Journal and Proceedings of the Institution of Agricultural Engineers

SPRING
1969

Vol. 24 No. 1

BRANCH HONORARY SECRETARIES

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JOURNAL AND PROCEEDINGS OF THE INSTITUTION OF AGRICULTURAL ENGINEERS

IN THIS ISSUE

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VOLUME 24 **NUMBER 1** **SPRING 1969**

THE INSTITUTION OF
AGRICULTURAL ENGINEERS

Annual Conference 1969

To be held at
The Institution of Mechanical Engineers
1 BIRDCAGE WALK LONDON SW1
THURSDAY 15 MAY 1969

MECHANIZATION OF SPACED ROW CROPS

09.45 Assemble for Coffee
10.15 Annual General Meeting of the Institution (for members of I AGR E only)
10.45 Paper 1 **The Requirements of the Fresh Vegetable Market**
by Dr J. LOVE, Horticultural Adviser to J. Sainsbury Limited
11.10 Paper 2 **The Requirements of Vegetable Processing**
by V. D. ARTHEY, Agricultural Officer, The Fruit and Vegetable Preservation Research Association
11.35 Paper 3 **Growing Vegetable Crops for Mechanization**
by Dr J. K. A. BLEASDALE, National Vegetable Research Station
12.00 Discussion . . . of Papers 1, 2 & 3
12.30 Lunch Interval
14.15 Paper 4 **Crop Establishment**
by G. L. MAUGHAN, NDA, FI AGR E, National Institute of Agricultural Engineering
14.50 Paper 5 **Crop Harvesting and Handling**
by W. BOA, BSC (AGRIC), NDA, MI AGR E, National Institute of Agricultural Engineering
15.30 Discussion . . . of Morning and Afternoon Sessions
16.30 Tea and Dispersal

Annual Dinner

To be held at
St Ermin's Hotel
CAXTON STREET
LONDON SW1
THURSDAY 15 MAY 1969

18.15 Reception
19.00 Dinner

The Guest Speaker will be:
Sir LEONARD DRUCQUER, C ENG
Chairman of The Council of Engineering Institutions

TICKETS

	Non-Members	Members (other than Students)	Student Members
Conference	60/-	50/-	30/-
Dinner	70/-	60/-	30/-

EARLY APPLICATION FOR TICKETS IS ADVISABLE

Applications should be accompanied by remittance payable to 'The Institution of Agricultural Engineers', and addressed to the Institution Secretary at Penn Place, Rickmansworth, Hertfordshire, WD3 1RE

INSTITUTION NOTES

Annual Conference and Dinner

All arrangements are now complete for what is always the outstanding day in the Institution's annual calendar, the Conference and Dinner. Both events will take place in London on 15 May. The Conference will be held during the day in the Lecture Theatre of the Institution of Mechanical Engineers. The programme has been carefully devised by Mr F. S. Mitchell of the National Institute of Agricultural Engineering, to give a broad coverage of the theme 'Mechanization of Spaced Row Crops' and is expected to attract a large audience. Details are given on the page opposite.

The Annual Dinner promises once again to be a happy means of bringing together some scores of Institution members and their friends, in company with many distinguished guests from various sections of the industry. This well-established annual event has gained renown for its excellent cuisine and pleasing atmosphere, free from undue formality.

The Council hopes that more members and their friends than ever before will attend the Conference and stay on for the Dinner, ensuring for themselves a full and pleasurable day.

Annual General Meeting

Members are asked to note that the Annual General Meeting of the Institution of Agricultural Engineers will be held on the premises of I Mech E, 1 Birdcage Walk, London SW1, on Thursday, 15 May 1969 at 10.15. This coincides conveniently with the Institution's Annual Conference which will start immediately after the close of the AGM. Formal Notice, Agenda, Annual Council Report and Accounts will reach all members a few weeks before the AGM date.

30-year Anniversary Endowment Fund

This much publicised Fund is remaining open indefinitely and it continues to be the hope of the Council that every member will donate what he can afford to this important capital fund, established in 1967 to assist the Institution's long-term development. Well over £2,000 has so far been received, thanks to the generosity of hundreds of members throughout the world who have given the Fund their support.

It is possible to spread donations over a seven-year period by means of a Deed of Covenant which allows the Institution to benefit from the recovery of income tax paid by the donor, provided his donation has been contributed from income on which he has paid income tax at the standard rate. A leaflet giving full details of this scheme was enclosed with the previous issue of the *Journal* (Volume 23, No. 4) and further copies are available from the Institution Secretary on request.

Forthcoming Activities

It can now be firmly announced that the 1969/70 session of the Institution is already well into the planning stage; the Autumn National Meeting will be held at the University of Loughborough on 4 September 1969 when a full-day programme of papers is to be presented on 'Ergonomics in Agriculture'. Full details of this and other national and branch meetings of the Institution for 1969/70 will be published in subsequent issues of the *Journal* and other literature.

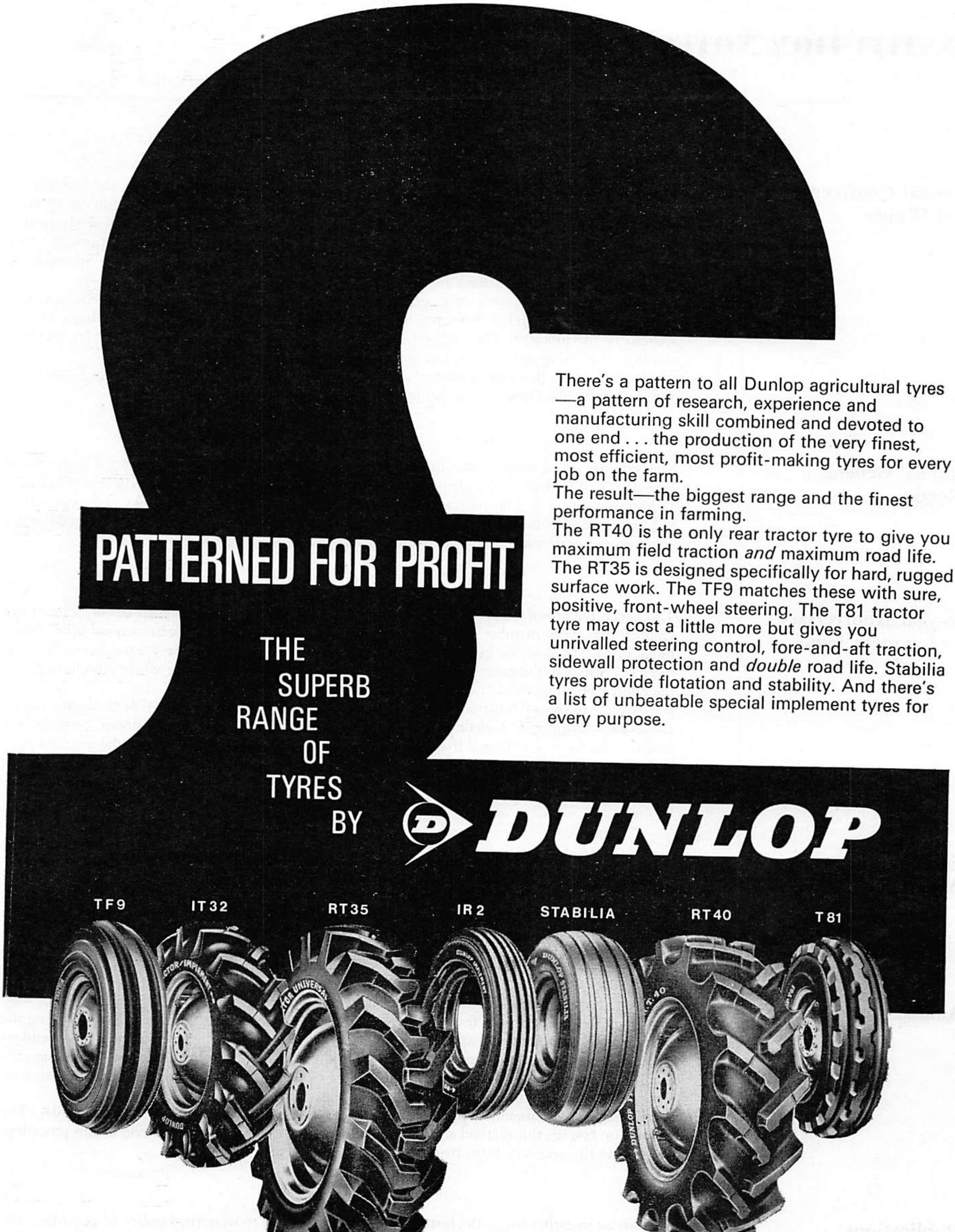
Annual Subscriptions

Although the majority of members have now paid their 1969 subscriptions, there are still some who have not. To avoid the need for individual reminders, it is hoped that this note will serve to jog the memory of those to whom it applies. It goes without saying that the Institution is wholly dependent upon its income from membership subscriptions if it is to play its full and vital part in the agricultural engineering industry and profession. A table of the annual subscription scales that came into operation this year is to be found on page 9.

Many hundreds of members prefer to pay their subscription by means of a banker's order. The Institution favours this method and any member who would like to change over to this procedure can obtain the necessary form from the Institution Secretary.

Publications

As forecast in earlier issues, the Institution has now reverted to its normal policy of publishing the *Journal* quarterly in April, July, October and January, the four parts constituting one annual volume. *The Yearbook and Membership Directory* will appear in October and the Institution *Diary* will be circulated in December.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Branch Notes

EAST ANGLIAN BRANCH

The Branch held its Annual Dinner at the Maid's Head Hotel, Norwich on 21 February.

