The Use of an Electronic Computer in Research Statistics: Four Years' Experience

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Summary: An electronic computer has now been in operation for four years in the Statistics Department of Rothamsted Experimental Station. This paper gives an account of the experience gained in applying the computer to statistical problems arising in agricultural and biological research.

INTRODUCTION

An electronic computer—the Elliott–N.R.D.C. 401—was installed in the Statistics Department at Rothamsted Experimental Station in April 1954 with the object of developing the use of electronic computers in agricultural and biological research statistics.

Rothamsted Experimental Station is the oldest and largest agricultural research station in the United Kingdom, with a graduate staff of approximately 150, and is mainly concerned with research on plants and soils. The Statistics Department had its origin in the appointment in 1918 of R. A. Fisher (now Professor Sir Ronald A. Fisher) as statistician to the station to 'apply modern statistical methods to the great mass of data accumulating at Rothamsted.' Over the years the Department has undertaken an increasing amount of work for other institutes, both in this country and overseas, and in 1947 it was assigned the additional duty of acting as an Agricultural Research Statistical Service for the Agricultural Research Council and the Ministry of Agriculture. In 1954, just before the computer was installed, it had a staff of 18 graduates and 20 non-graduates, and the present staff (1958) is 21 graduates and 21 non-graduates. A small Hollerith installation, consisting of a sorter and Junior rolling total tabulator, was acquired in 1949, and a reproducer/summary punch was added in 1951 and coupled to the tabulator. Some special fitments were added to the tabulator at this time. We also have access to a multiplying punch and collator when required.

The main lines of work of the Department are the design and statistical analysis of replicated field and laboratory experiments, the analysis and interpretation of the collected results of such experiments, and the planning, organization and analysis of surveys of the technical type, such as the survey of the way farmers use fertilizers. In addition, we have to deal with many other statistical problems arising in agricultural and biological research. The Department has from its inception been concerned with the development of basic mathematical statistical theory and new methods of statistical design and analysis. In particular, the whole of the modern theory of the design and analysis of replicated experiments was developed at Rothamsted and considerable contributions have been made to the theory and practice of sample surveys.

The computational needs of research statistics differ considerably from those met with in the compilation of official and business statistics. In both the latter the primary need is for the tabulation of voluminous material, whereas in research statistics considerably more complicated computations on smaller bodies of data are required, and critical examination is frequently necessary at intermediate stages. For such computations the use of punched-card tabulating machinery is relatively ineffective. Before the introduction of electronic computers, therefore, most computations were carried out on desk calculating machines. We had, indeed, attempted (as had others) to utilize punched-card machinery for the analysis of some of our replicated experiments and for other work normally carried out on desk machines, but experience showed that there was little if any advantage over the use of desk machines. Even for the analysis of much of our survey work the use of edge-punched cards was found to be more satisfactory than the use of tabulating machinery.

We were consequently very interested in the development of electronic computers, and for some time before 1954 had been considering the possibility of constructing such a computer. When, however, in 1953 a proposal that a start should be made was put to the Agricultural Research Council they were advised that in view of the fact that such machines were just beginning to be manufactured in this country it would be much better to obtain a complete machine. By a fortunate chance a prototype machine, the Elliott 401, built by Elliott Bros. under a development contract with the National Research Development Corporation, and then housed in the Mathematical Laboratory at Cambridge, was unassigned, and it was agreed between the Agricultural Research Council and the National Research Development Corporation that it should be transferred to Rothamsted at the end of its period at Cambridge.

PARTICULARS OF THE ELLIOTT 401

The 401 is a serial computer with a word length of 32 binary digits and a word time of 100 μsec. The highway diagram is shown in Fig. 1. The main store is a magnetic disc of 2,944 words, arranged in 23 tracks, numbered 0–6 and 7/0–7/16. Switching between the tracks 7/0 and 7/16 is by relays, the switching operations being controlled by a switching order. Switching between tracks 0–6 and the track 7 in circuit at the time is electronic and is controlled by the track numbers in

