Preferred citation: A.M. Al-Shaikh and D.B. Brewster. Entire pulpmill control. In **Papermaking Systems and their Control**, *Trans. of the IVth Fund. Res. Symp. Oxford, 1969*, (F. Bolam, ed.), pp 253–265, FRC, Manchester, 2018. DOI: 10.15376/frc.1969.1.253.

ENTIRE PULPMILL CONTROL

A. M. AL-SHAIKH and D. B. BREWSTER*
Westvaco Corporation, U.S.A.

Synopsis The hierarchical structure of pulpmill control is defined in terms of six levels—planning, scheduling, supervisory, multi-variable, direct and data acquisition. The functions of each of these levels for a continuous digester are discussed. The design of the scheduling level is investigated for the case of a single pulpmill that must produce two species sequentially. It is shown to be primarily the problem of designing a feedforward control system for a process with a major dead time.

The relationship of plant design to controllability is discussed, using the example of determining the size of the pulp storage tanks.

Introduction

INTEGRATED pulp and paper mills invariably have facilities for pulp storage between the pulpmill and the papermill. When pulping is done with batch reactors, this tankage is required to provide a buffer (or integrator) between the discontinuous pulp sources and the continuous papermachines. The inventory in the storage tanks will fluctuate, reflecting any temporary imbalance in the pulpmill and papermill production rates. If sufficient storage is provided, partial or complete shutdown of the pulpmill and papermill may be independently accomplished for maintenance purposes.

Generally, paper or board is manufactured from a blend of fibres. These are usually produced separately and the intermediate storage is normally designed to segregate the various types before continuously blending them to each papermachine.

This situation requires over the long run that the amount of each kind of pulp consumed equals the amount produced and that, in the short run, the storage tanks neither overflow nor run empty. The solution to this problem lies in proper pulp and papermill scheduling and in selection of tank sizes.

---

* Present address—Stapleton Dowdeswell Kelly & Hunt Ltd., 1717 Sun Life Building, Montreal 110, P.Q., Canada

Under the chairmanship of M. I. MacLaurin

Scheduling and tank sizing are dual problems and should be solved simultaneously at the design stage.

Continuous pulping provides many advantages for operating economy and improved process control. When more than one variety of pulp is required in the papermill and the pulpmill is to be continuous, a decision must be made whether a continuous pulping line should be provided for each pulp or whether a single pulping line will be used sequentially for each pulp.

If the latter decision is made—and, particularly, if there are only two varieties of pulp—a relatively simple example of the scheduling problem results. Such a system is shown schematically in Fig. 1.

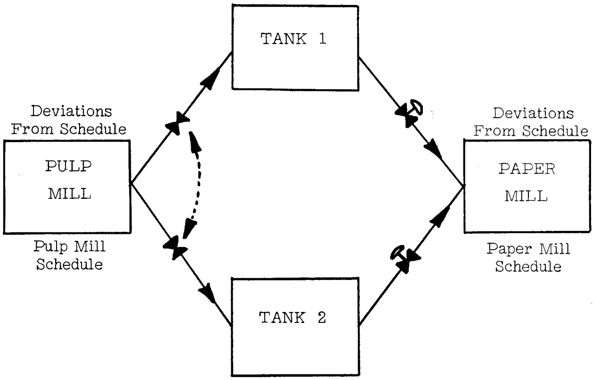

Fig. 1—Process schematic

In order to point out the important factors affecting the design of a schedule for such a problem, the various sections of the process must be considered.

Papermill

The production schedule of the papermill is determined from the order situation and the characteristics of the papermachines. This consists of a desired sequence of grade, fibre blends, tonnage rates and total tonnages required. Included in this schedule are time periods set aside for machine maintenance.

From this schedule, an estimate may be made directly of the pull rate of each kind of pulp for each hour as far into the future as the schedule goes.

During the implementation of the schedule, positive or negative deviations from the schedule targets usually occur because of favourable or adverse production conditions, including unscheduled down-time. These deviations cause the estimates of the pulp pull rates to be in error. The actual pulp pull rates can be measured with reasonable accuracy.

Pulp storage

In the example being considered, the storage tanks serve to convert the serial species operation of the pulpmill into the required parallel species demand of the papermill. The normal situation is that pulp is being fed to one tank only and that the level of that tank is rising, because the instantaneous supply rate is greater than the instantaneous demand rate for that species. The other tank is not receiving pulp and its level is dropping.