In the Chair for this successful and well attended event was Mr T. J. Rivers, the Branch Chairman, who extended a warm welcome to all present. The Toast of the Guests was proposed by Mr U. G. Curson, the response being made by Mr H. C. G. Henniker-Wright, President-Elect of the Institution. Mr Henniker-Wright said that as an East Anglian himself it gave him particular satisfaction to be visiting this Branch. He paid tribute to the policy of the Branch in holding meetings over as wide an area of its territory as possible. Referring to the new membership regulations, Mr Henniker-Wright said it was the future of agricultural engineering that gave the key to these changes. It was up to the older, well-established members to hold the torch that would illuminate the path for the youngsters who would inherit responsibility in ten or twenty years from now. The Institution would continue to cater for the industry by setting standards of competence at both degree-level and diploma-level, represented respectively by the Fellows and Members of the future. It was by this means that the industry could expect to benefit and the Institution would consequently prosper.

SCOTTISH BRANCH

The Branch held its Annual Conference in the MacRobert Pavilion, Ingliston, near Edinburgh, on 27 February. Over 300 members and friends attended from many parts of Britain.

The theme 'Crop Protection' was chosen for several reasons—little has been done conference-wise in this field, and with the ever increasing number of chemicals coming on the market as herbicides, pesticides and fungicides underlining the uses, limitations and dangers involved in their use plus the over-riding need to exploit crop protection as an economic factor take pride of place. Also, since this was basically a mechanization conference, the application techniques involving machines and their part in the future development of crop spraying was emphasized.

Four papers were presented—the first entitled 'First Principles' was given by Dr D. J. Martin, head of the Botany Department, the West of Scotland Agricultural College, and covered the chemical/biological complex with emphasis on the herbicide treatment; his present work covers the field of bracken control including the field of soil injection.

The second paper by R. C. Amsden, of Fisons Ltd., Cambridge Division, Chesterford Park was entitled 'Farm Sprayer Usage'. This was an applications technique paper as the word 'Usage' in the title aptly suggests. Mr Amsden is head of the Application Physics Section of Fisons Ltd., Cambridge, in relation to agricultural distribution equipment and aircraft. It may be said he is closely associated with the education of the user of distribution equipment and has been involved in large scale aerial spray application throughout the world.

The third paper was by J. B. Byass, of the National Institute of Agricultural Engineering, Silsoe, and covered the mechanization angle under the title of 'The Development of Farm Sprayers' including existing designs and future trends. Mr Byass has been working on spraying problems since 1952, particularly orchard spraying and more recently on a major project—the study of herbicide application in collaboration with the Weed Research Organization, Oxford.

The final paper entitled 'Crop spraying—an Economic Necessity' was given by R. F. Norman, Development Director, Fisons Ltd., Cambridge Division. Mr Norman has had wide experience in the field of pest control having, at present, overall responsibility for the technical servicing of the division's pesticide products both at home and overseas. He has special interest in, and serves on many committees concerned with the application of pesticides.

To back up the papers several manufacturers of both machinery and chemicals provided material for a static display along with technical representatives who backed up the question and answer session of the speaker panel at the close of the session.

Chairmen of the morning and afternoon sessions were respectively Mr J. Crozier, BSC(AGRIC), NDA and Mr R. Watherston, CBE, CDA. The Conference was formally closed by the President of the Institution, Mr T. Sherwen, C ENG, FI MECH E, MSAE, FI AGR E.

WEST MIDLANDS BRANCH

At the January Meeting of the West Midlands Branch at Leamington Spa, Mr J. E. Field, M INST M, Director and General Manager of Modern Farm Equipment Ltd., spoke on 'Service Aspects of Large Distributors'.

His company covers the Midlands and North Wales

Please turn to next page

BRANCH NOTES

—from previous page

and was faced with declining productivity and profitability in the service section. To improve this, various systems were tried and finally a scheme acceptable to employee and customer alike, was evolved.

It was based on a fixed price-time basis whereby the employee can gain a bonus if the job is completed before time, and the farmer knows what the job will cost. This, coupled with modern service facilities, and promotion of service and under managers to staff status, reduced overtime and increased profitability and productivity significantly.

With the introduction of this workshop bonus incentive scheme, there could be more labour selectivity, as potential earnings would become comparable to those of rival industries.

YORKSHIRE BRANCH

An Open Meeting was held at the Yorkshire College of Agriculture, Askham Bryan, York, on 24 January 1969.

The Speaker, Mr P. Wakeford of the Electricity Council, addressed twenty-three members and visitors, the title of his paper being 'Farm Feed Preparation Now and in the Future'. He considered that the trend to larger operating units would increase and thus appear attractive for on-the-farm feed preparation. Inadequate research work exists on the requirements by stock of ground feeds particularly in respect of particle size, and also in the presentation of the food (as cube, pellet, etc.).

Mr Wakeford illustrated the range of equipment available for this type of work and referred in detail to material flow in the systems illustrated. By careful design a high degree of automatic operation could be obtained without excessive expenditure on equipment or power. The relative capacities of component machines was discussed, it being pointed out that the mixer was often the point of hold-up. The use of bins as 'buffers' was advocated.

While perfect mixing cannot be obtained in practice, Mr Wakeford referred to test work which showed the degree of mixing desired. Trace additives required premixing to ensure adequate dispersion through the final product. Mixing capacity only became a serious problem with output above 500 tons annually.

The aim should always be to develop continuous flow of feed right through to the stock. Manhandling should be avoided wherever possible, but pneumatic conveying gives rise to problems of dust, and a high power requirement. Mr Wakeford illustrated some modern systems using direct metering of ingredients, and also modern air conveying systems operating on low volume/high pressure principles.

Following Mr Wakeford's paper, a prolonged question and discussion ensued, covering many aspects of the subject including capital, economics, wet/day mixing and choice of machinery.

At a meeting held at the Museum Hall Supper Room, Selby, on 28 February Mr J. Matthews of the N.I.A.E. spoke on 'Ergonomics in Current and Future Tractor Designs'. Defining his subject, Mr Matthews suggested that for at least the next ten years steady development of tractors without sudden evolution was likely. Also, the driver would continue to ride on the tractor.

Limitation of tractor output was being noted following driver discomfort. Thus the potential output was not always fully realized. Field confirmation of hazards is demonstrated by high incidence of e.g. spinal deformities among tractor drivers. A draft standard discusses exposure time to vibration, before the effect on safety becomes serious. Tractors have a high level of vertical vibrations, but the introduction of suspension seats has done much to mitigate their effect. Static rigs are used for testing this, whereas dynamic tests were necessary for studying track vibrations. Bad seat design may amplify vibration. Further developments may be to employ vehicle suspension, or a suspended cab for the driver.

Regarding the noise problem, Mr Matthews commented that levels today are similar to 1960. Their effects were 1. Annoyance, 2. Risk of effect on hearing. Proposed limits have been indicated, and most current tractors are above these. Cabs were an additional problem and could amplify noise considerably. Development such as anti-vibration mountings, and separation of e.g. fuel tank from cabs could help.

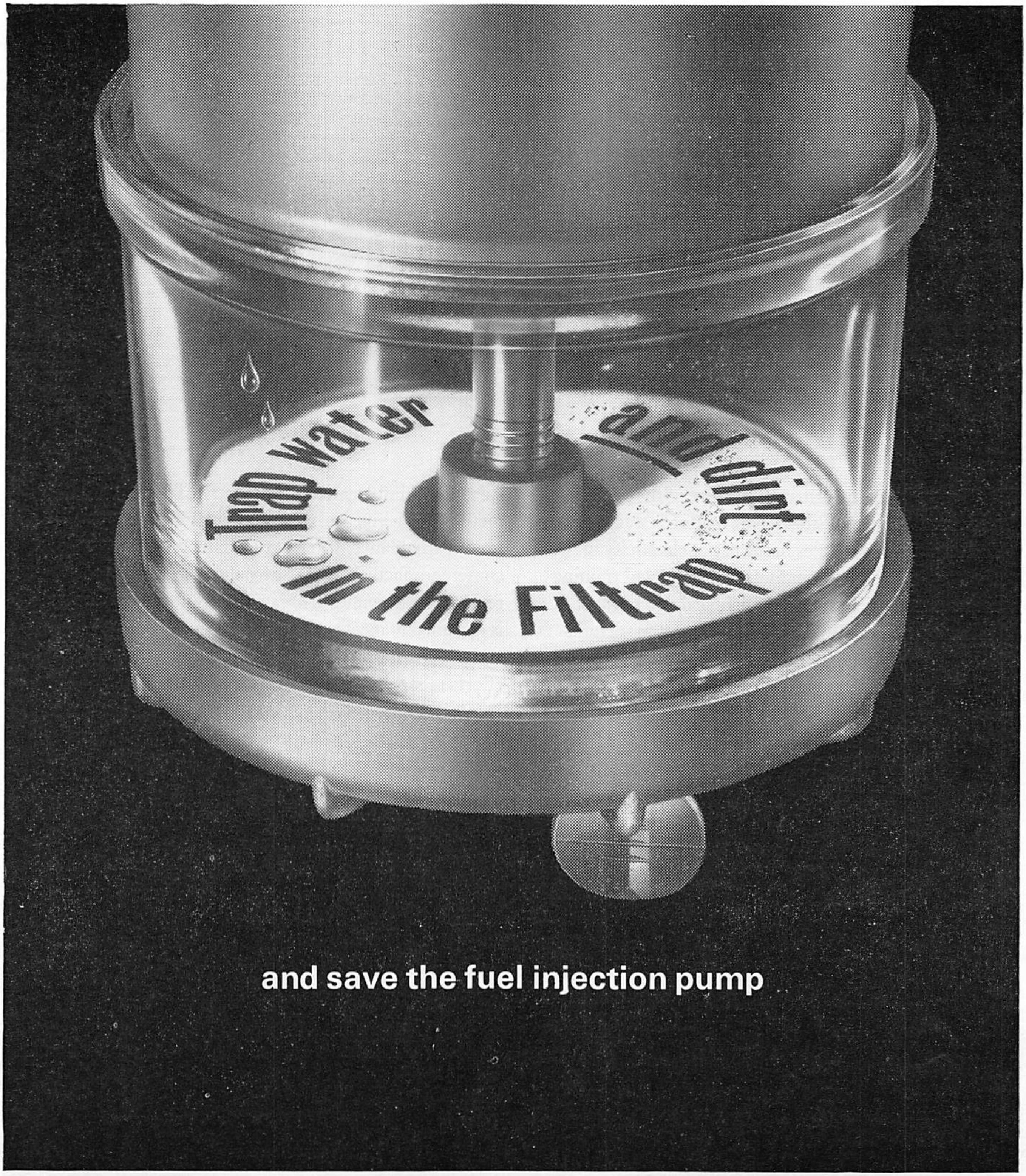
Engineering the workplace is studied by muscular activity and energy use. Control groupings being studied on a functional basis, or relate movement to results. Mr Matthews also discussed the use of words versus symbols for describing controls. In an emergency the operator must be in no doubt. Automatic sequencing of e.g. loaders is likely to be developed.