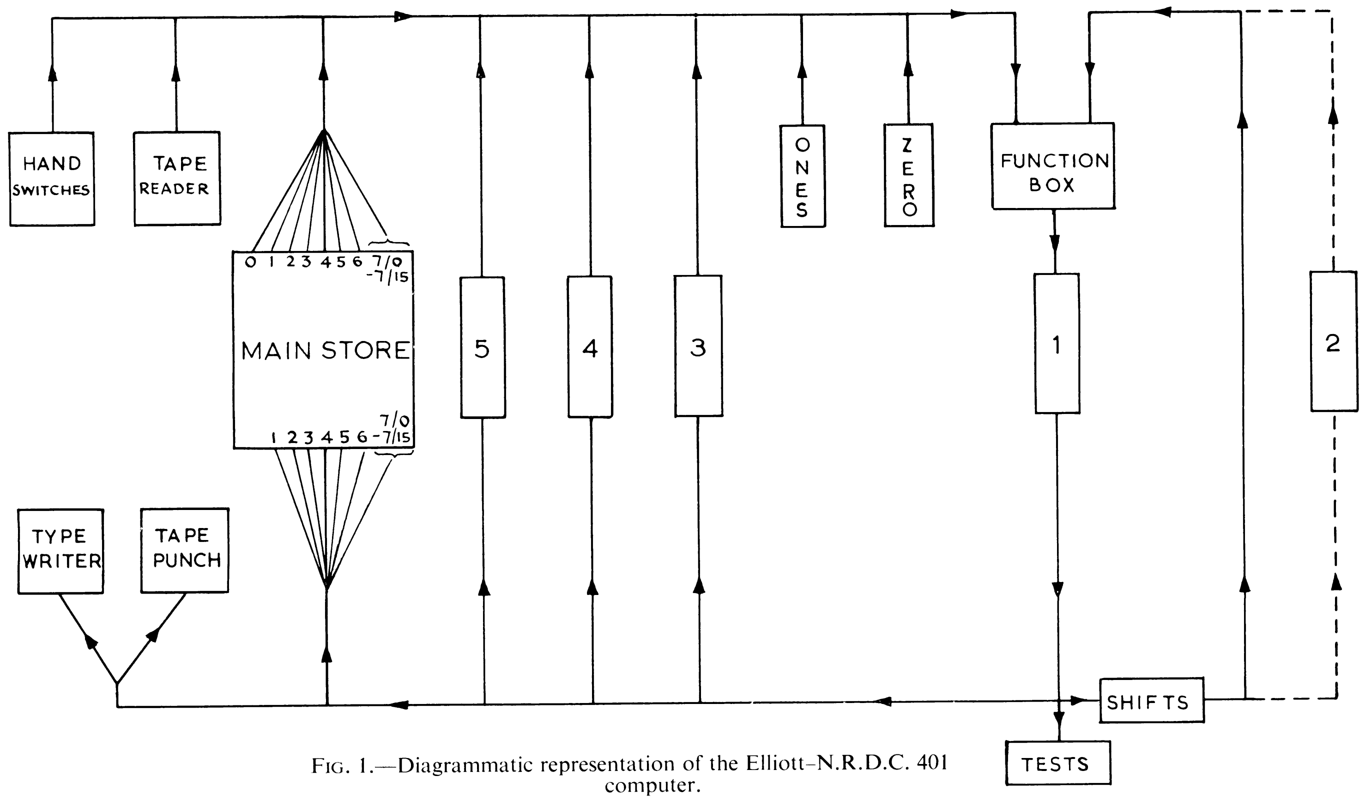

FIG. 1.—Diagrammatic representation of the Elliott-N.R.D.C. 401 computer.

the address parts of the orders. In addition to the accumulator, which can be coupled with a second register for double-length working, there are three single-word immediate-access registers,* each of which can be used to modify orders (B modification) as well as for temporary storage of numbers. Addition and subtraction take one word time to carry out, a shift of n places takes n word times and multiplication 32 word times (3·2 msec). Relay track switching takes about 10 msec.

The order structure of a word is as follows:

	A_2	S F D K	A_1
Number of digits	10	3 3 3 3	10

A_2 gives the address of the next order, A_1 the address of an operand (if referred to) or the address of the alternative next order in a discrimination order. S gives the source, F the function to be performed, D the destination of the contents of the accumulator at the beginning of the order, and K additional functional instructions (discrimination, double length, B modification of the next order). Numbers can be sent to and from the immediate-access registers, or one such register and the store, simultaneously, but not simultaneously to and from the store. Thus for the store the address system is $1 + 1$, but for the immediate-access registers or an immediate-access register and the store it is $2 + 1$. The address A_0 of the order itself, A_1 and A_2, all have timing significance in certain types of order.

The machine came to us in an incomplete state. In particular the relay track switching still had to be put into operation, and practically no subroutines had been written.

* Now six—see below.

MODIFICATIONS AND IMPROVEMENTS TO THE MACHINE AND ANCILLARY EQUIPMENT

(*a*) *Input and Output Facilities*

Since a large amount of input and output is required in statistical computations, even of the research type, considerable attention has been paid to the improvement of input and output facilities. Originally the machine was fitted with a non-standard tape reader, reading at 35 characters per second, and an electrically operated typewriter operating at 10 characters per second. These have now been replaced by a Ferranti tape reader for input (about 100 characters per second) and a Creed punch for tape output (25 characters per second). A second (spare) reader has recently been obtained, and a second punch is on order. We have retained the typewriter as this form of output is useful for certain purposes; change-over between punch and typewriter can be programmed.

Our present tape equipment, in addition to the tape reader and teleprinter in the machine room, is as follows:

- A Creed reproducer, consisting of a combined keyboard perforator, printer, and tape reading unit.
- A similar non-standard unit.
- A verifier.
- A keyboard perforator.

The first two units can be used for punching, editing or printing as required. The verifier can be used for punching and for preparation of a corrected tape during verification.

We still require a tape comparator. We are also considering ways of printing from two tapes, one containing the actual results of a computation and the other controlling the layout and furnishing standard headings, etc.

(*b*) *Input and Output Code and Permanent Orders*

Originally the machine used different codes for input and output, input being by the ordinary 5-hole binary unchecked code, and output by a 2-out-of-5 checked code for the digits 0 to 9, and other values for the other typewriter characters, minus, decimal point, space, carriage-return/line-feed (1 symbol). This complicated the programming of output and had the unfortunate consequence that input tapes could not be printed by the teleprinter equipment used for printing the output tapes. The original permanent input orders on track 0 were also somewhat unsatisfactory, since only orders could be read in by them and no provision had been made for carriage-return/line-feed on order tapes. Consequently such tapes could not have been satisfactorily printed even had a correctly coded teleprinter been available.

