = 19\,683$, an iteration over A (that is, over the adjoint vector) will lead to excessive computations.

As the problem must be solved using a process computer,[5] this method is not realistic. Instead we will derive an iteration over the a vector in the next section.

Solution method illustrated on a two-dimensional example

The solution of the optimisation problem derived in the preceding section will now be discussed. Especially, we will discuss—

1. Determination of the a vector.
2. Utilisation of the physical interpretation of the A vector.
3. Numerical solution of the problem.

We will derive an iterative technique to solve the optimisation problem, using iteration over the a vector and utilising the ability of the A vector to keep the production at a certain level a, to reduce the production or to increase it. The iteration method does not ensure convergence to the true minimum (in terms of production rate changes), but it has been found to give solutions close to the optimum one and the saving of computational time is considerable. We will carry out the discussion using a simple two-dimensional example.

We will use a model, illustrated in Fig. 9 and consisting of—

1. Papermachine (v).
2. Process units (u_1, u_2).
3. Storage tanks (x_1, x_2, x_3).

One flow of the system has no storage tank (the steam) and steam balance in the system is maintained by an extra steam producer, S. In accorance with the model of Gruvön mill, this simplified model is not controllable.

The model is described by the tanks and the demand for steam balance of the system—

$$\dot{x}_1 = u_1 - c.v \quad (3.1)$$

$$\dot{x}_2 = b_{21}u_1 - u_2 \quad (3.2)$$

$$\dot{x}_3 = -b_{31}u_1 + b_{32}u_2 \quad (3.3)$$

$$S = d_1u_1 - d_2u_2 + e.v \quad (3.4)$$

In matrix form, we get—

$$\dot{x} = B.u + C.v \quad (3.5)$$

$$S = D.u + E.v \quad (3.6)$$

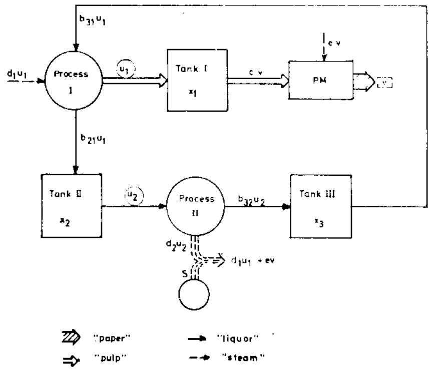

Fig. 9—A two dimensional model, consisting of
1 papermachine, 2 process units and 3 storage tanks

Put $b_{21} = b_{31} = b_{32} = d_1 = 1, \quad d_2 = e = 2$ and we get the system matrices—

$$B = \begin{bmatrix} 1 & 0 \\ 1 & -1 \\ -1 & 1 \end{bmatrix}$$

$$C = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}$$

$$D = [1 \quad -2]$$
$$E = [2]$$

The capacity restrictions of the system are given by—

$$0{\cdot}5 \leq u_1 \leq 1 \qquad (3.7)$$
$$0{\cdot}2 \leq u_2 \leq 1 \qquad (3.8)$$
$$0 \leq S \leq 2 \qquad (3.9)$$
$$0 \leq x_i \leq 1,\ i \leq 1,2,3 \qquad (3.10)$$

The planned paper production and the initial tank levels are given. The length of the planning period is assumed to be 5 time units. When solving the problem numerically this period is divided into 5 intervals of equal length. The production of the processes, that is—

$$u_i(1),\ldots,u_i(5) \quad i = 1,2$$

is to be calculated.

According to the derivation in the second section, we obtain the following optimisation problem for each time interval k—

Minimise—

$$V_k = |u_1(k)-a_1|+|u_2(k)-a_2|+A_1u_1(k)+A_2u_2(k) \quad . \quad . \quad (3.11)$$

subject to—

$$0{\cdot}5 \leq u_1(k) \leq 1 \quad . \quad . \quad . \quad . \quad . \quad (3.12)$$

$$0{\cdot}2 \leq u_2(k) \leq 1 \quad . \quad . \quad . \quad . \quad . \quad (3.13)$$

$$0 \leq D.u(k)+E.v(k) \leq 2 \quad . \quad . \quad . \quad . \quad (3.14)$$

$$0 \leq x_i(k-1)+[B.u(k)+C.v(k)]_i \leq 1,\ i = 1,2,3 \quad . \quad . \quad (3.15)$$

where

$$A = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} = p^*B = [p_1p_2p_3].B = \begin{bmatrix} p_1+p_2-p_3 \\ -p_2+p_3 \end{bmatrix}$$

$x_i(0)$, $i = 1,2,3$ and $v(k)$, $k = 1,\ldots,5$ are given.