On 4 March, the Branch held a joint Open Meeting with the Automobile Division of the Institution of Mechanical Engineers, at the University of Leeds.

The speaker was Mr C. H. Hull of David Brown Tractors Limited, who said 'There's more to a tractor than . . .' Commenting that a tractor might appear as a crude automobile, Mr Hull undertook to show that this was not so. Briefly sketching the background to the first tractors, Mr Hull pointed out that since World War II developments had almost entirely arisen from the use of mounted implements, this giving a light, manoeverable unit.

Mr Hull described the linkage now used to mount implements on tractors in some detail including the relevant geometrical theory. He discussed both fully and semi-mounted implements and their relationship with the tractor pointing out that the trend to larger tractors was resulting in more extensive use of semi-mounted equipment.

Discussing the control systems for mounted implements, Mr Hull identified these as servo-mechanisms with negative feedback giving a state of stable equilibrium, but which was capable of rapid change in response to variations in external conditions.



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NEWSDESK

NIAE Open Days 1969

After an interval of seven years, the National Institute of Agricultural Engineering is holding Open Days on Wednesday and Thursday, 7 and 8 May 1969, when most aspects of the Institute's work will be shown by a comprehensive range of static and live exhibits.

Over 15 main subjects will be covered by examples of the Institute's research, development and testing activities. Also to be featured will be the work of the NAAS Liaison Unit and of the Overseas Liaison Department, as well as workshop, laboratory and library facilities.

Open Days provide an opportunity for seeing the Institute's work in its entirety and all interested in any aspect of agricultural engineering and the mechanization of agriculture and horticulture are cordially invited to attend. Tickets are not necessary and the Institute will be open from 10.00 to 16.30 hours on each of the days. Free car and coach parking facilities will be available and there will be licenced catering arrangements.

The attractive Park and Gardens containing several buildings of historic interest will be open to all visitors.

Further information can be obtained from:

The Information Department,
National Institute of Agricultural Engineering,
Wrest Park,
Silsoe, Beds.
Telephone: Silsoe 421 Extension 13

Indian Society of Agricultural Engineers

ISAE held their Seventh Annual Convention at Pantnagar in U.P. The 3-day convention, opening on 17 February 1969, was presided over by Padma Shri Dr J. S. Patel. Mr Keshub Mahindra, a prominent industrialist, addressed the inaugural session. Other guest speakers included Mr G. A. Narasimha Roa, Chairman, Central Water & Power Commission and Major H. S. Sandhu, a well-known authority on agriculture in India.

The meeting was attended by some 300 agricultural engineers from all over the country. Also present were experts from Organizations such as US AID, World Bank, Ford and Rockefeller Foundations.

Three concurrent sessions were held on:

Farm Power and Equipment
Soil and Water Engineering
Processing, storage, structure and rural electrification.

An agricultural machinery parade and an agro-industrial exhibition was also organized.

Scholarship Awards in Agricultural Engineering

In the last issue of the *Journal*, we announced that the winner of the 1968 Dunlop Scholarship, Mr R. E. Kidd, had been thinking of furthering his studies at Reading University. We should have gone on to mention that in the end Mr Kidd went to the National College of Agricultural Engineering at Silsoe, where he is now in his first year of the BSC (AGR ENG) course.

In our reference to another scholarship award, we said that Mr H. J. Holme, one of the winners of a Shell Mex & BP Bursary, was studying at the West of Scotland Agricultural College for the National Diploma in Agriculture. This was incorrect as Mr Holme, having already attained his NDA was actually on the Scottish College course leading to the ND AGR E.

'The Requirements of Tractor Transmissions'

The above-titled paper by Mr G. J. Edwards appeared in Volume 23, No. 4 of the *Journal* (the Autumn/Winter issue 1968). Our attention has been directed to the fact that the captions to Figures 8 and 9 are incorrectly shown and should read as follows:

Figure 8: Power take-off and draw bar hitch locations (540 rev/min).
Figure 9: Typical performance curve of nine speed gear box.

Just a reminder

to members of the Institution that under the new membership regulations that came into effect on 1 January 1969 annual subscriptions are now as shown opposite.

Annual Subscriptions

	United Kingdom £ s. d.	*Abroad* £ s. d.
Honorary Fellow	Nil	Nil
Fellow	10 0 0	9 0 0
Member	9 0 0	8 0 0
Companion	10 0 0	9 0 0
Associate	6 0 0	6 0 0
Graduate	5 0 0	5 0 0
Student	2 0 0	2 0 0

ELECTIONS AND TRANSFERS

Approved by Council at its meeting on 16 *January* 1969

ADMISSIONS

Fellow		Owen, V. M.	Berks
Member	*Overseas*	Esuruoso, E. O.	West Africa
		Gardiner, A. D. B.	Sussex
		Hardy, R. J.	Staffs
		Trimble, J. C. A.	Northampton
		West, C. J.	Essex
Associate		Bindloss, K. W. E.	Hants
		Blackmore, W. J.	Devon
	Overseas	Forrester, R.	Canada
	Overseas	Gunasinghe, W.	Ceylon
		Hammerton, J. G.	Kent
	Overseas	Jaffer, S. A.	E. Africa
		Lincoln, W. B.	Lincoln
		McCosh, J.	N. Ireland
		Mahamoor, M. H.	Berks
		Nelson, P. G.	Notts
		Rosher, C. G. W.	Yorks
		Searle, H. F.	Northants
	Overseas	Simpson, R.	Zambia
		Taylor, K. A.	Bucks
		Torrance, J. H. S.	Scotland
		Walker, R. B.	Staffs
Graduate		Allen, T. R.	Kent
		Andrew, T. M.	Scotland
		Beattie, W.	Herts
		Cluett, M. G.	Dorset
		Duggleby, T. J.	Norfolk
		Eyers, B. J.	Berks
		Farnaby, P. R.	Yorks
Student		Adams, G.	Somerset
		Alagendra, A. R.	Scotland
		Bailey, A. H.	Somerset
		Brooks, C. F.	Wilts
		Butler-Cole, J. A.	Kent
		Coppock, M. A.	Beds
		Denny, R. T.	Beds
		Dix, M. C.	Yorks
		Dunn, S.	Essex
		Foskett, M. D.	Essex
		Fraser, J. M.	Berks
		Fuller, R. S.	Surrey
		Griffin, A. G.	Somerset
		Handbury, J. M.	Beds
		Hiscock, K. C.	Surrey
		Holme, H. J.	Scotland
		Hull, P. J.	Devon
		Idah, G.	Beds
		Kidd, R. E.	Cambs
		Lattin, J. D.	Lancs
		Lewis, P. G.	Hants

ELECTIONS AND TRANSFERS *(continued)*

Student	.. .. ..	March, J. H.	Cornwall
	.. .. ..	Miller, P. C. H.	Beds
	.. .. ..	Nyamekye, P. W.	Beds
	.. .. ..	Plant, I.	Beds
	.. .. ..	Singh, D. P.	Scotland
	.. .. ..	Soobrian, L. H. P.	Scotland
	.. .. ..	Spyvee, P. W.	Lincs
	.. .. ..	Stead, P. F.	Yorks
	.. .. ..	Stirling, H. G.	Scotland
	.. .. ..	Turyamureebba, S.	Scotland
	.. .. ..	Walker, C. C. B.	Scotland
	.. .. ..	Weston, D. B.	Lincs
	.. .. ..	Wheelock, R. C.	Monmouth
	.. .. ..	Willy, R. J.	Dorset
	.. .. ..	Wood, C. J.	Surrey

TRANSFERS

Fellow	*Overseas* ..	Allen, D. I.	New Hebrides
	.. .. ..	Base, K. M.	Somerset
	.. .. ..	Billington, H. V.	Warwicks
	Overseas ..	Campbell, L. G.	Trinidad
	.. .. ..	Campbell, S.	N. Ireland
	.. .. ..	Chatterton, J.	Lincs
	.. .. ..	Crabtree, G.	Yorks
	.. .. ..	Davies, R. H.	Berks
	.. .. ..	Dewes, T. D.	Lancs
	.. .. ..	Graham, K. A.	Scotland
	.. .. ..	Hodges, L. S.	Warwicks
	Overseas ..	Ramchandra, R.	W. Africa
	Overseas ..	Saravanamuttu, G. L.	Italy
	.. .. ..	Shovelton, P. L.	Bucks
	Overseas ..	Wikramanayake, V. E. A.	Ceylon
Member	.. .. ..	Billot, M. R.	Jersey
	.. .. ..	Codd, H. E.	Lincoln
	.. .. ..	Dalton, R.	Lincs
	Overseas ..	Jones, M. E.	Rhodesia
	.. .. ..	Kilgour, J.	Bedford
	Overseas ..	Lartey, P. A.	Ghana
	.. .. ..	McClement, W. J.	Scotland
	Overseas ..	Mensah, J. A.	Ghana
	.. .. ..	Middleton, J. S.	Scotland
	.. .. ..	Mills, J. T.	Devon
	.. .. ..	Pyne, F. W. H.	London
	.. .. ..	Scott, P. F. C.	Warwicks
	.. .. ..	Sharp, W.	Notts
	Overseas ..	Tullberg, J. N.	Australia
	.. .. ..	Underwood, J. B.	Surrey
	.. .. ..	Willcocks, T. J.	Beds
Companion	.. .. ..	Swift, F. D.	Birmingham

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Publications

The following books, papers and data have been received or noted by the Institution.