When a species interface reaches the outlet of the pulpmill, the pulp is diverted to the other tank and the filling and emptying state is reversed.

In order to meet the papermill demand, neither tank must completely empty. Pulp will be wasted should either tank overflow. In order to meet the species blending requirements for the papermill, in a practical manner, the two species are restricted to their own tanks.

Pulpmill

The major control characteristic of the pulpmill is the large dead time between changing species of the chips and the resulting appearance of the species change in the fibre. For a continuous bleached pulpmill of conventional design, this could take up to 20 h.

Process down-times, both scheduled and unscheduled, occur for maintenance purposes.

Difficulty occurs also in trying to set the pulp production rate precisely. This is because of the problems of material balance control usually inherent in this type of process. The actual production rate may be measured and the difference between the papermill pull rate and the pulpmill production rate may be also measured from the time derivatives of the storage tank levels.

Scheduling the entire integrated mill must take into account all the above factors. In addition, each species change and production rate change in the pulpmill leads to a transient period, during which pulp quality will probably deviate from target. This results in economic loss from overuse of raw materials and from degraded performance on the papermachines.(1)

Minimisation of the number of species changes is equivalent to obtaining maximum utilisation of the storage tanks. This can be accomplished by arranging for the first tank to be just reaching the emptying point at the same time as the second tank becomes full. At this instant, the species change must reach the outlet of the pulpmill and the pulp must be diverted to start filling the empty tank.

Because of the dead time (L) in the pulpmill, the change in chip species must be made L hours before this critical instant. This implies that a prediction of the state of the tank levels L hours ahead must be made.

The scheduler must also determine the desired pulpmill throughput, after each species change, necessary to produce the simultaneous empty/full tank inventories at L hours after the time of the next species change. This requires a prediction over the full time of the species run. Failure to determine this production rate accurately and to enforce it will lead to underutilisation of the storage tanks and/or will necessitate changes in pulpmill throughput.

These predictions and the implementation of the control actions (species change time and throughput) are a type of feedforward control. Feedforward control and predictions are, of course, never perfect and the whole scheduling control must therefore include feedback.

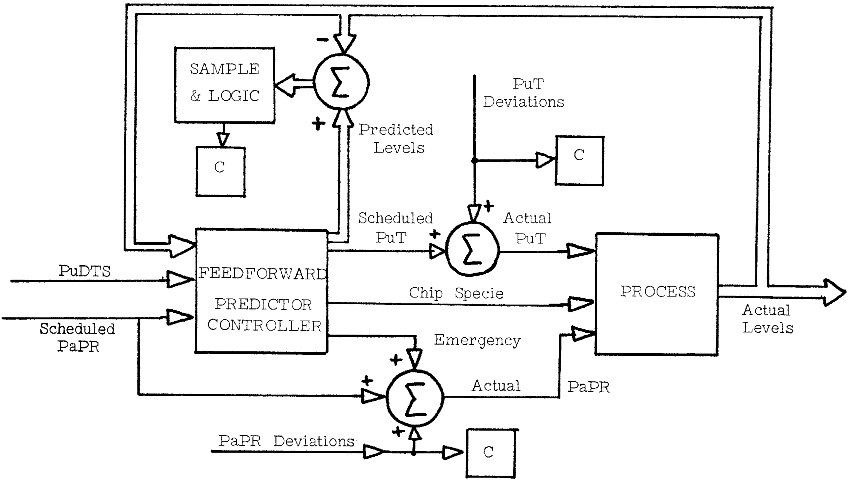

Fig. 2—Schedule control system

Fig. 2 shows the block diagram of this system. The process so-called is the two tanks together with the chip species change to pulp species change dead time. The inputs to the process are the chip species, the actual pulpmill throughput (Actual PuT) and the actual papermill pull rate (Actual PaPR). The outputs of the process are the actual tank levels. The feedforward predictors uses a model of the process and its inputs are the pulpmill down-time schedule (PuDTS) and the scheduled papermill pull rate (scheduled PaPR). The feedforward predictor outputs are the chip species and the scheduled PuT, which are then implemented as control actions on the process. Owing to various factors, the pulpmill throughput deviates from the scheduled PuT and the papermill deviates from the scheduled PaPR. Detection of these deviations triggers the recomputation (C) of the feedforward action. Within the dead time L after a chip species change has been made, it may be necessary to take emergency action by changing the PaPR.