It was therefore decided, after we had had the computer for 18 months, to reorganize the input-output system and permanent orders. A common code, with alternative checked and unchecked forms, was adopted for both input and output. The checked form is an ordinary 4-digit binary code, giving 0 to 9, +, −, point, starting symbol, space, carriage return, the fifth hole being inserted as required to give an odd number of holes. In checked input only the binary number corresponding to the first four holes is transmitted to the accumulator, and if an even number of holes is read on checked input the machine comes to a halt. In unchecked input the full 5-digit binary number is transmitted. In checked output the four digits are transmitted from the accumulator and the fifth digit is supplied, if required, to make the number of holes odd; consequently the addition or omission of a single hole results in the printing of a non-numerical character on the teleprinter. Programming of checked and unchecked input and output is controlled by the parity of A_1.

The permanent orders were also re-written at this time to enable decimal integers and fractions, as well as orders, to be read in, with greatly improved flexibility in other ways. These changes were naturally not undertaken lightly, as they necessitated revision of already existing programs, but subsequent experience has shown that they were very well worth while.

When these changes were made the whole of the tape preparation, editing and printing was reorganized and additional equipment obtained, a new keyboard layout was adopted instead of the standard teleprinter keyboard, and the use of a combined symbol for carriage-return/line-feed, which had always proved unsatisfactory for teleprinter operation, was abandoned.

(*c*) *Punched Cards*

We can now read data directly from punched cards at 100 cards per minute; the contents of any 32 columns (selected by means of a plugboard) are transferred row by row to the 32 digits of the hand switches, whence they can be transmitted to the accumulator of the machine by means of the ordinary order code. This project was carried out jointly by ourselves and the British Tabulating Machine Company staff.

We have also recently acquired a B.T.M. tape-to-card converter. This will enable simple functions such as percentages and other indices to be computed from the data on individual cards, punched out on tape and transferred back to the original cards. Further analysis can then be carried out on standard punched-card machinery.

(*d*) *Additional Registers*

The substitution of the single-plate delay lines, recently introduced by Elliott Bros., for the original three-plate type has enabled us to duplicate the three immediate-access registers without modification of the order code. Changeover from one set to the other is effected by the unwanted order "collate on 1's," i.e. S = 1's, F = collate.

(*e*) *Inhibition of Writing on Specific Tracks*

Inhibition of writing can be effected on any chosen tracks 1 to 6 and the relay tracks (track 7) as a group. Control is by hand switches. This modification, which was primarily introduced in order to prevent mutilation of programs during program checking, has not proved as useful as expected. This is partly because, to be effective, it is necessary to segregate store positions in which writing occurs onto a particular track on which writing is permitted, but more especially because it was only possible to inhibit writing on tracks 7 as a group, and these are being increasingly used for orders in our longer programs.

(*f*) *Magnetic Tape*

The N.R.D.C. has placed at our disposal a Pye magnetic tape unit, and we are now working on the task of linking this to the machine as an auxiliary store.

POLICY OF DEVELOPMENT IN THE USE OF THE MACHINE

Since the machine was assigned to us to explore the possibilities of electronic computers in research statistics, and not on the grounds that it would save money in the execution of already existing jobs, we were in the fortunate position of treating the whole undertaking as a research project. It was obviously important, however, that the machine should be put to useful work as soon as possible and we therefore decided as a matter of policy not to attempt anything spectacular at the outset but rather to develop the use of the machine by tackling relatively simple and self-contained jobs first, and to extend its application to bigger tasks as experience was gained.

The jobs for which it appeared that the machine would be useful can roughly be classified as follows:

(*a*) Existing standard jobs carried out on desk and punched-card machines. In some jobs of this type improvement and extension of current desk and punched-card methods is definitely required.

(*b*) Jobs which should be standard but which in the past have been undertaken only rarely because of excessive computational requirements.

(*c*) Special jobs requiring heavy computational work.

In addition to making a start on what appeared to be the most important and easily executed jobs under heading (*b*), and such special jobs as offered under heading (*c*), we decided to try out the machine on jobs of type (*a*), both because our own departmental computing facilities were already overloaded with standard jobs of this type, and also because we considered it very important to make an early assessment of the potentialities of electronic computers for carrying out such computations. An account of the way in which we have developed the use of the machine for the routine analysis of replicated experiments, together with a list of the other main classes of work and references to papers published at that time, has been given by Yates, Healy and Lipton (1957). Later papers are included in the references at the end of the present paper.

POINTS CONCERNING THE CONSTRUCTION OF PROGRAMS

(*a*) *Need for Generality and Flexibility in Programs for Standard Jobs*

In research statistics, jobs of the same general type differ considerably in detail. It is therefore essential that programs should be so written that they can expeditiously handle all jobs of a given type which are commonly met with. The necessary flexibility and generality must be built into the program itself, since we have found that later modification of programs is always a slow and laborious business even if undertaken by the writer of the program, and that the testing of such modification is liable to be wasteful of machine time.

(*b*) *Importance of carrying out the Complete Job on the Computer*

When first faced with an electronic computer the research statistician is inclined to think mainly of its use in carrying out the more burdensome and repetitive parts of a computation, such as the computation of the sums of squares and products required for the formation of a correlation matrix, and the inversion of a matrix in regression work. The additional work required to marshal the data and complete the computation is, however, often quite substantial and much of the advantage of the machine is lost if this is relegated to desk machines.