Abstracts of Rumanian Technical Literature—by Central Institute for Technical Documentation.

The Central Institute acts as a methodological adviser and co-ordinator for the activity of technical documentation organizations sponsored by the ministries, institutions and enterprises belonging to all branches within the framework of the Rumanian national economy.

The abstracts contain a comprehensive agricultural section. Copies of the abstracts and further information may be obtained from The Central Institute for Technical Documentation, Bucharest, Calea Victoriei 100, Rumania.

Agricultural Tractors and Machinery in France—by The Syndicat General des Constructeurs de Tracteurs et Machines Agricoles.

This Encyclopaedia of French agricultural machinery is illustrated profusely with photographs of most of the equipment manufactured, together with history and specifications.

The volume is well produced, divided into five sections, and the text is in four languages—French, German, Spanish and English.

Aktuellt Fran Jordbrukstekniska Institutet—by The Swedish Institute of Agricultural Engineering.

Bulletin No. 327 is a well illustrated booklet and gives a survey of the activities of the Institute, results from the investigations carried out during the last few years and plans for further works are briefly mentioned. Printed in Swedish, a typed edition printed in English is in course of preparation.

Farm Building Progress—by The Scottish Farm Buildings Investigation Unit.

This is a synopsis of farm building developments and reports progress on the Unit's projects. The Unit is responsible for the co-ordination of farm buildings investigation work in Scotland. Its programme is the concern of a Joint Advisory Committee on which there are representatives of the three Scottish Agricultural Colleges, the Department of Agriculture for Scotland and the Agricultural Research Council. The Unit will entertain correspondence on matters concerning investigation and research.

Home-Grown Cereals Authority—An Introduction 1968-69—by the Home-Grown Cereals Authority.

This booklet describes the constitution, powers and purpose of the Authority, and the ways in which it is tackling its responsibilities.

Report of the Agricultural Research Council for the Year 1967-68—by Her Majesty's Stationery Office.

The report covers the wide field of the Research Council's work in 1967 and 1968, the relations with Universities, the outbreak of foot and mouth disease, proceedings of Technical Conferences and recent developments.

Scientific Reports—by The Agricultural College of Norway.

The College has issued Volume 47, in the form of Twenty-one independent booklets during 1968.

The reports have been compiled in conjunction with The Institute of Wood Technology, The Botanical Institute, The Institute of Agricultural Hydrotechnics, The Institute of Genetics and Plant Breeding, The Institute of Poultry and Fur Animals, The Department of Pomology and The Department of Forest Economics.

A catalogue and further information may be obtained from:

The Library of the Agricultural College of Norway,
Vollebekk,
Norway

West Pakistan Journal of Agricultural Research—by Department of Agriculture, Government of West Pakistan.

This Journal contains a large number of papers, covering all the aspects of research work undertaken in Pakistan.

Further information can be obtained from:

The Manager,
West Pakistan Journal of Agricultural Research
50 Aryanagar,
Samanabad,
Lahore,
West Pakistan

AN OUTLINE OF SYSTEMS ENGINEERING

by

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Presented at the Autumn Open Meeting of the Institution on 26 *September* 1968 *at University of Reading*

1. Definition

Although system planning has been going on in some fashion from the beginning of time, Systems Engineering as a discipline is a very new concept. First of all therefore I start with two definitions from the May 1967 Newsletter of the I.E.E.E. Group on Systems Science and Cybernetics.

1. A system is a collection of interacting diverse functional units, such as biological, human, machine, information and natural elements, integrated with an environment to achieve a common desired objective by manipulation and control of materials, information, energy and life.
2. Systems Engineering is the art of application of systems sciences to a specified purpose.

The first thing therefore is always to formulate the specified purpose, by which is meant the set of objectives for which the system is required and for which it is to be planned and designed. When this has been done the system has not only to be planned as a whole instead of as a collection of components but also as a part of its environment in so far as the environment affects its behaviour or the set of objectives and the system itself reacts back on its environment. There will be a number of clearly defined stages in the inevitably lengthy process of bringing a system into successful operation; these are set out in Figure 1. When the system is in operation either the environment will be continually changing or there will be wear and tear of some of the components or the raw materials cannot be obtained to the exact specification so some adjustment of the operating conditions of the system will be required and some control system is an essential part of the design as indicated in Figure 2.

Figure 2 also shows how the system often reacts back on its environment and how in the planning stage the interaction with other parts of the environment must be taken into account.

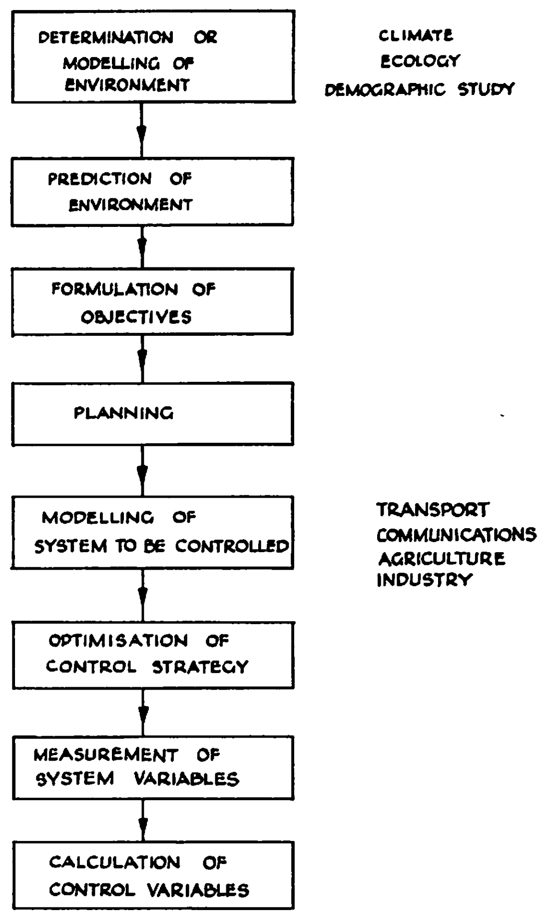

Fig. 1

2. Application to Manufacturing Processes

Until recently all manufacturing plant has been designed to make a specified product from closely specified raw materials and has then been maintained to do just this. If there were no wear and tear of the plant and the raw materials were always within specification, the plant could run untended indefinitely and there would be no need for control. However, there is always wear and tear

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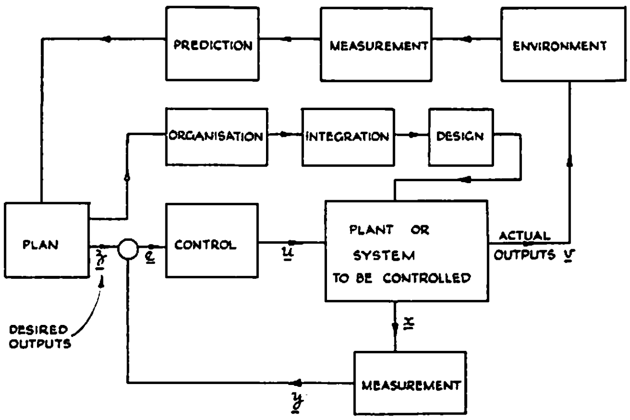


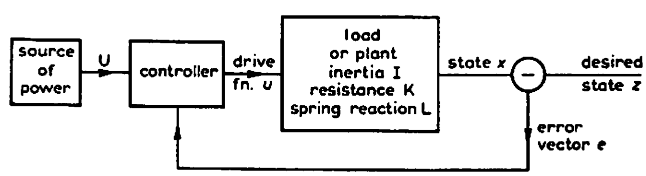
Fig. 2

of the plant and raw materials cannot always be kept within specification, and so operating conditions have to be changed from time to time. At this stage it is necessary to distinguish between batch and continuous processes, and it is easiest to consider the difference in relation to chemical processes. You will recall that when two or more chemicals are mixed together a reaction takes place. Unless it is a chain reaction the rate of reaction decreases as the concentration of the product increases and the concentrations of the reagents decrease until at a certain point the reaction ceases. Then if more of the product is required either some of the product must be extracted to reduce the ratio of concentrations or a new batch of raw materials must be used. This then is a batch process in which the rate of reaction changes continuously as the reaction proceeds. In mathematical terms it is therefore a system with time varying parameters and this is a characteristic feature of all batch processes. In many processes the rates of reaction will depend on the temperature and pressure within the reactor as well as the concentrations of the reagents, and so it is usually possible to change the temperature and pressure during the course of the reaction to give more efficient operation. Provided neither the reactor nor the reagents used are changed the best pattern of temperature and pressure will be the same for all batches, and can be scheduled in advance. This scheduling is generally known as open-loop control. If, however, the product of the reaction can be continuously separated from the reagents and more of the reagents can be added in such a way that the concentrations of the reagents and the product remain constant then the rate of reaction will also remain constant provided the temperature and pressure of the reactor are also held constant. The process will now be continuous and time-invariant and to operate it at maximum efficiency it will only be necessary to maintain the concentrations and the temperature and pressure of the reactor at the appropriate values, which we will assume to have been determined by previous experiment. It will now be obvious that control of the plant is very much simpler and it is for this reason that wherever possible industry endeavours to convert batch processes into continuous ones. In continuous processes so long as there is no wear and tear of the plant it is only necessary to provide simple controls to maintain the in-flows of the raw materials, out-flows of the product and the temperatures and pressures constant. Unfortunately, the conditions under which the plant operates seldom remain constant and so these quantities have to be controlled. An example of this may be that due to the conditions in which the plant is working the heat losses from it may change, resulting in a rise or fall of temperature and this must be corrected by an appropriate change of the heat input. In this case the temperature of the reactor must be measured continuously and used to control the amount of heat supplied to it, and this can usually be done by conventional feedback or closed-up control.