Feedback is provided on a sampled data basis and compares the actual tank levels with the predicted tank levels. If the deviation is important, the feed-forward controller is computed.

The design of the scheduling system is dealt with later in more detail.

Process design

In recent years, with the rapid development of systems engineering techniques being accelerated by the availability of inexpensive computational facilities, it has become possible to consider the interaction of plant design and controllability at the design stage. In the example under consideration, the size of the tanks is clearly an important design parameter. Larger tanks obviously provide the capability of reducing the frequency of species changing. Determination of the optimum size of the tanks is illustrated qualitatively in Fig. 3. Quantitative determination of the optimum size of the tanks requires that a scheduling method be available. The efficiency of the scheduling method will have a bearing on the optimum tank sizes selected as shown in Fig. 3.

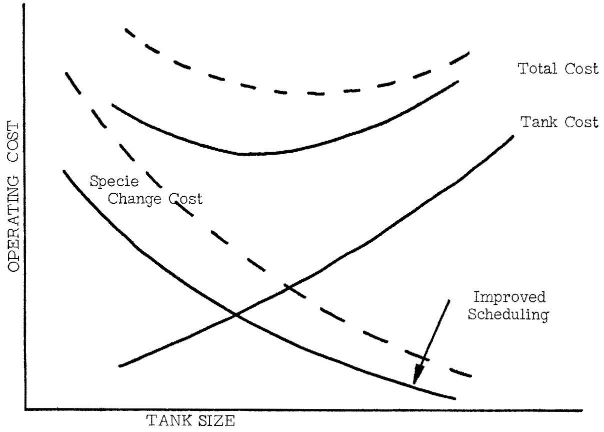

Fig. 3—Determination of optimum tank size

Hierarchical structure of pulpmill control system

The recent rapid advances in control technology have made it possible to develop large-scale, integrated control systems for complex industrial processes. This has created a burden for the system designer in developing an understandable structure for such systems. Fortunately, the concept of a hierarchical or multi-level system has been proposed in various forms.(2–12)

The complex system is broken down into a number of subsystems at various levels in the hierarchy, most of which are interconnected. This allows work to proceed on each subsystem without too much concern about its interaction with other subsystems. Various subdivision schemes have been proposed, depending on the purpose and taste of the inventor. The function of each level(6) is to use data supplied by all the lower levels, together with specific information from the level immediately above it, in order to make decisions that affect the level immediately below it.

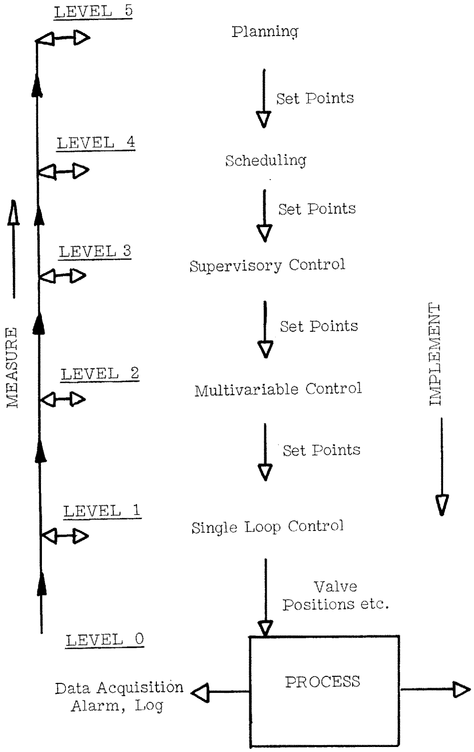

Fig. 4—Multi-level control

Fig. 4 shows a scheme that the authors have found useful in dealing with pulp and paper processes.

In general, as the hierarchy is ascended, the following characteristics can be observed(2)—

1. Increasing complexity of control calculation.
2. Decreasing frequency of control action.
3. Variables become more probabilistic and less deterministic.
4. Variables become more economic (abstract) and less physical.

This scheme will be discussed using a continuous pulp digester in an integrated pulp and paper mill as an example, although it is equally applicable to other pulp and paper processes.