According to the Pontryagin theory, the piecewise constant vector p should be chosen in a way satisfying the boundary condition $x(5)$ given.

An iteration over p, however, will lead to excessive computations (see second section). Instead, we will use an iteration over the a vector and utilise the physical interpretation of the A vector (now we are leaving a strict application of the Pontryagin theory).

An initial a value can be calculated from the planned paper production, the initial tank levels and the final tank levels The a value can be physically interpreted as a desired mean value of production of the processes during the planning period.

The total paper production is given—

$$\int_O^T v(t)dt = \sum_{i=1}^{5} v(i) \quad . \quad . \quad . \quad . \quad . \quad (3.16)$$

The initial and the final levels of tank No. 1 are known, that is—

$x_1(0)$ and $x_1(5)$ given.

Thus, the total flow—

$$\int_O^T u_1(t)dt = \sum_{i-1}^{5} u_1(i) \quad . \quad . \quad . \quad . \quad (3.17)$$

is determined by the material balance—

$$\int_O^T u_1(t)dt = x_1(T)-x_1(o)+c.\int_O^T v(t)dt \quad . \quad . \quad . \quad (3.18)$$

An average production—

$$\overline{u_1} = \frac{1}{T}\int_O^T u_1(t)dt \quad . \quad . \quad . \quad . \quad . \quad (3.19)$$

can thus be calculated. Now, assume that the storage capcity of x_1 is very great. Then a good control strategy would be to run process I with the rate—

$$u_1(t) = \overline{u_1} \quad . \quad . \quad . \quad . \quad . \quad (3.20)$$

during the whole planning period. Thus, putting $A_1 = 0$ and choosing $a_1 = u_1$, we would reach the desired end point and no production rate change is required. However, even when the capacity of x_1 is limited, we have found that—

$$a_1 = \overline{u_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3.21)$$

is a useful initial value.

In the same way, put—

$$a_2 = \overline{u_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3.22)$$

$$\text{Where } \overline{u_2} = \frac{1}{T} \cdot \int_O^T u_2(t)dt \quad . \quad . \quad . \quad . \quad (3.23)$$

is calculated from—

$$x_2(0),\ x_2(5) \text{ and } \int_O^T u_1(t)dt.$$

Now, we have no possibility to control the final level of x_3. As a numerical example, consider the following planning problem: assume that the planned paper production is described by—

$$v(1) = v(2) = v(4) = v(5) = 0{\cdot}9, \quad v(3) = 0$$

where $v(3) = 0$ can be interpreted as a 'wire change'.

Initial tank levels—

$$x_i(0) = 0{\cdot}5 \quad i = 1,2,3$$

Desired final tank levels—

$$x_1(5) = x_2(5) = 0{\cdot}5$$

(Since the system is not controllable, all final tank levers cannot be fixed.)

Calculate $u_i(1),\ldots,u_i(5)2\ i = 1,2$

Numerically, equations (*3.16*), (*3.18*) and (*3.19*) give—

$$\overline{u_1} = 0{\cdot}72$$

In the same way, we find—

$$\overline{u_2} = 0{\cdot}72$$

Thus put—

$$a_1 = a_2 = 0{\cdot}72$$
$$A_1 = A_2 = 0$$

and minimise for $k = 1,\ldots,5$

$$V_k = |u_1(k) - 0{\cdot}72| + |u_2(k) - 0{\cdot}72| \quad . \quad . \quad . \quad (3.24)$$

subject to the constraints (*3.12*)–(*3.15*).