From the outset, therefore, we have endeavoured to write programs for standard jobs so that as much as possible of the job is carried out by the machine. Thus our program for the computation of sums of squares and products computes also the means, variances and covariances and, if required, the correlation coefficients. Our program for regression analysis computes the regression coefficients, their standard errors, and the residual mean square. Our programs for the analysis of replicated experiments accept the data in random order and provide all necessary tables of means, effects, and interactions and their standard errors. In this respect we may contrast our program for the analysis of 2^n factorial design with that provided for Pegasus. The latter merely computes the effect and interaction totals from the treatment totals, presented in standard order, whereas our program carries out the whole computation and will deal with total or partial confounding (without prior specification of the confounded degrees of freedom), fractional replication, the estimation of error from high order interactions, factors at 4 and 8 levels, and 8×8 quasi-Latin squares.

On the other hand, the variety of computations that are required in research statistics precludes having programs for all complete trains of computation that may be required, and subdivision of the work, so that different programs can be serially combined, is of considerable importance. Thus, in our programs for the analysis of replicated experiments, the preliminary computations required for the calculation and conversion to cwt. per acre of such quantities as plot-by-plot yields of total sugar in a sugar beet experiment from the plot-by-plot figures for yields of roots and sugar percentage, form one standard program, known as General Input for Experimental Designs, which is used for all types of experiment. This is combined with the various programs appropriate to the analysis of the particular types of experimental design.

Considerable further development of our programs on these lines is still required. An example which has recently occurred is the analysis of some 1,500 $3 \times 3 \times 3$ single replicate fertilizer experiments. We already have a program for the analysis of individual experiments of this type, but the analysis on desk machines of the collective results obtained from 1,500 of these analyses would be a very formidable task. We shall therefore have to write a further program for carrying out this analysis. The construction of this program should point the way to the construction of a more general program which can be applied to the results of groups of experiments of any type.

(*c*) *Presentation of Data to the Machine*

One characteristic of most statistical work is the large amount of basic data that has to be handled. It is very essential that programs should be so written that the data can be presented to a machine in a manner which simplifies punching as much as possible. Not only is punching time thereby saved, but the likelihood of error is greatly reduced. In replicated experiments, for example, the plot-by-plot values of the different variates are frequently booked separately; in sugar beet experiments the yields of roots and tops are booked in the field, whereas the sugar percentages are determined in the laboratory. Moreover, each variate is booked in the numbered order of the plots, which is the order of the plots in the field and not the systematic treatment order. Consequently we have arranged for the data of our replicated experiments to be read in variate by variate in the numbered plot order. The experimental treatment of each plot is also read in separately in the same order, using the treatment code which is actually used in the experiment, with a block code also if required. Thus in a $3 \times 3 \times 3$ factorial experiment the treatment code for each plot consists of three numbers indicating the level of each factor. These numbers commonly run from 0 to 2 or 1 to 3, depending on the nature of the treatment. The input orders are so written that the code can be punched exactly as recorded with a key which gives the lowest level of each factor. On input the code is transformed to the standard 0, 1, 2 form.

The great flexibility that is possible in input arrangements with an electronic computer may be contrasted with the relative inflexibility that is necessary when using punched cards. Thus the analysis of replicated experiments on punched-card machines can best be conducted by allocating one card to each plot, the values of the variates being punched in different fields of the card. With the type of recording described above the preparation of such cards is clearly considerably more trouble than punching variate by variate on tapes.

Even in the case of survey analysis, where it might be thought at first sight that punched cards were ideal, we have found that for certain types of survey tape input is more convenient. The reason for this is that with tape input one has the option of designating each item of information. If this is done blank items need not be punched. With punched cards designation is usually effected by locating each item in a specific field, blank items being punched with zeros.*

(*d*) *Control of Operations carried out by the Machine*

The need for generality and flexibility in programs implies that the operations carried out by a program must be capable of variation to suit the requirements of the particular analysis. Thus our program for multiple regression analysis deals with up to 31 variates, any one of which may be nominated as the dependent variate. The regression of this variate on up to 9 of the remaining variates is calculated by a step-by-step process; at each step it is possible to (*a*) add a new independent variate, (*b*) replace the last independent variate added by another, or (*c*) remove an independent variate already included. After each step the residual mean square, and the regression coefficients and their standard errors, are printed out; the inverse matrix can also be obtained if required. This procedure enables the regression relations to be explored in a much more thorough manner than is customary or practicable on desk machines.

The various alternative operations must be readily controllable. In jobs of an exploratory nature, control by words set on the hand switches during the progress of the computation is suitable. This process, however, tends to be wasteful of time and liable to error, and in jobs for which decisions can be made on what is required before the job is started we have found it best to use punched control words which are read in with the data.

(*e*) *Presentation of the Results*

In standard jobs we have found it important to give considerable attention to the layout of the results. The aim has been to present the results in a form which allows teleprinter copies to be despatched direct to the worker concerned without copying or annotation.

The programming of a good layout is both time consuming and extravagant of orders, and considerable attention has had to be paid to devising effective ways of producing the desired results.

(*f*) *Provision for Special Contingencies*

Programs must as far as possible be so written that special contingencies can be dealt with without undue labour. Much statistical material, for example, suffers from the defect of missing observations. Our experience suggests that in the long run electronic computers may considerably facilitate the handling of such data, though to bring about this desirable state of affairs some research into method, and considerable programming effort, are required. As an example, we may mention the case of missing (or rejected) plot yields in replicated experiments. If a number of yields are missing, or if the experimental design is at all complicated, the necessary computations are decidedly troublesome on desk machines. We have evolved a computational procedure suited to electronic computers which is applicable to any type of experimental design and any number of missing yields, and which is also simple to program (Healy and Westmacott, 1956).