Level 5—Planning is not of interest in this case. This level is generally concerned with allocation of orders to specific machines in a multi-machine company. Linear programming has been used for this purpose.

Level 4—Scheduling is the control function of most interest in this paper. Further discussion will show how this function fits in with other levels for the digester and papermill. It receives information of the papermill schedule, also on the pulpmill scheduled down-time. The pulpmill level 0 system provides data on the actual levels of the storage tanks and on the tank inflows and outflows. From these data, it determines the chip species change time and the desired digester production rate, which it transmits to the digester level 3 control. Emergency changes to the papermill throughput are transmitted to the papermill level 3 subsystem.

Level 3—Supervisory receives the following information—

Chip species change time
Desired production rate
Desired K number
Actual production rate
Actual K number

and calculates trajectories of the level 2 variables to accomplish the required changes in species, production and K number. These calculations involve the simultaneous solution of unsteady state kinetic, stoichiometric and heat and material balance equations for the digester.

The results of these calculations are a time sequence of adjustments to be made to the set points of the digester level 2 variables. When these are accurately enforced, the result will be rapid, precise changes in K number, production rate and/or species.

Level 2—Multi-variable control.

The variables to be controlled at this level have a more direct bearing on the pulping reaction and on the material balance control of the digester than do the conventional level 1 control variables such as pressures, flows and temperatures. The level 2 variables are often calculated from one or more lower level variables. To adjust any level 2 variable without changing another level 2 variable usually requires adjustment of more than one level 1 variable.

Examples of level 2 variables are the active alkali-to-wood ratio or the washing zone upflow.

Because of the dead time in the digester, it is desirable to eliminate as many disturbances as possible. Regulation of the level 2 variables helps accomplish his.

Level 1—Direct control. This level of control is the traditional process control level in which a single variable such as pressure, temperature or flow is measured and controlled to a set point by manipulation of a valve position or other device.

It should be noted that, in structuring the control system in this way, no assumptions are made about how the control system should be practically realised. In the vast majority of cases in present-day practice, only level 1 is automatic, being implemented by conventional analog controllers. The present availability of digital process control computers makes the automatic implementation of all levels a practicality. Some authors have equated levels in the control hierarchy with levels in a computer hierarchy.(10, 11) Others have implemented several levels in the control hierarchy with a single computer.(3, 4)

Mouly(2) claims that the effectiveness of traditional control at the higher levels is generally quite poor compared with level 1. From a technological point of view, the tools are now being sharpened to make improvements at the higher levels, but better methods must be used to determine the economics of control at these levels. It is interesting to note that, in the petroleum refining industry, most control development has been at level 5 and level 3, although a recent paper by Lasher(5) describes hierarchical control from levels 1–5 for petrol blending.

Design of the pulpmill scheduling system

COMMON to most engineering problems, there are many solutions to the design of the level 4 scheduling system. The solutions will have a range of cost, robustness and effectiveness. The designer must choose one that seems best in his judgment. In general, an analytical solution based on sound assumptions is preferable. This approach will now be discussed. The design criteria used are that the frequency of species changes should be minimised, the tanks should neither empty nor overflow and pulpmill and papermill throughput changes should be avoided.

The solution proceeds as follows. Recall that the argument was made earlier that in order to meet the above criteria, the first tank should just reach the empty point at the instant that the second tank becomes just full. To satisfy conservatism, *empty* and *full* can be defined as a chosen distance from the bottom and top of the tanks, respectively.

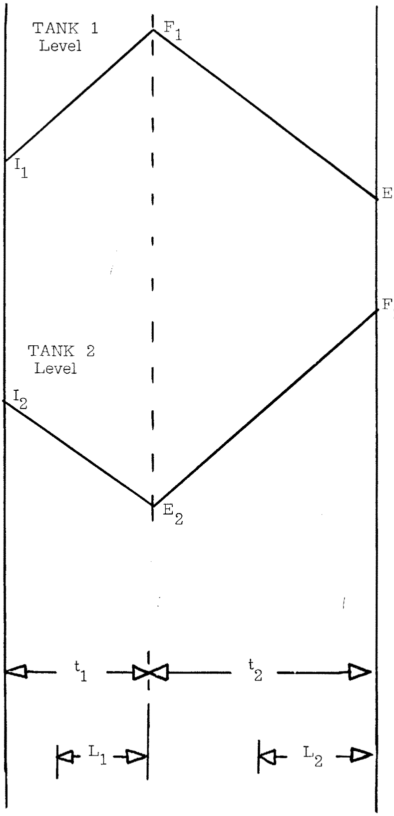

Fig. 5—Tank level variations

Fig. 5 provides an idealised picture of the process under analysis. The following symbols will be used—