The result of the optimisation is illustrated in Fig. 10. No production change of u_1 has been necessary and x_1 has reached the desired value, but the production of u_2 has been reduced during interval No. 3, since the S variable has reached its lower limit. As a consequence of the production change, the final level of x_2 is incorrect.

To obtain the correct final level of x_2, the production of u_2 must be increased during intervals 1, 2, 4 and 5. This can be done by solving the optimisation problem once more, using a higher value of a_2. In this way, we can iterate until the desired tank levels are reached. This iteration technique implies, however, that the optimisation problem must be solved many times. Since the computational time is critical,[5] this consequence is disadvantageous.

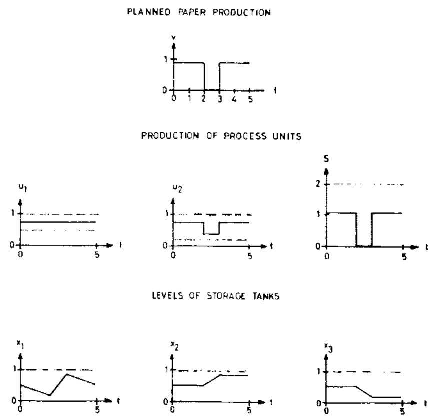

Fig. 10—Optimum solution to the two-dimensional example, using the objective function—$V = |u_1 - 0{\cdot}72| + |u_2 - 0{\cdot}72|$ Dotted lines are capacity restrictions, heavy lines are calculated solution and, since the production of u_2 has been reduced during interval No. 3, the desired final level of x_2 has not been reached.

The following technique will utilise the production and storage capacities more and will sometimes increase the number of production rate changes. The computational time required is reduced drastically, however, since the problem must be solved only once.

The optimisation problem is solved with the original a values until, during a certain interval k, some production change is obtained. Then, for intervals greater than k, the a vector is recalculated with regard to the production change during interval k. Thus, the change is compensated for during the remaining intervals only.

In our example, $a_1 = a_2 = 0{\cdot}72$ is used during intervals No. 1, 2, 3. During interval No.3, the optimisation gives—

$$u_2 = 0{\cdot}36$$

That is, we have got a production drop out of—

$$0{\cdot}72-0{\cdot}36 = 0{\cdot}36 \text{ units.}$$

To compensate for this drop out, the production during intervals No. 4 and 5 must be—

$$\frac{(2\times 0{\cdot}72)+0{\cdot}36}{2} = 0{\cdot}90$$

If the problem is solved using this technique, we will get results according to Fig. 11. The desired tank levels have now been reached.

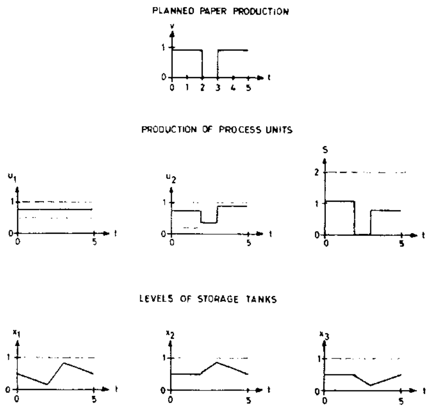

Fig. 11—Optimum solution to the two-dimensional example, using the objective functions—

$V = |u_1 - 0{\cdot}72| + |u_2 - 0{\cdot}72|$ during intervals 1, 2, 3

$V = |u_1 - 0{\cdot}72| + |u_2 - 0{\cdot}90|$ during intervals 4, 5

The desired final tank levels have been reached.

It can be shown that the minimum number of production rate changes of this example is 2 and that there is an infinite number of solutions with two production rate changes, all satisfying the constraints and giving the desired final tank levels. Thus, the solution illustrated in Fig. 11 is not unique.

In this example, we have only used $|A_i| < 1$, but the ability of $|A_i| > 1$ to increase or reduce the production can also be utilised. Assume that we are planning a maintenance shut-down of the process u_i during some interval k. This can be formulated as a constraint—

$$u_i(k) = 0$$

This formulation implies a risk, however, that the problem will be so rigidly structured that no feasible solution exists. To avoid this, the production reducing ability of $A_i > 1$ can be utilised. Thus, put—

$$A_i > 1, \ |A_j| < 1 \quad j \neq i, \ u_i^{min} = 0$$

If the restrictions permit, u_l will be reduced to its lower limit. Otherwise, we will obtain the smallest possible production.