(*g*) *Checks and Numerical Accuracy*

We are very commonly asked how we can tell whether the machine has given the correct answers. Our general policy in this respect is to build into a program a certain number of numerical checks. Such checks may be exact or approximate. If an exact check fails the machine is usually instructed to repeat the relevant part of the computation; if the check is approximate and the discrepancy exceeds what is considered to be the permissible limit of error, the actual discrepancy is printed out and the computation proceeds. The reason for not instructing the machine to repeat the whole or part of the computation in this latter case is twofold. In the first place, in many computations the actual discrepancy depends on the magnitude of the quantities being analysed; it would be inconvenient to lay down different permissible discrepancies to cover such variation, whereas with a little

* Card input to a computer can of course be used for designated information in much the same manner as tape. The essential point is that computers can easily be instructed to recognise and act on designations at the input stage, whereas tabulating machinery requires information to be in the correct fields.

experience it is usually possible by cursory examination of the actual discrepancies to say whether an error of any importance has occurred. In the second place, it is often impossible to repeat the relevant part of the computation without reading in the data afresh, so that repetition will in any case require the intervention of the operator.

We do not attempt to guard against all possible sources of error by means of checks. Some types of error would indeed be difficult to control except by repetition of the computation. In statistical work absolute numerical accuracy, particularly in the early stages of an analysis, is rarely essential, since the data themselves are subject to error. Gross errors must, however, be excluded, and the frequency of all computational errors must be kept very low. One important use of built-in checks is to give an assurance that the machine is functioning satisfactorily and that in consequence the probability of error in the unchecked portions is exceedingly low. In certain computations we also maintain some control of gross errors (which may be nothing to do with the machine) by printing out extreme values.

Our experience to date, particularly in the analysis of replicated experiments, suggests that the standard of numerical accuracy attained on our electronic computer far exceeds that which has been customarily accepted when using desk machines, and is in fact adequate for all practical purposes. In only one case out of some 7,500 variate analyses in replicated experiments has an error been detected subsequent to the results having been passed as correct. This was an error in the input computations, and though large was not of sufficient magnitude to produce any very serious disturbance in the results.

WRITING AND CHECKING OF PROGRAMS

(*a*) *Machine Aids to Programming*

For many of the types of work we undertake, somewhat elaborate programs are required; for the more complicated standard jobs programs containing upwards of 1,000 orders are by no means uncommon. In programs of this complexity we have found that not only the writing but also the checking present considerable problems. Indeed it is always difficult to be certain that all contingencies have been adequately checked, and it is by no means uncommon to find residual errors even in programs that have been in use for some time. Fortunately these errors are usually of such a nature that their consequences are either obvious in the results or else the program fails to operate properly.

In order to facilitate writing and checking programs we have found it advisable to develop various machine aids to programming. The main aids are:

(i) A routine which will print out the orders of the program in logical sequence, i.e. in the sequence given by the A_2 address of the next order. A description has been given by Lipton (1957). This program is useful not only for providing a clean copy in logical sequence embodying all corrections, but will also show if a sequence does not follow the expected route, thus providing a partial check on rarely used routes which may have escaped the testing process, and enabling refractory cases of jumping out of the program to be traced.

(ii) A routine to print out the contents of the registers, etc., at chosen points. This is a standard type of test program which enables the computation to be stopped at any desired point and a printed record to be taken of the contents of the registers and selected store locations before re-entry into the program under test.

(iii) An automatic programming routine. This has been described by Yates and Lipton (1957). It has been somewhat improved since that description was written.

(*b*) *Use of Special Subroutines*

In addition to our library of standard subroutines we make free use of special subroutines written for particular programs; indeed, the tendency is to embody all but the simplest operations which are used more than once in a program in special subroutines. This facilitates both the writing and the checking of the program and also makes the completed program more intelligible.

RECORDS OF PROGRAMS

Since we have a large variety of jobs, many of which require to be repeated at somewhat rare intervals, it is very important to keep a good record of any program which may possibly be of value subsequently. Each program which is likely to have any general interest is therefore included in a program book, of which several duplicated copies are kept. The particulars given in this book are essentially working instructions for the user, and are intended to be sufficiently detailed to enable anyone to use the program without consulting others.

In addition to the particulars given in the subroutine book, the writer of the program is responsible for seeing that accurate records of the flow diagrams and the orders are filed, and that any subsequent amendments and corrections are entered in these records. This is very essential since it is frequently necessary to make minor modifications in existing programs in order to take care of variants of the original problem. Indeed, experience has shown that further improvement of this type of record is still required.