Subscripts

1—Species 1
2—Species 2
p—Pulpmill
m—Papermill

Symbols

F—maximum usable tank level, tons
E—minimum usable tank level, tons
I—actual inventory level in tank, tons
$\overline{R}$—average pulpmill production rate, tons/h
$\overline{M}$—average papermill pulp pull rate, tons/h
t—total time of species run or time remaining in species run, h
T—allowance for unscheduled down-time, fraction
L—dead time between changing chip species and species change reaching tanks, h

Considering the condition at time zero (left side of Fig. 5), we wish to calculate t_1.

The emptying equation for tank 2 is—

$$(I_2-E_2) = \overline{M}_2 t_1(1-T_m) \quad . \quad . \quad . \quad . \qquad (1)$$

The unknowns are $\overline{M}_2$ and t_1. The rate $\overline{M}_2$ is unknown, because the pulp pull rate must be averaged over the unknown time t_1. This clearly cannot be done unless t_1 is known. An iterative solution must therefore be used to obtain t_1 and $\overline{M}_2$. The allowance for unscheduled down-time in the papermill T_m may be obtained from statistics of previous experience, taking into account both the mean and standard deviation.

The species change from 1 to 2 must be made after (t_1-L_1) hours.

The filling equation for tank 1 is—

$$(F_1-I_1) = \overline{R}_1 t_1(1-T_p)-\overline{M}_1 t_1(1-T_m) \quad . \quad . \quad . \qquad (2)$$

The rate $\overline{R}_1$ may thus be calculated. From this value and the list of pulpmill scheduled down-time, the required production rate of the pulpmill may be determined.

The pulp production rate $\overline{R}_2$ after the species change and the length of time t_2 for the second species run are given by—

$$(F_1-E_1) = \overline{M}_1 t_2(1-T_m) \quad . \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

$$(F_2-E_2) = \overline{R}_2 t_2(1-T_p)-\overline{M}_2 t_2(1-T_m) \quad . \quad . \quad . \qquad (4)$$

Evaluation

THE process considered so far is a simplification of an actual pulp and paper mill. During the design phase, a scheduling system was designed for the mill to enable the tanks to be sized and for use during operation. Two different solutions to the problem were tried and compared. The first was equivalent to the analytical solution already described, the second we will call heuristic. In the analytical method, the unsteady state material balances were used to predict the feedforward action necessary for control. The results were checked by using the schedule on a computer simulation of the process.

The heuristic method consisted of a set of rules of thumb developed by an experienced plant supervisor during experiments that he conducted using the process simulation.

Although the analytical solution to the example given earlier in the paper was quite straightforward, the addition of a few complications to the plant would make the solution by hand quite tedious.

Despite the experienced supervisor running through the equivalent of many months of plant operation, to develop the rules for his heuristic solution, the efficiency of his method fell much below that of the analytical method. These results are shown in Fig. 6. This illustration shows that the heuristic method required nearly 50 per cent more species changes, overflowed one tank and caused the papermill to shut down at one point. Fortunately, this was only a simulation. These events never occur in practice!

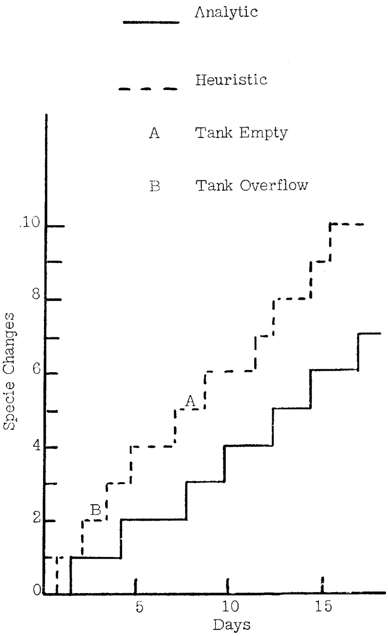

Fig. 6—Relative performance of scheduling systems

It would be unwise to draw the conclusion from these results that an analytical solution will always be better than a heuristic one. This will depend, among other factors, on the extent to which the assumptions, necessary for the analysis, describe the real situation. The simulation used for evaluation did, in fact, meet the assumptions used in the analysis. It would be equally unwise to draw any unfavourable conclusions about the capability of the experienced plant supervisor from these data. The problem that he was attacking was essentially that of solving several non-linear algebraic equations simultaneously, without having the advantage of automatic computing facilities. His time scale was highly compressed so that the normal learning and experience factors did not fully come into play.