The optimisation problems in this section are easily solved graphically or by hand calculations. Of course, this is not possible for the real 9-dimensional planning problem, but the objective function used—

$$V = \sum_i (|u_i - a_i| + A_i u_i) \quad . \quad . \quad . \quad . \quad (3.25)$$

can be linearised by introducing auxiliary variables gi and h_i, defined by—

$$u_i = a_i + g_i - h_i, \;\; g_i \; h_i \geq 0 \quad . \quad . \quad . \quad . \quad (3.26)$$

and minimising the objective function—

$$V = \sum_i (g_i + h_i + A_i u_i) \quad . \quad . \quad . \quad . \quad (3.27)$$

instead of *(3.25)*.

Since all constraints are linear, our optimisation problem can now be solved as a linear programming problem for the variables u_i, g_i and h_i. Since the LP problems can be solved sequentially, each LP problem will be relatively small. This is further discussed in the next section.

Final problem formulat on and solution technique

In this section, the results of the third section are applied to the model of Gruvön mill and the final formulation and solution of the scheduling problem is given.

The model of Gruvön, illustrated in Fig. 2, has been verified by simulations and measurements, performed during normal operating conditions.[6] With this model as a basis, the scheduling problem has been formulated as an optimum control problem for a multi-variable deterministic system. The solution technique developed is a fusion of methods and ideas taken from the maximum principle, linear programming, heuristic argumentation and physical interpretation of the mathematical relations. The solution technique can be characterised as a successive solution of a number of linear programming problems, defined and linked together by means of the maximum principle. It can also be interpreted as a decomposition of a large LP problem. The methods developed have been tested on number of full-scale planning examples[6] and have been found to give good production schedules.

The planning period is divided into a number of time intervals, not necessarily of equal length. During each interval, the production of the processes is assumed to be constant. For each LP problem, the objective function has the form—

$$\sum_i (|u_i - a_i| + A_i u_i)$$

A_i are parameters, related to the adjoints variable of the Pontryagin theory and a_i are components of a vector a that can be physically interpreted as a desired average of the production vector $u(t)$. An initial a value can be calculated from the planned paper production, initial tank levels and final tank levels. The solution technique implies an iteration over a. The LP problems are solved sequentially. The transfer of information between the LP programs is handled partly by the vector $a(t)$ and partly by the adjoint vector. The execution time of an IBM 1800 for a typical problem is about half an hour.

Problem formulation

Given the system equations—

$$\frac{dx(t)}{dt} = B.u(t)+C.v(t) \quad (4.1)$$

$$S(t) = D.u(t)+E.v(t) \quad (4.2)$$

the constraints—

$$u_j^{min} \leq u_j(t) \leq u_j^{max} \quad j = 1,\ldots,9 \quad (4.3)$$

$$x_j^{min} \leq x_i(t) \leq x_i^{max} \quad i = 1,\ldots,10 \quad (4.4)$$

$$S^{min} \leq S(t) \leq S^{max} \quad (4.5)$$

the initial state of $x(0)$ and the function $v(t)$, $0 \leq t \leq T$, calculate $u(t)$, $0 \leq t \leq T$, satisfying the restrictions and the scheduling objectives.

Problem solution

Suitable boundary values $x(T)$ are fixed. The planning period T is divided into a number of intervals τ_k (not necessarily of equal length)—

$$T = \sum_{k=1}^{N} \tau_k \quad (4.6)$$

For $k = 1,2,\ldots,N$, the following optimisation problems are solved successively.