OPERATING EXPERIENCE AND WORK LOAD

Records of operating time have been maintained since the machine was installed. The recording system was tightened up and made more detailed in April 1956, and Table 1 shows an analysis of the last two years' working. The results are not unsatisfactory. The machine was worked (including time occupied by the

TABLE 1

LOG ANALYSIS—APRIL 1956–MARCH 1958

		Hours	*Percentage*
System modification	M	118·4	2·3
Scheduled maintenance	S	643·6	12·4
Unscheduled maintenance	U	285·8	5·5
Program checking	C	1,152·9	22·2
Production runs	N	2,687·9	51·9
Abortive efforts	A	115·9	2·2
Idle time	I	180·5	3·5
Total machine hours	T	5,185·0	
Normal laboratory hours	E	3,892·5	

		%
Overtime	$= (T - E)/E$	= 33·2
Availability	$= (C + N + I)/T$	= 77·6
Efficiency	$= (C + N + I)/(T - S - M)$	= 90·9
Usage	$= (C + N)/(C + N + I)$	= 95·5

TABLE 2

BREAKDOWN OF U AND A TIMES
APRIL 1956–MARCH 1958

Unscheduled Maintenance (U)	*Hours*	*Abortive Efforts* (A)	*Hours*
Total	285·8	Total	115·9
Due to machine	208·9	Due to machine	62·0
Due to tape-punch	15·8	Due to tape-punch	21·9
Due to tape-reader	52·9	Due to tape-reader	21·4
Due to typewriter	4·7	Due to typewriter	2·4
Due to card input	3·5	Due to card input	8·2

engineers) for 133·2% of normal laboratory working hours, i.e. 33·2% overtime. During 77·4% of the working time the machine was in good running order and available for productive work, and of this time somewhat less than one-third was used for program checking. During 90·9% of the time during which the machine was nominally available for production work it operated satisfactorily.

So far it has been found possible to work the required amount of overtime without any formal overtime arrangements, but should the demand for machine time increase further, some formal arrangement will have to be made. One of the main problems here is the provision of engineering services so that minor faults can be remedied without a hold-up of the work. Such hold-ups not only disrupt the timetable of production, they are also particularly irritating to workers who have arranged to use the machine outside laboratory hours.

Table 2 gives a further breakdown of the unscheduled maintenance (U) and abortive efforts (A). Abortive efforts are times when work is attempted but is ineffective owing to faults in the machine or ancillary equipment. This breakdown reveals the relative weakness of the ancillary equipment. One-quarter of the U time and nearly one-half of the A time is attributable to this equipment.

The time trends of the components going to make up Table 1 are shown in Fig. 2. From this figure it will

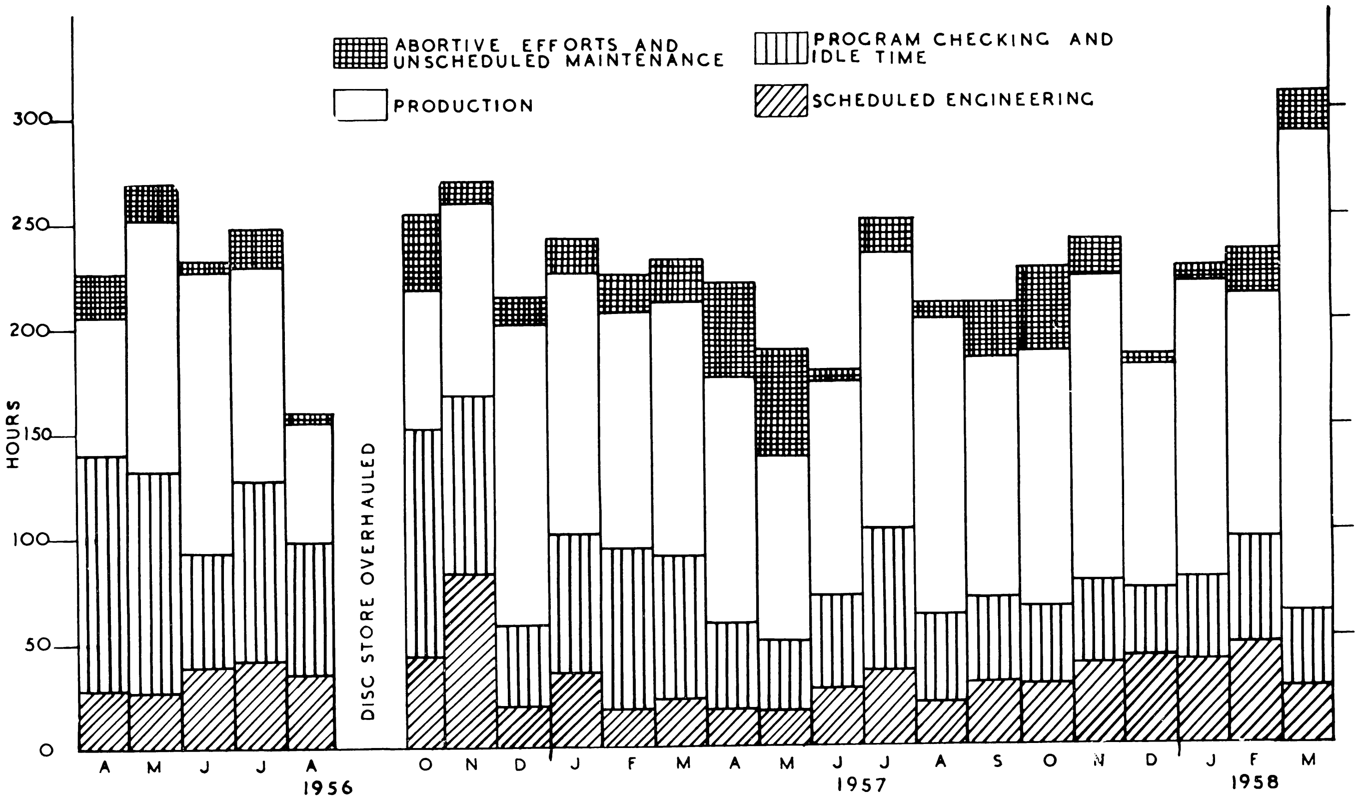

FIG. 2.—Time trends in the log analysis.