Thus in the process industries wherever possible manufacturing plant has been designed to operate continuously in a steady state condition with the temperatures, pressures, fluid-flows and other operating conditions held constant, and only to change these when necessitated by changes in the plant characteristics, due to fouling of pipes and valves or changes in catalyst activity, or by changes in the raw materials, and simple local control loops are used to hold the temperatures, pressures, etc. constant at pre-determined values. Since all control systems have much in common I must now make some comments about control system design.

3. General Theory of Control Systems

The most essential feature of any control system is that the task to be performed always involves moving something or changing its speed or direction, heating something up or increasing pressure or flow, all of which can be achieved only by the application of energy. The control problem is therefore always to control the flow of energy to the load, where it will be either dissipated in overcoming resistance, or stored in overcoming inertial and spring reaction or their equivalent, whether we are dealing with mechanical, electrical, hydraulic, chemical or, indeed, biological systems. Further it follows that, since it is only in these ways that energy is stored or dissipated, the controller is always operating on a second-order load, i.e. one which can be represented by a second-order differential equation. This is shown diagrammatically in Figure 3 from which it is seen that, if the load (or plant) is linear



$$e = z - x$$
$$u = f(e)$$
$$\ddot{x} + A\ddot{x} + Bx = Cu + \xi$$

Fig. 3

and has inertia I, resistance K and spring reaction L, the equation of motion will always be

$$I\ddot{x} + K\dot{x} + Lx = u(t) \quad (1)$$

where u(t) is the torque supplied by the power source in accordance with the way it is controlled. The energy being transferred from the source to the load is at any instant ux, and it is this that must be controlled in such a way as to make the position, speed or acceleration, or any combination of them, follow the desired values, $\ddot{z}$, $\dot{z}$ or z, which are, in general, functions of time.

Equation 1 can be rewritten

$$\ddot{x} + a\dot{x} + bx = cu(t) + \xi(t) \quad (2)$$

where a=K/I, b=L/I, and c=1/I. ξ(t) represents unwanted disturbances reaching the load from outside, such as may result from changes of ambient temperature. Then, given the initial values of $\ddot{x}$, $\dot{x}$, and x, their future values can be obtained by integrating twice; the control problem is usually to find that function of u(t) which reduces some norm of the error function e(t), e.g. the mean-squared error e, to a minimum. This introduces the concept of performance criterion, which is usually written in the form

$$J = f(e)dt \quad (3)$$

which is to be minimised.

In the simplest cases, which I shall call 'single variable', we are only interested in one output quantity, such as position or speed in a mechanical system, temperature in a thermo-dynamic system, voltage, current or frequency in an electrical system. Now it will be obvious that, if the desired output quantity is changing, since it always has inertia, the load can only follow the desired output exactly if infinite power is available, and this can never be the case in a practical system. The larger the maximum power available, the better will be the following and the smaller the mean-squared error, or more generally f(e), averaged over a period T. There will thus be an exchange relationship between the 'error criterion' J and the maximum power available U. However, the greater U, the more expensive the system as a whole, because larger motors and valves are required, and since economics must be taken into account in designing any engineering system, it is now usual to minimise a cost function C which is a function both of some norm of the error and of the energy required or some function of it, so that u(t) must be chosen to minimise C, where

$$C = \int_0^T f(e,u)dt \quad (4)$$

In the simplest case this may be of the form

$$C = \int_0^T (e^2 + \lambda u^2)dt \quad (5)$$

where λ is a Lagrangian multiplier, but it is usually more realistic and useful to use more sophisticated cost functions.

Of course, more often than not the valve or power amplifier that controls the power also has inertia and damping. Hence the overall system may be third-, fourth- or of even higher order; but, although this may affect the form of the function u(t) and the stability of the system, the amount of power dissipated in these components is negligible and does not affect the cost function. The principle therefore remains the same. The optimal function u(t) to minimise the cost function will be unchanged, but may not be obtainable as a function of e(t) because the controller now has to include these additional inertias etc.

If the load or plant is non-linear or time-varying, of course, equation 1 must be rewritten in the general form

$$F(\ddot{x}, \dot{x}, x, t) = u(t) \quad (6)$$

but the principle remains the same, and the optimum function u(t) can be found by the application of the classical calculus of variations.

In most practical applications, however, more than one plant variable has to be changed, e.g. elevation as well as bearing for a guided antenna, or speed as well as distance and direction when driving a car. In the control of a chemical plant a number of temperatures, pressures and fluid flows must be changed if a small change is required in product composition, and in the manufacture of almost any commodity there are always a large number of dimensions and properties which must be maintained within specified limits and which must therefore be controlled by one means or another. This means that there are a large number of desired output quantities, $z_1, z_2, \ldots z_{12}$, which can be considered as an n-component desired output vector *z*. This desired output has to be obtained by performing a number of operations on the raw materials, which also have certain dimensions and properties $v_1, v_2 \ldots v_l$ that can be represented as an input vector v. These input quantities have to be operated upon by a large number of processes such as milling, turning, heat-treatment etc. or by chemical reactions that are affected by temperature, pressure etc. All these processes and reactions require the application of energy in one form or another which must be controlled in such a way as to produce the desired result *z*. In general, the actual result will only approximate to the desired output, and so it must be distinguished by representing it by an n-component vector *x*.

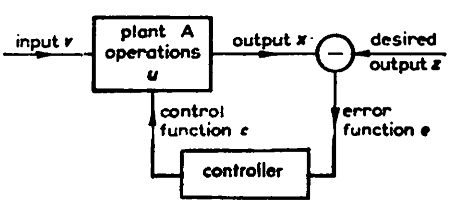


Fig. 4

The whole complex of processes may be represented diagrammatically as in Figure 4. The operations may be

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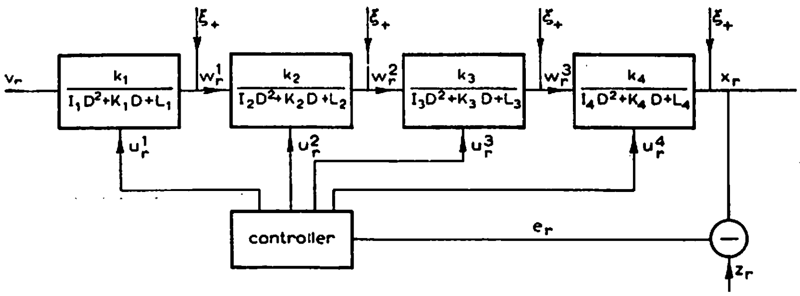
Fig. 5



in series or in parallel, i.e. if there are l specified components in the input vector, there may be l parallel operations, one affecting each component. These produce simultaneous differential equations to give a new state vector w^1 for an intermediate product in accordance with

$$f(\ddot{w}, \dot{w}, w, t) = u_\gamma + \xi_1 = \phi(c_1) + \xi_1^2 \qquad (7)$$

where u are the drives, which are functions of some components of the control function c and are unwanted fluctuations occurring in the operation of the plant. If there is no interaction between the operations (i.e. one does not affect the performance of another), w will be defined by a set of easily solved independent second-order differential equations. This, however, is a very unusual state of affairs. In almost all industrial processes, not only are there a large number of variables in the specification of input or raw materials, but there is strong interaction between ensuing operations. This means that instead of a simple set of equations

$$f_i(\ddot{w}_i, \dot{w}_i, w_i, t) = u_i + \xi_i = 1 \rightarrow l \qquad (8)$$

there are l equations of the form

$$\left.\begin{aligned} f_1(\ddot{w}_1 \dots \ddot{w}_l, \dot{w}_1 \dots \dot{w}_l, w_1 \dots w_l, t) &= u_1 + \xi_1 \\ f_2(\ddot{w}_1 \dots \ddot{w}_l, \dot{w}_1 \dots \dot{w}_l, w_1 \dots w_l, t) &= u_2 + \xi_2 \\ f_i(\ddot{w}_1 \dots \ddot{w}_l, \dot{w}_1 \dots \dot{w}_l, w_1 \dots w_l, t) &= u_l + \xi_i \\ f_l(\ddot{w}_1 \dots \ddot{w}_l, \dot{w}_1 \dots \dot{w}_l, w_1 \dots w_l, t) &= u_l + \xi_l \end{aligned}\right\} \text{ given } w(o) = v \qquad (9)$$

These equations can now always be put in the canonical form of a set of 2_l first-order differential equations in 2_l variables by writing

$$\dot{w}_1 = w_{l+1}, \dot{w}_2 = w_{l+2}, \dots \dot{w}_l = w_{2l}$$

so that we now have

$$\dot{w}_r = f_r(w_1, w_2 \dots {}_{2l}, u_1, u_2, \dots u_l, \xi_1, \xi_2, \dots \xi_l, t) \qquad (10)$$

If the system can be assumed to be linear over the range considered, equation 10 can be simplified by means of matrix notation to

$$\dot{w} = Aw + Bu_1$$

provided that unwanted fluctuations are negligible, where $\dot{w}$, w and u are usually all l vectors, because the spring terms are usually missing and A is an $l \times l$ matrix.