Minimise—

$$V = \sum_{d=1}^{9} [g_j(k)+h_j(k)+A_j u_j(k)] \quad (4.7)$$

subject to $$u_j^{min} \leq u_j(k) \leq u_j^{max} \quad j = 1,\ldots,9 \quad k = 1,\ldots,N. \quad (4.8)$$

$$S^{min} \leq \sum_{d=1}^{9} d_j u_j(k) + \sum_{d=1}^{3} e_j v_j(k) \leq S^{max} \quad k = 1,\ldots,N \quad (4.9)$$

$$x_i^{min} \leq x_i(k-1)+\tau_k[\sum_{d=1}^{9} b_{ij}u_j(k) + \sum_{d=1}^{3} c_{ij}v_j(k)] \leq x_i^{max} \quad i = 1,\ldots,10$$

$$k = 1,\ldots,N \quad (4.10)$$

$$u_j(k) = a_j(k)+g_j(k)-h_j(k) \qquad j = 1,\ldots,9 \quad k = 1,\ldots,N \qquad (4.11)$$

$$u_j(k),\ g_j(k),\ h_j(k) \geqslant 0 \qquad (4.12)$$

b_{ij}, c_{ij}, d_j and e_j are elements of the matrices B, C, D and E, respectively; $a_j(1)$ are calculated from $x(o)$, $x(T)$ and $v(t)$; $a_j(k) = 2,\ldots,N$ are calculated from the result of the optimisation for interval No. $k-1$.

A_j are components of a vector A, related to the adjoint vector p of the Pontryagin theory by—

$$A = p^*B \qquad (4.13)$$

Usually, $A = 0$. The numbers A_i influence the optimum solution in the following way—

$|A_i| \ll 1$ the production of u_i is kept at the rate a_i (if possible)
$A_i \gg 1$ the production of u_i is reduced
$A_i \ll -1$ the production of u_i is increased

Each time interval gives rise to a linear programming problem with 27 variables (not including slack variables and artificial variables) and 49 restrictions.

A computer program written in basic FORTRAN IV has been developed to carry out the scheduling calculations.

The program size is about 15 000 words on an IBM 1800 (software floating point, single precision) and the execution time for a problem with 15 time intervals is about half an hour (off-line execution, 4 μs cycle time).

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Discussion

The Chairman This session has taken us through the forest operations, the chemical pulping of the wood, its semi-chemical and its mechanical pulping and the interphase to the papermill.

Mr G. E. Annergren Mr Alsholm mentioned updating of the packing of the measuring wheel in the continuous digester. Have you done so? If so, how and what accuracy have you obtained?

Mr O. Alsholm I said that possibly we could get greater accuracy by doing so. We are looking into this matter, so I cannot give you an answer at present.

Mr Annergren We have tried to do so, but we have failed so far.

Dr N. K. Bridge May I direct two questions to Mr Alsholm.

I think you said in your paper that the production scheduling program uses 15 K words and takes about half an hour to run, off-line. Could you give us a breakdown of this program? For instance, could you indicate how much of the program is involved in the Pontryagin optimising calculations and how much in the scheduling routine proper?

The second question is— to what extent have you written the program in order to take care of the mishaps that occur in the best regulated mills, such as the machine wire dropping off?

Mr Alsholm On the first question about size, our variable core is 8 K. The calculating part requires just about this size. The rest of the 15 K are divided into one input and one output core load.

In the sense you have mentioned constraints, we have now ordered a 56 K machine (2 µs) with floating point hardware. Without this, the calculating time is about half an hour off-line, corresponding to maybe more than an hour on-line. It is rather unlikely that we are able to use this program to the full extent before we get the features mentioned. We plan that, if the wire drops off, as you say, to run the program again. I also think it will be important for the production management to be able to run trials that take only, say, 5 min on the computer and change the input if necessary (and if possible).

Mr J. A. Robinson Can you give us any specific figures of the accuracy of your method of calculating chip moisture content? Secondly, the method seems to imply that all changes in chip bulk density are in fact caused by changes in moisture content. I would like your comments on the validity of this assumption in the general case of a mill receiving chips from many sources?

Mr Alsholm Starting with the last point, we are at this stage assuming a constant packing density independent of moisture content. I have not shown any accuracy figures today, because we are working on this. We are trying to see, for instance, if the high speed of the chip metering wheel will give higher offsets compared with manual samples? Moreover, if it is very dry, as it was during this very hot summer, do we get other packing densities, etc.? The only comment that I am prepared to make now is that we use the calculated moisture for closed loop control!