TABLE 3

ANALYSIS OF OPERATING PERIODS
APRIL 1956–MARCH 1958

		0 to 5 hours	251
		5·1 to 10 hours	107
0·1 to 0·5 hours	26	10·1 to 15 hours	61
0·6 to 1·0 hours	43	15·1 to 20 hours	24
1·1 to 2·0 hours	57	20·1 to 25 hours	21
2·1 to 5·0 hours	125	25·1 to 30 hours	12
		30·1 to 35 hours	9
		Over 35 hours	22
			507

Longest good operating period: 67·8 hours

be seen that the reliability of operation has remained substantially constant, but that there has been considerable reduction in time required for testing programs, and a corresponding increase in the time used for productive work. This may be attributed to:

(*a*) Greater skill in writing and testing programs.
(*b*) The increasing library of programs.
(*c*) The increased demand for production time, which has itself compelled programmers to spend less time on the machine locating faults in their programs.

Table 3 shows the distribution of the length of run between faults requiring the intervention of the engineers. These show a roughly exponential distribution, indicating that the development of faults is more or less randomly distributed.

The increase in time devoted to productive work does not fully reflect the increase in output of work. It would be very difficult to maintain a single quantitative measure of production covering all the varied jobs that are carried out on the machine. We do, however, keep records of the number of replicated experiments which are analysed on the machine and also of the number of variate analyses. These records do not take account of the variation in size of the different experiments, and for simplicity we have omitted the breakdown by types of design from Table 4, which shows the development of this line of work.

The increase in the number of experiments analysed, and still more in the number of variate analyses, is very impressive, and it is significant that the large increase in load during the last 15 months has been carried without any appreciable increase in total working time, except for the first three months of 1958.

TABLE 4

NUMBERS OF REPLICATED EXPERIMENTS ANALYSED IN THE DEPARTMENT

	Number of experiments			*Number of variates*
	By hand	*On computer*	*Total*	*On computer*
1934	115	—	115	—
1951	437	—	437	—
1955	384	419	803	834
1956	181	683	864	1,701
1957	98	1,253	1,351	5,041
1958 (Jan.–March)	53	551	604	1,907

ORGANIZATION OF WORK

The present staff engaged on machine work is as follows:

(*a*) On the engineering side: 2 Scientific Officers, 1 Experimental Officer, 1 Laboratory Assistant.

(*b*) On the programming side: 3 Scientific Officers, who are engaged more or less full time on machine work (this includes decisions on methods of analysis, some running of jobs on the computer, and the writing up of the results of specific pieces of work), 3 Scientific Officers engaged part time on similar work; various other members of the Department and workers outside the Department also do a certain amount of programming work, and running of their jobs.

(*c*) On the preparation of work for the computer and running of routine jobs: the punching and checking of data tapes now occupies about 30% of the time of the staff of computers, and about the same amount of time is occupied in other work connected with the machine; one girl is specifically allotted to machine operation and similar work; two Experimental Officers are engaged much of their time on supervising the analysis of replicated experiments.

We have been steadily progressing towards more routine operation of production work on standard jobs, but many special jobs are still run by the scientists who have prepared the programs. On balance this probably leads to more efficient utilization of machine time and gives programmers an insight into the problems of machine operation which have to be taken into account when writing programs, but tends to be wasteful of scientists' time. We believe that a gradual transition to more routine operation, of the type now adopted for the analysis of replicated experiments, will be desirable.

Table 5 gives the statistics of recent experience in running jobs. A run is recorded as successful if it goes through without hitch on the first attempt or if any necessary correction can be made on the spot; 88% of the analyses of experiments were accomplished in a single run. Machine faults accounted for about half the failures, most of the remainder being due to punching errors and incorrect specification of requirements (i.e. errors in the control words). The proportion of failures in other work is about half that in the analysis of experiments.

FUTURE DEVELOPMENTS

One of the most pressing needs of our own Department at the present time is the improvement of current methods in the analysis of survey material, and the speeding up of the process of analysis. We have already made some progress in the use of the electronic computer for this purpose, and in 1957, for the first time, the Survey of Fertilizer Practice was analysed on the machine. The 1957 survey was three times the size of any previous fertilizer practice survey and it was clear from the outset that if the analysis was to be completed in reasonable time it would have to be done on the computer. We were, however, somewhat uncertain whether the computer would prove really suitable, particularly since we had found, from previous experience, that for this survey, edge-punched cards were preferable to the use of punched-card machinery. In the event the analysis on the computer has proved highly successful. It has enabled the results to be obtained far more speedily than had been the case in the past; the results of two districts for which the field data were received on 9 December, for example, were available on 13 December, and were incorporated in a report issued on 19 December. Moreover, contrary to early fears, it has been found that a more detailed analysis of special points can be made than was possible with edge-punched cards.