The w and $\dot{w}$ now become the initial state vector or initial conditions for the next set of parallel operations, which may result in the final product or may be followed by yet another set of operations. Let us assume the unusually simple case in which only four sets of parallel operations with no inter-action between them are required to produce the final specification x, which approximates to the required specification z. This situation can be described diagrammatically as in Figure 5 for one series of operations acting on the rth property of the raw materials. We can now, after putting the set of characteristic equations into canonical form and using matrix notation, write

$$\dot{x} = Cx + u^4 + \xi^4 \qquad (11)$$

where $\dot{x}$, x and u are m vectors, C is an m x m square matrix. The specification of the final product was to include n measured components, some of which may have been specified in the raw materials and not operated upon at all. In this case they may not enter into the operating equations as variables but only as coefficients, as in the case of material hardness in a machining operation. On the other hand, many of the components of the final product specification will be obtained only as a result of a large number of operations in series. If there were no inter-action from other parallel operations, each of these could be represented by a series of several, say q, second-order operations in series, resulting in a differential equation of 2qth order to describe the operations by which, say, the rth component of the output vector is obtained from one component of the input raw materials. This 2qth order equation can be put in the canonical form of 2q first-order equations and will be written

$$\dot{w} = Gw + u, \text{ given } w(0) = v(0) \qquad (12)$$

where w is a 2q vector which includes $\dot{x}_r$ and x_r as well as all the intermediate products w^1_r, w^2_r etc. and their derivatives $\dot{w}^1_r$, $\dot{w}^2_r$, etc. as indicated in Figure 6.

Thus it is seen that any operation or series of operations can be described by a set of first-order differential equations of the form

$$\dot{w} = F(w, a, u, \xi, t) \text{ given } w^1(0) = v(0) \qquad (13)$$

in which the w represents the actual output vector x and any intermediate variables w^1, w^2, etc., which have to be

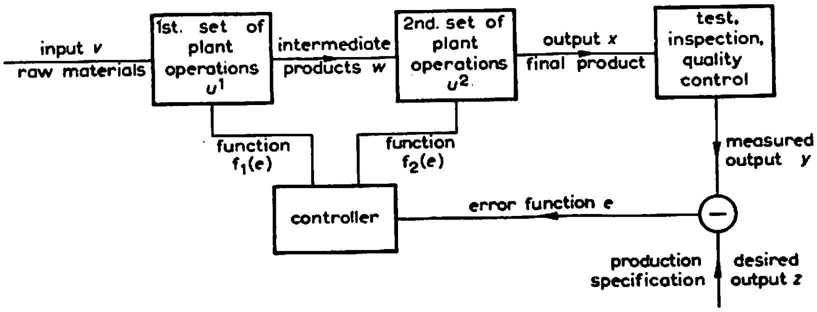


Fig. 6

included. The v represents the initial conditions, i.e. the specifications and other significant properties, e.g. weight, volume and temperature of the raw materials. The u represents all the drive functions which do work in one way or another on the raw materials and intermediate products, to heat them up or move them from one piece of plant to another, to remove metal or to squash it into a different shape. Thus the u, v, w are the quantities which must be measurable and known if the operations are to be properly controlled, and are the dependent variables of the system. The a are the parameters which define the plant and which appear in the equations as coefficients that will be constant provided that the plant is a continuous process that does not change with time owing to wear of tools, fouling of pipes, change of load or deterioration of catalyst activities. When this is the case the equations will be time-invariant, and the time t will appear only as the independent variable in the derivatives w ξ represents unwanted fluctuations resulting from measurement noise or changes in ambient conditions that cannot be either measured or predicted, which it is usually hoped will be negligible. On the other hand, random variations of load or of the plant parameters a can often be approximated in the model by unwanted fluctuations ξ inserted in the appropriate equations. In this way, plant operations, which, for exact representation, would require a set of time-varying differential equations, can often be approximately represented by a time-invariant model.

Theoretically equation 13 can be integrated to give

$$w = \Phi(a, v, u, \xi, t) \qquad (14)$$

and by elimination of intermediate variables this can be reduced to

$$x = H(a, v, u, \xi, t) \qquad (15)$$

which, for a steady-state process where the unwanted fluctuations are negligible, reduces to

$$x = H\left\{a, v(0), u(t)\right\} \qquad (16)$$

which knowing a and the specification of the raw materials v(O), defines the output as a function of time for any given control function u(t) of the drives as a function of time. Again, theoretically we can now apply the calculus of variations to determine the function u(t) which minimises some norm of the error function $e(t)=z(t)-x(t)$, such as mean-squared error e^2. Furthermore, we can apply such constraints on the u(t) and on the intermediate variables w_1, w_2 etc. as may be necessary to account for power limitations, and we can apply restrictions on such quantities as speeds, temperatures and pressures as may be necessary as safety precautions. Alternatively a cost function as indicated in equation 7 may be set up and minimised to determine the optimum drive function u(t) that will reduce the cost to a minimum.

It will be immediately apparent that this is exactly what all manufacturing industry would like to do. If it were possible, the efficiency of all industries would be improved by several per cent, resulting in increased industrial output of hundreds of millions of pounds sterling per annum, and our balance-of-trade problems would be at an end.

4. Application to a Steel Mill

To illustrate what I mean let us consider the organization of a steel mill. Figure 7 shows diagrammatically the production flow at the Park Gate Iron and Steel Works. This

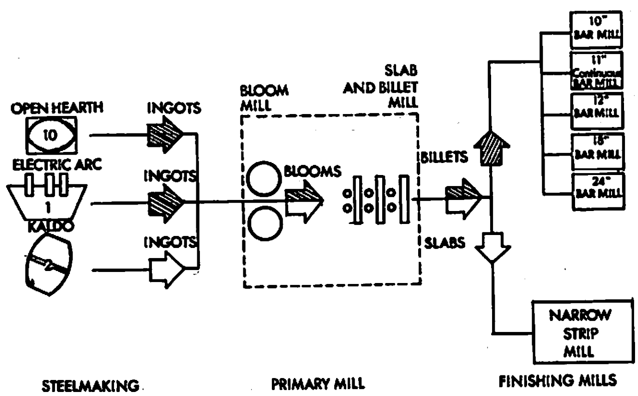


Fig. 7

Steelworks Production Flow

mill is primarily concerned with making narrow steel strip for electrical resistance welded steel tube, but it also produces steel bar for a number of customers outside the main group. Because of this, besides the strip mill there are five bar mills which have to be kept employed if the whole steel works is to operate efficiently. You will see that steel for the strip mill is produced by the Kaldo process but that in order to meet the customers' requirements for bars of different metallurgical properties, open

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hearth and electric arc furnaces have to be used to provide steels of the required specifications. The problem is that blooming or roughing mills become more efficient the bigger they are, and so in this works only one, labelled primary mill in the figure, is required to keep all the finishing mills employed. There are always savings to be made in the steel industry by increasing the size of the plant and it has been shown that if we could start again from scratch the twenty five million tons of steel required in this country could best be produced in three integrated steel works, in which case the cost per ton would be almost halved[9] Most big steelworks work with twenty-ton ingots but at Park Gate the mill is designed to use five-ton ingots. The process is that pig-iron is bought in and steel is made in one of the furnaces shown on the left of the figure. The steel is made in melts of fifty to one hundred tons and these melts are then poured into five-ton ingot moulds so that from each cast ten to twenty ingots are made. The moulds have to be allowed to cool so that they can be withdrawn from the ingots, which are then put in furnaces known as soaking pits to bring them to the right temperature throughout for rolling. The problem then is to take the ingots, which have different metallurgical specifications according to the cast from which they were made, in the appropriate order so that all the finishing mills are kept supplied with slabs and billets of the correct specification to keep them as nearly as possible fully employed. Determination of this production plan for the primary mill is a complicated procedure which depends on the customers' orders that have been received, the capacities of the different steel-making furnaces and the through-puts of the various finishing mills. At Park Gate a digital computer is used to calculate this production plan as we shall see later. The operations on the heated ingots are shown diagrammatically in Figure 8. After weighing, the ingot goes to the roughing mill in which it is rolled into blooms of the appropriate dimensions depending on for which finishing mill it is destined. The bloom has to be scarfed to remove the scale and is then sheared into slabs. Some slabs go straight to the hot strip mill while others are further rolled into blooms and then sheared into billets for the bar mills. When possible the billets go direct to the finishing mills via re-heat furnaces but some go to cooling beds to be stored and later re-heated and used as required. The hot strip finishing mill is shown diagrammatically in Figure 9.