Mr D. L. Cooper Have you found the model that you use sensitive to the parameters introduced at the beginning—for example, the conditions that the tank should begin and end at a 50 per cent level and vary between not more than 15 per cent and 85 per cent? The figures in the diagrams indicate that the levels change by almost the full amount that you allow. I wonder whether the restriction that they should be at 50 per cent at the beginning and start of the operation constrains the model unduly.

Mr Alsholm In the calculation, we always start with the levels that we can measure 'now', but we do not intend to run on recommended schedule until we reach the end of the period. Before we reach that point, we recalculate, maybe several times. We have to have some goal for the future, though this may not necessarily be 50 per cent. We have found that 50 per cent gives us better 'chances' in the next planning.

Mr B. Pettersson In principle, another choice of end point will change the production schedule. This fact is not so critical, however, since the solution technique developed implies that we try to reach the end points if we can. If we cannot, we will achieve final levels as close to the fixed ones as possible.

Dr L. G. Samuelsson With what accuracy was Mr Alsholm able to calibrate the moisture gauge on the machine by the weighing of the reel?

Mr Alsholm We have been investigating the accuracy of this method, especially when we had a fixed head meter. Today, we have a traversing meter and it is not so critical any longer. I recall the estimated accuracy, however, to be $\pm 0{\cdot}3$ g/m^2 (at 70 g/m^2), in reality better than ± 1 g/m^2. The calculated changes are of the order of less than 0·5 g/m^2.

Dr D. B. Brewster The paper by Alsholm & Pettersson gave a detailed description of the mathematics involved in production scheduling at Billerud. The problem at Holmens Bruk is similar, but no information is given in the paper on the method for its solution, except to say that it involves some simple equations.

Mr O. Svensson We are using a heuristic model with very simple mathematics.

Dr Brewster That covers a broad field.

Dr R. L. Grant Would Mr Alsholm please give us his estimate on the time that it took (or will take) to pay off the cost of installing and starting up the installation and tell us of the areas from which the improvements in economics came?

Mr Alsholm That is a very interesting question. There is no basis of comparison on a new machine, for you do not know how the machine would have started up without computer control. Some of our findings are as follows. We started up the second project by putting the digester control on before the papermachine control. This resulted in a very significant rise in production capacity of the papermachine. We have not seen the same large rise when closing the loops on the papermachine itself. Other parts of the system were of great help during start-up for process studies. Being somewhat concerned about the NSSC sulphate pulp ratio, we designed a system, for example, that continuously calculates heat transfer coefficients in the evaporators. I think that nobody in the world has the ratio of about 130 000 tons per year NSSC pulp to about 150 000 tons per year of sulphate pulp.

The process control was not meant to be the bread and butter, only the bread. It would break even and it would give some return on the investment, but the major point was the entire planning system, as we considered that optimum scheduling could not be achieved manually. We have not yet put this part into operation, so I could not give you the whole answer today. On the other hand, the process control part seems to be more profitable than expected. In addition, the intangible benefits from, say, the extensive reporting system have to be credited.

Mr H. B. Carter I wonder if either of the two speakers has considered the possibilities for changing the system with all the new facilities available. Actually, in spite of a large amount of control equipment in the form of computers that have been installed at Sundsvall, we apparently have not changed the system; we still have the same people working, we are going the same way and the other mill at Hallsta still has the same large number of tanks. Does anybody consider with all this sophisticated brainpower that we might be able to do away with the pure man on the papermachine?

Mr Alsholm I think this is a very important point. During our last expansion and even more during the coming one that I mentioned, we have worked and will work along the systems engineering path. We have made very thorough simulations to see how large the storage tanks need to be and so on. On the other hand, we have done nothing really revolutionary, although we have, for example, a rather unconventional machine chest configuration for our fourth papermachine.[2] I believe such solutions are of real importance and that more of such things will have to come—of course, Rome was not built overnight.

Your question about the number of people is 'a wrong question', as savings in personnel yield very little compared with an increase in production.