TABLE 5

ERRORS LEADING TO REPETITION OF COMPUTATIONS, JANUARY–MARCH 1958

REPLICATED EXPERIMENTS

Number of single runs	677
Number of double runs	78
Number of treble runs	15
Total	770

Reasons for Failure

	M	O	T	S	P	C	A	Total
(*a*)	0	1	4	5	0	0	0	10
(*b*)	40	1	12	21	1	3	0	78
(*c*)	4	2	5	4	0	0	0	15
(*d*)	4	3	4	2	1	0	1	15

OTHER WORK

Number of single runs	239
Number of double runs	15
Number of treble runs	2
Total	256

Reasons for Failure

	M	O	T	S	P	C	A	Total
(*a*)	0	0	0	0	0	0	0	0
(*b*)	5	4	2	1	3	0	0	15
(*c*)	1	0	0	1	0	0	0	2
(*d*)	1	1	0	0	0	0	0	2

M Computer faults, including ancillary equipment.
O Operator errors.
T Punching errors on tapes.
S Incorrect specification of requirements.
P Program limits.
C Repeat runs for checking only.
A Abortive runs—due to variate missing from data.

(*a*) Errors corrected during first run.
(*b*) Errors leading to the failure of the first of two runs.
(*c*) Errors leading to the failure of the first of three runs.
(*d*) Errors leading to the failure of the second of three runs.

In parallel with the development of the analysis of survey results, which will include both the generalization of our survey programs and the introduction of more thorough methods of analysis than are possible with punched-card machinery, we intend to devote considerable attention to machine scrutiny of survey and other data. Survey data is from its nature particularly liable to field errors, and thorough checking at the initial stage is required if material errors are to be avoided in the results. Adequate checking of this type was virtually impossible before the introduction of electronic computers.

Work of this kind is in many respects analogous to the large-scale data processing that is required in the preparation of official and business statistics. There is, however, the difference that the full analytical requirements can rarely be foreseen with certainty at the outset, and provision has therefore to be made for supplementary analyses, which may be of very varying types.

In addition to surveys there are many other activities in agricultural and biological research that result in the collection of large quantities of numerical data, much of which is at present very inadequately analysed. Here also we believe that the development of the appropriate methods of data processing on electronic computers may lead to a much better utilization of the information that has been collected.

SUMMARY OF DISCUSSION

The following points were made during the discussion which followed the presentation of the above paper to The British Computer Society in London on 21 April 1958.

Mr. J. D. Croston (*Kodak Limited*): During hand computation a statistician will frequently detect errors in the original data and may also take note of intermediate results obtained to modify the approach to the rest of the calculation. Part of the work which Dr. Yates described has been carried out on a service basis at quite a distance from the organization collecting the data. To what extent has this proved a disadvantage?

I should also like to know whether it has proved necessary to print out intermediate results obtained by the computer, and the amount of such print-out found to be desirable when carrying out a multivariate analysis on a service basis.

The experience gained at Rothamsted in this field will clearly have an application in the presentation of business statistics, particularly with respect to the extent to which similar exception techniques will be acceptable to Management.

Dr. A. S. Douglas (*University of Leeds*): I noticed in the figure showing performance figures for the computer that scheduled maintenance appears to have taken up an increasing proportion of time since it was first started. However, the general operation appears to have been of a high standard throughout and fault time has not been significantly large at any time. I venture to ask, therefore, whether the introduction of scheduled maintenance has been justified, in your view, by an increase in performance efficiency. Can any correlation between the amount of scheduled maintenance and the number of unscheduled faults be deduced from your figures?

Mr. H. Gearing (*The Metal Box Co. Ltd.*): Statisticians, who for twenty years or so have followed with interest the significant contributions to improved statistical methods made by Sir Ronald Fisher, Dr. Yates and their colleagues at Rothamsted, were interested to learn a year or two ago that they had acquired an electronic computer. The Rothamsted team has now made a significant contribution to the application of computers not only to research statistics but also to the development of techniques for editing and processing data over a wide range of management information routines.

The authors (*in reply*): We believe that in general machine scrutiny is far more effective in the detection of errors in the original data than is casual scrutiny in the course of a computation, particularly since the marshalling and initial reduction of any large body of data is usually done by computers rather than by qualified statisticians. Moreover, once the main computation is started the correction of errors subsequently discovered in the data is exceedingly laborious and itself frequently leads to further errors.

In our machine analysis of the Survey of Fertilizer Practice a preliminary scrutiny is carried out and exceptional values are printed with their reference numbers. In the analysis of replicated experiments the maximum and minimum value of each of the original variates and of all derived functions of these variates is printed; in replicated experiments also, the residuals of the plot values can be and usually are printed after analysis.

Our practice on the printing of intermediate values varies with the nature of the problem and would take too much space to discuss here. In complicated problems the analysis is often carried out by stages, with an examination of the results at each stage in order to determine what is required at the next stage. When doing work for other organizations there is frequently consultation at each stage. Geographical separation is a hindrance to this, but not a major one.

Working for other organizations does of course raise problems; in particular we are sometimes asked to carry out computations which we suspect will be of little value. In some cases when the amount of work is not large and the necessary programs are available we do what is asked, as this is one good way of testing who is right. In other cases we submit a sample of what has been asked for. In general, however, the methods to be adopted are decided jointly by our own staff and the workers concerned. We are not a service bureau in the ordinary sense, and need not accept work which we do not consider worth while. We do not charge for work done for agricultural and biological research organizations.

Dr. Douglas's query arises from a misunderstanding. In Fig. 2 scheduled maintenance and system modification have been grouped together. Moreover, scheduled maintenance includes both routine daily tests and times reserved for the location and rectification of faults where notice is given by the previous evening at the latest. There has, in fact, been a reduction in amount of routine daily tests that have been found to be necessary.

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