Quite clearly we should like to plan the whole factory so that it was working in the most efficient manner possible, and with all the plant working at full capacity, week in week out. Theoretically, it would be possible to do this if we knew exactly what orders to expect, and we knew exactly how each piece of plant would behave. Unfortunately, we cannot predict exactly what orders the works will receive because this will depend on the market conditions. The customers' orders will therefore, depend

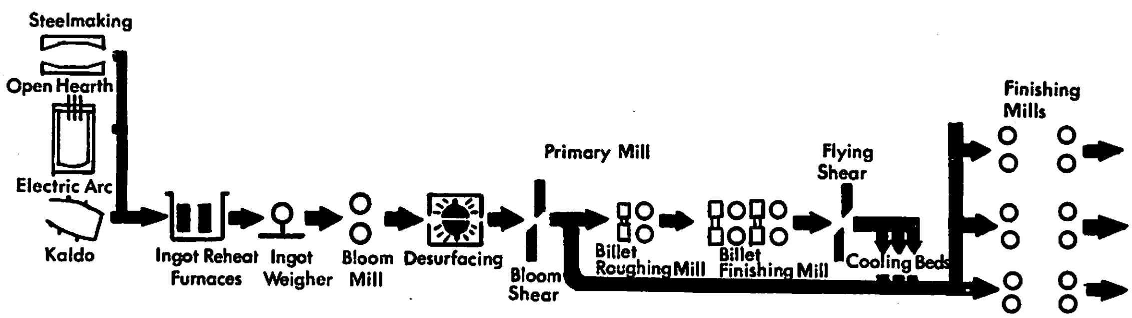

Fig. 8

Steelworks Primary Mill

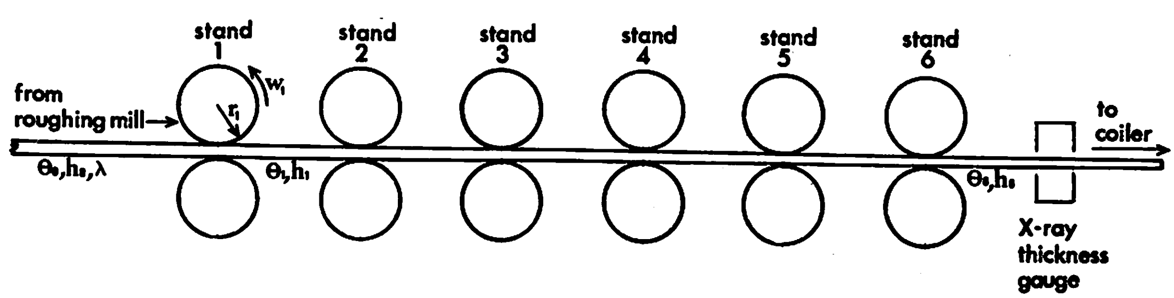

Fig. 9—Arrangement of Hot Strips Finishing Mill

on the environment in which the plant is working, and as already indicated before the works can be designed prediction of the environment is essential. However, for the time being we will assume that a reasonable forecast has been made and that the plant has been planned to fulfil an estimated mix of orders. The planning of the plant should itself be an optimizing procedure to get the best equipment available to produce the required output at minimum cost and maximum profit. Theoretically it would be possible to do this accurately provided the characteristics of the various pieces of plant were known. In practice, however, even if the plant characteristics were accurately known, the number of variables would be so great, as we shall see later, that an accurate computation would probably be excessive even with the very powerful computers now available. We will, therefore, assume that the plant exists and has been designed to be reasonably well-balanced for the average run of customers' orders, and the problem is to run the plant in such a way that it produces the maximum profit.

In order to get an idea of the magnitude of this problem let us first consider two of the individual processes in detail, the open hearth furnace and the hot strip mill. The hot strip mill which is shown diagrammatically in figure 9 is basically a continuous process, but because the capacity of the coiler is limited, the mill has to be stopped about every thirty seconds and a new slab has to be rolled on to a different coiler. This means that not only are there severe discontinuities as the slab enters and leaves the mill but, since no two slabs are exactly the same in thickness, temperature and metallurgical properties, different mill-settings are required for each slab. Since the thickness, temperature and metallurgical properties cannot be accurately measured before the slab enters the mill, it is not possible to adjust the mill correctly before the particular slab enters the first set of rolls. Further, the reduction at each stand depends on the tension between stands and since there can be no tension between all the stands until the nose of the slab has entered the last set of rolls, the mill settings which are right for the middle of the coil are quite wrong at the beginning of it, and this results in about five per cent of the strip rolled being outside the required specification. If, however, an accurate mathematical model of the rolling process were available it should be possible to set up the mill correctly and programme the screwdowns and tensions to roll a coil of strip entirely within specification provided the thickness, temperature and metallurgical properties of the incoming slab were accurately known. Unfortunately, it is not usually possible to measure these quantities with sufficient accuracy. However, in a medium width strip mill which is mechanically very stiff the mill-housing strain gives an accurate measure of the percentage reduction as the slab goes through a set of rolls and therefore if this reduction is known, it is possible to up-date the values of the thickness, temperature and metallurgical properties of the incoming slab after it has passed the early stands of the mill provided the mill housing strains are measured. Equations 17-19 have been shown to be an adequate mathematical model for a single stand.

Gaugemeter equation

$$\Delta h_i = \Delta S_i + \Delta F_i / M_i \quad \text{(c.f. Hooke's law)} \qquad (17)$$

Rolling equation $F_i = f_i\,(h_{i-1},\ \theta_{i-1},\ \omega_i,\ \lambda,\ S_i)$ (18)

giving

$$\Delta F_i \simeq \frac{\delta F_i}{\delta h_{i-1}} \Delta h_{i-1} + \frac{\delta F_i}{\delta \theta_{i-1}} \Delta \beta_{i-1} + \frac{\delta F_i}{\delta \omega_i} \Delta \omega_i + \frac{\delta F_i}{\delta \lambda} \Delta \lambda + \frac{\delta F_i}{\delta S_i} \Delta S_i \qquad (19)$$

where

F_i is the roll force at the i^{th} stand, S_i the unloaded roll gap, M_i the housing stiffness.

θ_i, h_i are the outgoing temperature and thickness.

ω_i is the angular velocity and r_i the roll radius.

λ depends on the metallurgical properties of the strip.

If then, the initial conditions of the slab can be up-dated to more accurate values as a result of measurements on the early stands it should be possible to programme the later stands of the mill in such a way as to reduce the amount of strip outside specification very considerably. The difficulty, of course, is that in order to do this effectively it is necessary to use a model of the complete mill employing all 6 stands and since the model for a single stand involves 15 variables, the model of the whole mill will have 6 times as many, that is 90 variables. Fortunately, however, it is found that in this particular mill the tension on the strip has relatively little effect and there is a simple relationship between the total reduction of thickness and the sum of the mill housing strains in the stands through which it has passed as shown by Figure 10.

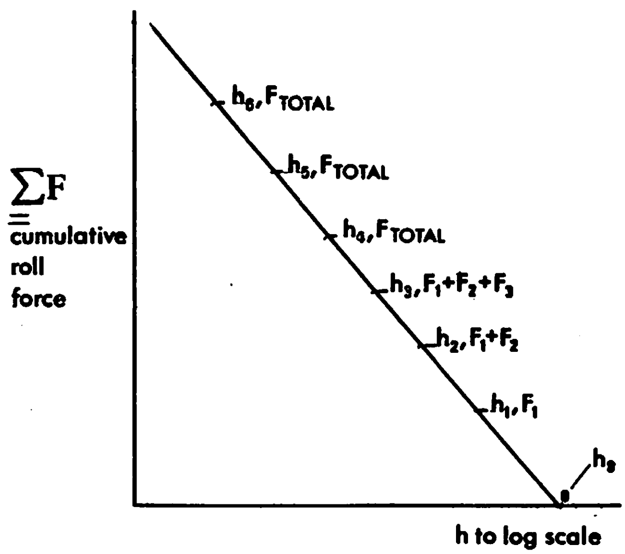

Fig. 10—Equation for Prediction of absolute roll force

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It has been found from experimental investigation that ΣF can be represented by an equation.

$$\Sigma F = A\alpha).\, l\, n \left(\frac{h_o}{h}\right) .\, l^{-B(\theta - \theta_d)} \qquad (20)$$

in which
A and B are parameters which can be determined,
A depending on the metallurgical properties λ.
θ is the strip temperature, θ_d the nominal rolling temperature.

The roll force F_i at any given stand the i^{th} is given by

$$Fi = A/n \left(\frac{h_{i-1}}{h_i}\right) l^{-B(\theta_i - \theta_d)} \qquad (21)$$

Thus from measurements of F at the early stands the reduction $\frac{h_o}{h}$ can be determined and the screw down of later stands adjusted to give approximately the desired output thickness.

This work is still in an early stage but it indicates, I believe, that, provided a mathematical model can be derived, there is a possibility of making major advances in the control of quasi-batch processes which could greatly increase their yield.

Turning now to the open hearth furnace this was one of the first batch processes to be investigated and it is very typical. Although the chemical reactions are complicated it was found possible to develop and prove a dynamic mathematical model for the process of the form

$$\dot{x} = f\,(x, u, a, \xi, t),\; x\,(o) = c \qquad (22)$$

where x is the state vector, in this case (see Figure 11) the concentrations of Fe, C, O, P, S, Mn, and Si in the metal, the concentration of CaO, FeO, SiO_2, MnO, P_2O_5, S_s and MgO in the slag and the temperature Tm and Ts of metal and slag, 16 variables in all.