Conclusions

THE hierarchical structure of a pulpmill control system has been shown to be valuable for isolation and study of the scheduling control function.

This type of control, which is not traditionally considered in the control engineering field, can have an important bearing on the performance of the whole process system.

The major characteristic of the process is the large dead time between changing chip species and the arrival of the pulp species interface at the tanks. Because of the essentially feedforward nature of the control action, this requires that a prediction of behaviour of the tank levels over this time interval is made. For the simple example studied, this leads to an iterative solution of a single material balance equation.

For a more complex, but still relatively simple example, a comparison was made of the scheduling efficiency of the analytic method and of a heuristic method. The superiority of the analytic method was demonstrated by simulation.

References

1. Brewster, D. B., 'Economic gains from improved quality control': TAPPI Annual Meeting, February 1969
2. Mouly, R. J., 'Systems engineering in the glass industry': *Proc. 8th International Congress on Glass* (London, July 1968, in the press)
3. Ekstrom, A. and Sangregorio, G., 'Automating the control loops on a Swedish kraft papermachine': *Pulp & Paper*, 1967, **41** (14), 30–34
4. Baker, L. E., Barron, J. D., Mason, R. E. A. and Swan, D., *A single processor hierarchical computer control system* (IFAC, Toronto, June 1968)
5. Lasher, R. J., *Computer Control of Gasoline Blending*, Reprint CC-67-84 (National Petroleum Refiners Association computer conference, November 1967)

6. Schoeffler, J. D., Wilmott, T. and Dedourek, J., *Programming Languages for Industrial Process Control* (IFAC, Menton, June 1967)
7. Hammerton, J. C., 'Integrating process and business control': *Business Automation*, April 1967, 35–39; May 1967, 38–42
8. Bernard, J. W., 'Plan control on the right level': *Control Eng.*, September 1966, 195
9. Rynsdorp, J. E., 'Chemical process systems and automation control': *Chem. Eng. Progress*, 1967, **63** (7), 97
10. Williams, T. J., 'Control theory and applications in chemical process control': *Proc. IBM Scientific Computing Symposium* (IBM, 1966), 103–134
11. Hodge, B., 'Company control via computers': *Chem. Eng.*, June 1965, 177
12. Chestnut, H. and Williams, S., 'Business process modelling': *Automation*, December 1967, 44–50

Discussion

Mr B. Pettersson This week, three papers on the production control problem of a pulp and paper mill have been presented. These are the papers by Al-Shaikh & Brewster just presented, by Svensson on Tuesday and by Alsholm and myself the same day. We have been asked to make some comments on the similarities and differences between the problems and methods, especially to explain just why our formulas are so complicated.

Firstly, all the papers deal with a single problem. Given the planned paper production and the initial values of the storage tanks, how to determine the way other processes may be run in the production chain. The difference lies mainly in the definition of the boundaries to the problems and in the number of processes and storage facilities involved. Mr Svensson has 1 process and 1 tank, Dr Brewster has 1 process and 2 tanks, whereas we were forced to take care of 9 processes and 10 tanks because of the complexity of the Gruvön mill and the interaction among different parts of the mill. I think that this fact explains the different approaches to the problem.

In fact, we spent quite a lot of time looking for a suitable method of attacking the problem. Thus, our first approach was a rather straightforward application of linear programming, but the size of the problem obtained was far beyond the capacity of our 1 800 computer.