We have decreased the number of people in the papermill, however, about as much as we have the people on the computer project. In the new fluting mill, for example, we have one man at the chip pile, one at the digester, three at the papermachine and two at the winder. This is a 130 000 ton per year mill, which gives a very low man-hour/ton figure.

The Chairman There is a project management in between also.

Mr J. A. Smith Ever since Pontryagin's work became known, there have been papers that aimed to apply his work to a practical situation. About halfway through many of these papers, however, the mathematics became quite intractable. The problem would then be modified to allow of a solution that was computationally feasible, but no longer applied to the practical problem. The authors are to be congratulated for reaching the same moment of truth about halfway through and inventing some new mathematics to allow the original problem to be solved.

My question relates to a mill producing pulp for sale as well as for supplying the papermachines for which maintaining the maximum rate of pulp production is the extra objective. In this case, does the solution of the problem lead to intractable computations once again or can the methods described in the paper cope with this?

The Chairman You really scared me, because we have recently changed the project to involve market pulp as well in the program and I hope therefore Mr Pettersson does not have to do all those formulas over again.

Mr Pettersson It is not necessary to develop other methods, we can handle this case, too. It is quite possible to include in the optimising function a requirement for maximisation of the pulp production.

Dr J. H. Sandblom In this last discussion on whether or not a computer system can have any influence on the papermill layout, it is quite obvious that it may. In the Hallstavik case, the computer strategy and the process was simulated in a way that is well-known nowadays at the ASEAS computer centre. This gave rise to changes in the process, specifically to buffer tanks and a few pipes.

The planning program in the Hallstavik systems is simple in principle and straightforward. It is an iteration procedure, in which the computer in each iteration lays out the electric power limits, calculated from the given power limits, production and consumption at every instant of the planning period for all the mills in the Holmens Group. The reason for this, of course, is that all the machines in the various mills are consuming power, but are also producing power when in operation. The program searches the best way through all the various limitations.

Dr J. Grant One of my principle interests is pulps from non-woody fibres and these are usually produced in comparatively small mills in out-of-the-way places of the world where the problems are entirely different from those we have been talking about.

Firstly, such mills are usually in countries that have little or no pulp or papermaking industry background. Secondly, they are comparatively small; thirdly, they handle raw materials that are mostly entirely different from wood; fourthly, the cost of installing computer control may be a very much larger proportion of the total cost of the mill than for a large woodpulp mill. Fifthly, the question of saving labour is seldom important—in fact, in many cases, an object of the mill is to provide employment. It seems, however, that computer control not only saves labour, but also performs operations more accurately than by hand—an important consideration on its own. Sixthly, there is the problem of the maintenance of delicate instruments and sophisticated electrical systems in a developing country.

Can anyone here guide me how to estimate in advance whether one should install a computerised system and, if so, to what extent, bearing mind that these are usually integrated pulp and papermills? This is a very important question that frequently arises.

Mr K. D. Blundell My experience in developing countries suggests within the context of the question the use of simple and minimum essential instrumentation only. Unfortunately, in these areas, the skills required for the maintenance of sensitive equipment are not easy to come by.

Mr A. J. Ward Could I ask Mr Svensson to enlarge on the point he made in his presentation that they decided not to develop the computer control scheme themselves, only contributing one man to the team. In our experience, the computer control field is extremely volatile and we would feel very reluctant to allow an outside organisation provide so large a part of the technical skills. Could you enlarge on the decisions that were taken and the criteria that were used?

Mr Svensson Our philosophy was to take out a sector of our process where computer control indicated that it would give satisfactory profitability. This sector constituted the first phase of a greater project, which would be profitable in itself. The first phase is now completed.

Our intention was also to buy the whole system as a package from a supplier with a minimum share in the programming work. I think our way of realising this computer project was the most convenient for our company.

Mr Alsholm I think we have so far taken the stand that we should be able to do everything ourselves. This does not mean that we are doing or will do all ourselves. Certain development of standard packages must be the responsibility of the vendor and you may need assistance during expansion periods from a systems consultant. So long as you build up a system on which you want to continue to work, I believe you should carefully decide how much you buy from others.