The next attempt was simulation. By this, I mean simply, given the planned paper production and the initial tank levels, guess how to run the processes. Then calculate the variations of the tank levels. If all restrictions are fulfilled, the problem is solved. If they are not, we must try a new production schedule and so on. If I have understood Mr Svensson's paper correctly, this is essentially the way the problem he discussed was solved. This method is quite powerful and attractive in one or two dimensions, but it is very cumbersome and unsystematic when we are working in three dimensions. We worked quite a lot on simulation, but it was judged to be impracticable for our purposes, especially during operating conditions. As was stressed by Dr Brewster, however, simulation is a very valuable means when trying to get insight into problems of this kind.

Thus, we were led into the optimisation area again. Dynamic programming was judged to be unrealistic, because of the dimensionality of the problem, although a formulation based upon the Pontryagin theories turned out after some work to give satisfactory solutions within the computer capacity available.

This is the history behind our complicated formulas. To summarise, the similarity among these three papers is, given the paper production, the problem of determining how to run other processes. The differences lie mainly in the dimensionality of the problems.

Lastly, following in the footsteps of Mr Alsholm, I would like to give a short pep talk. I wish to stress the importance of trying to attach major control problems. It is very important, of course, to control each process within a production system, but it is just as important to control the whole system. This means, in our case, that we must try to control the whole papermaking system from forest harvesting to shipping and sales forecasting. It is a very difficult problem indeed, but, if we succeed, I think it will pay overwhelmingly. Besides, I think there are methods available today that make such an attack promising and these methods are in my opinion to be found by combining methods of modern control theory, operations research and industrial dynamics.

Dr J. H. Sandblom It has been extremely interesting to listen to Dr Brewster's paper, because almost on every point it fits in with the thinking behind the Hallstavik project.

You mentioned that your simulation, with the control strategies included, was the first time a simulation had had an influence on the design of a papermill. I think it would be fair here to give credit to Mr Svensson's paper. Benefits have been found with the same type of simulation in connection with the modified layout of the process, made in 1965. Maybe I should add another point. In the Hallstavik case, there are restrictions of other kinds as well, one being the power situation, not only for the Hallstavik mill, but for the whole group of the Holmen's Group.

Mr Svensson talked about some problems that have just been solved at Hallstavik, one of which was to find the values of those constants and parameters that Dr Brewster showed in his equations, similar to the Hallstavik system equations. At Hallstavik, we have tried all the time to make everything as simple as possible—for instance, the parameters are not automatically updated by the computer. It would be quite interesting to have Dr Brewster's comments on this point.

A second development at Hallstavik is the power situation. It has recently become much more stringent than was originally set out in the detailed system's descriptions and this new situation has taken some time to finalise.

Dr D. B. Brewster In reply to your first point on the impact of control systems engineering technology on process design, I will try to clarify my point. Despite the prophecies of the systems engineering pioneers ten years ago, there are few dramatic examples of processes being built that would be uneconomic without an advanced control system. I believe that the process layout described in the paper, however, is one of these rare examples. One major U.S. company is successfully operating such a mill with species changes under computer control and is building another mill that I believe is of similar design.

I was not quite clear what you meant about the constants. In the paper, two of the 'constants' are the maximum and minimum permissible tank levels. Safety margins would be chosen here that can be gradually relaxed as experience is gained. Other constants are T_p and T_m, which of course can be estimated only from past experience. For a new mill, this involved much guesswork based on data from existing processes. $\overline{M}_1$ and $\overline{M}_2$ are input data from the papermachine production schedule. At the design state, this could be quite unreliable and the design results should be examined by some sort of sensitivity and contingency analysis.

Dr Sandblom If you have a fixed model and try to forecast these figures, it might be difficult to get the right numbers.

Dr Brewster I agree.

Dr D. Rusten In pulpmills where more than one grade of pulp is produced in the same stream, there will be a certain quantity of mixed pulp produced at the changeover. This is of course through blending in chests and through deviation from plug flow, with consequent mixing in the bleaching plant and other parts of the system. Have you tried to minimise the amount of this mixed pulp produced and, if so, how have you done it?

Dr Brewster There are ways of dealing with this at the design stage and during operation. During design, every effort should be made to minimise the mixing volumes of process tankage. It is also valuable to have a well-mixed segregation tank to accept the mixed species pulp, which provides a means for feeding it gradually to the papermill. During operation, a well-designed control system to perform the level 3 and level 2 control functions described in the paper will help to minimise the extent of the 'twilight' pulp. There was a press announcement that Westvaco will install a process computer at the mill in question.