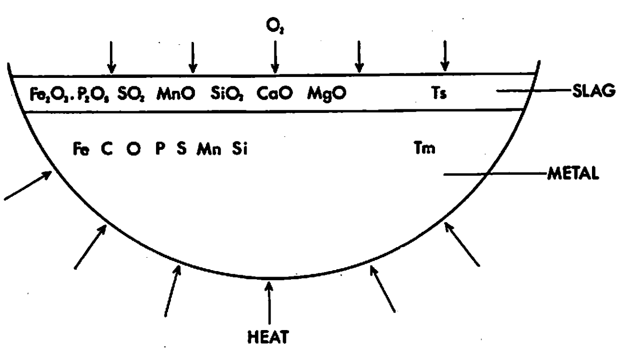

Fig. 11—Diagram of open hearth furnace

The u are the control variables such as heat and oxygen inputs and additives, the a are the plant parameters which appear as coefficients in the differential equations, t is time and ξ are unwanted fluctuations, which can include the noisiness of the measurements of the state variables. The process is highly non-linear but provided the state variables can be measured the a can be calculated by a hill-climbing procedure assuming that the initial conditions c are known. Unfortunately, in practice the initial concentrations in metal and slag are far from accurately known so the estimated a will be in error, not only due to noisy measurement of the state variables but also due to incorrectly estimated initial conditions c. The best procedure is to assume the initial conditions accurate and to ignore the ξ in the first instance and then estimate the a by minimising a function of the form

$$S(a) = \sum_i \sum_j \left[y_i - g_i \left\{ x_i(\, a) \right\} \right]^T x$$
$$W_{ij} x \left[y_j - g_j \left\{ x_j\,(a) \right\} \right] \qquad (23)$$

where W_{ij} and weighting functions, $y_i\, y_j$ are noisy measured values of x at times t_i and g(x) is found by integrating the model equation with $\xi = O$.

Having estimated the x for a large number of melts off-line it is then possible to go back and get improved values for the initial conditions for these melts and by successive approximations get a well-proved model with good values for the a. When using such a model in real time the initial conditions can be treated as additional variables and corrected as the run proceeds but in order to do this the integrated form of equation (1) must be used

$$x = g(x_o, u, a, t) \qquad (24)$$

and in the calculation the sixteen x_o become additional variables. When this has been done it becomes possible to predict the course of the reactions and in theory the control variables u can be adjusted to optimise the system. It should be noted that the system now has an additional 16 variables making, with the u, 37 in all.

We should, of course, like to optimise this whole works dynamically in accordance with a set of differential equations of the type given above in equation 13, but with a large number of different products, such as are made at Park Gate, the desired output vector z required to specify only a few customers' orders would alone contain many tens, if not hundreds, of components. Even at the input to the primary mill the vector v defining the raw materials, i.e. the steel ingots, will contain tens of components, and clearly there will be many intermediate products as the steel makes its way through the mills, so that there will be hundreds of intermediate variables, the w^1, w^2 etc. of equation 12. Thus, in order to define the

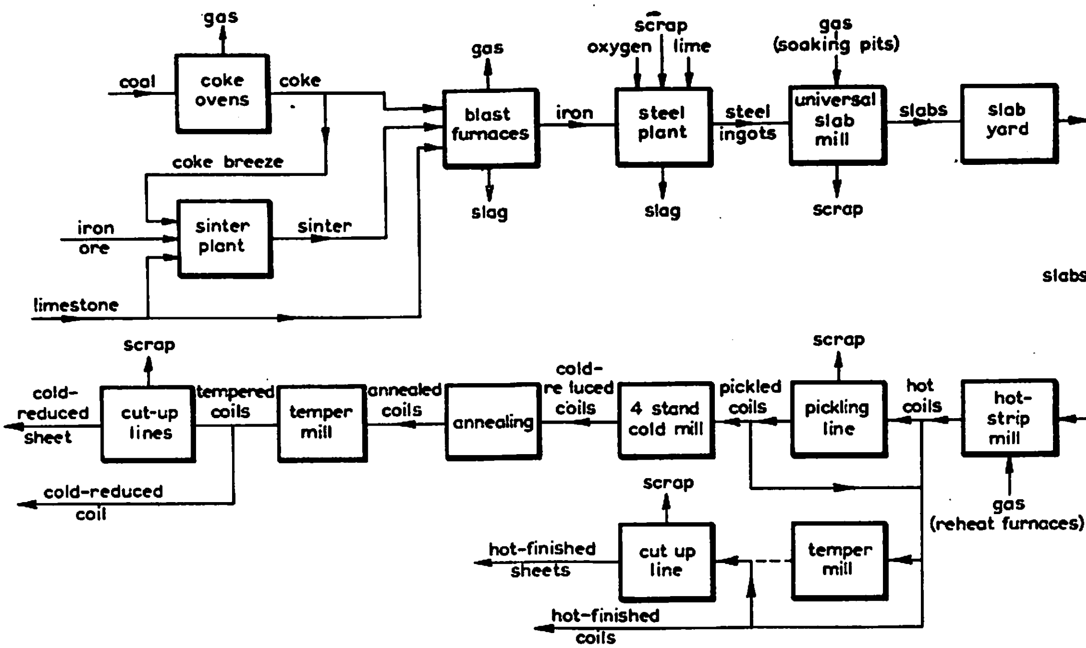

Fig. 12—Main processes of the Spencer Steelworks

dynamics of the whole mill, a set of hundreds of differential equations of the type indicated in equation 9 will be required. At present, we have no means of optimising such a system, even if we know how to define the processes in this way.

Even if the steel mill were only producing one product of known and constant specification for months on end, which might be the case if it were producing steel sheet for the motor industry, the number of variables that would have to be controlled would be many hundreds, as will be seen from Figure 12 which shows diagrammatically the main processes of such a works. In this case, although the works may be producing a standard product, the raw materials—coal, iron ore and scrap—are variable and many of the processes cannot be accurately controlled, so that dynamic control is needed to take account of these variations in the raw materials.

If we want to have optimal control of the whole plant, so that when the raw materials change the plant is driven from its initial state A to the required new state B in the shortest possible time or with the least amount of spoilt product, it is theoretically possible to calculate the optimal path, i.e. the drive function u(t) which minimises the cost function, by the use of Pontryagin's maximum principle based on the classical calculus of variations. In order to do this a dynamic model of the system must be available, and it must be put into the canonical form of equation 12, so that the adjoint equations can be used to solve the two-endpoint boundary problem. Provided that the changes of raw-material specification are slow and the number of variables is small, say less than ten, it may be possible to do this using a digital computer, but if changes of raw-material specification are random and rapid they will change before the new state has been reached, and there is at present no known method of using Pontryagin's maximum principle for random variables. This also means that it cannot be used when measurement noise is large or when for any other reason the unwanted fluctuations cannot be ignored. In such cases dynamic programming techniques[2] must be used, but it is only in the simplest cases with very few variables that this is possible, even when very large computers are available. It is not always possible then, because the amount of computation is always large and increases as the square of the number of variables.

If the number of variables for individual pieces of plant can be reduced to single figures, then, provided that the random fluctuations are slow, it may be possible to apply optimal control in real time using digital computers, but if the random variations are rapid, it is almost certain that approximate control strategies, such as predictive control,[3, 4] will have to be used. As yet very little work has been done on approximate strategies, but we are finding, as in the case of the steel-rolling mill, that these can be very effective.

It will be evident that at present there is no possibility at all of reducing the hundreds of variables which would have to be included in the dynamic model of an industrial plant, such as the steelworks depicted in Figure 12 to a sufficiently small number to make optimal control possible. We now have methods for optimising the

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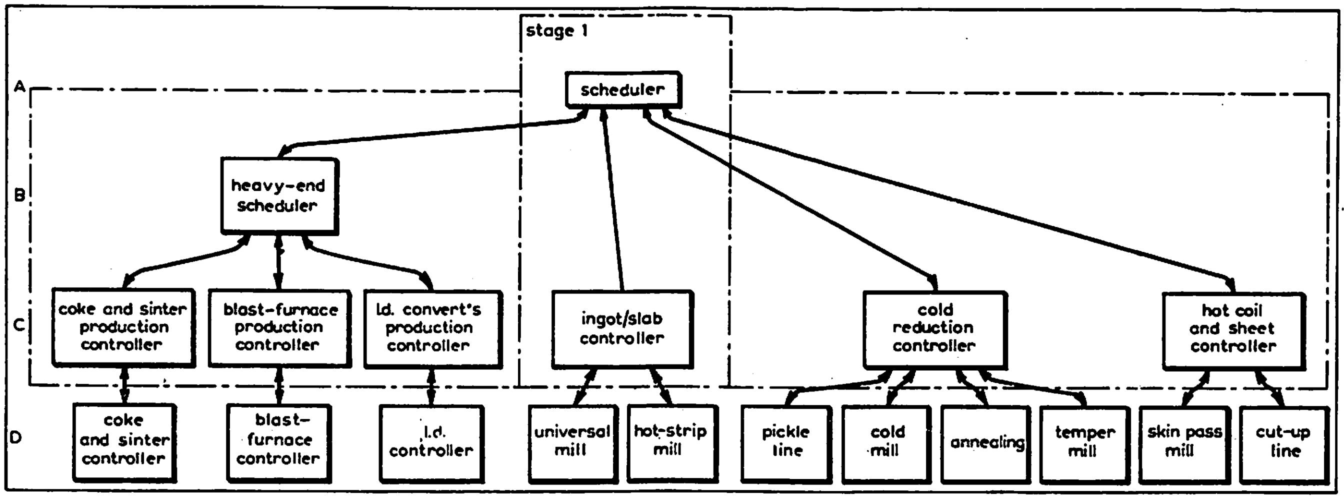

Fig. 13—Interconnections between computer systems (Spencer Works)

Level A Plant Scheduling
B Plant Optimisation
C Production Control
D Process data logging plus Production Control

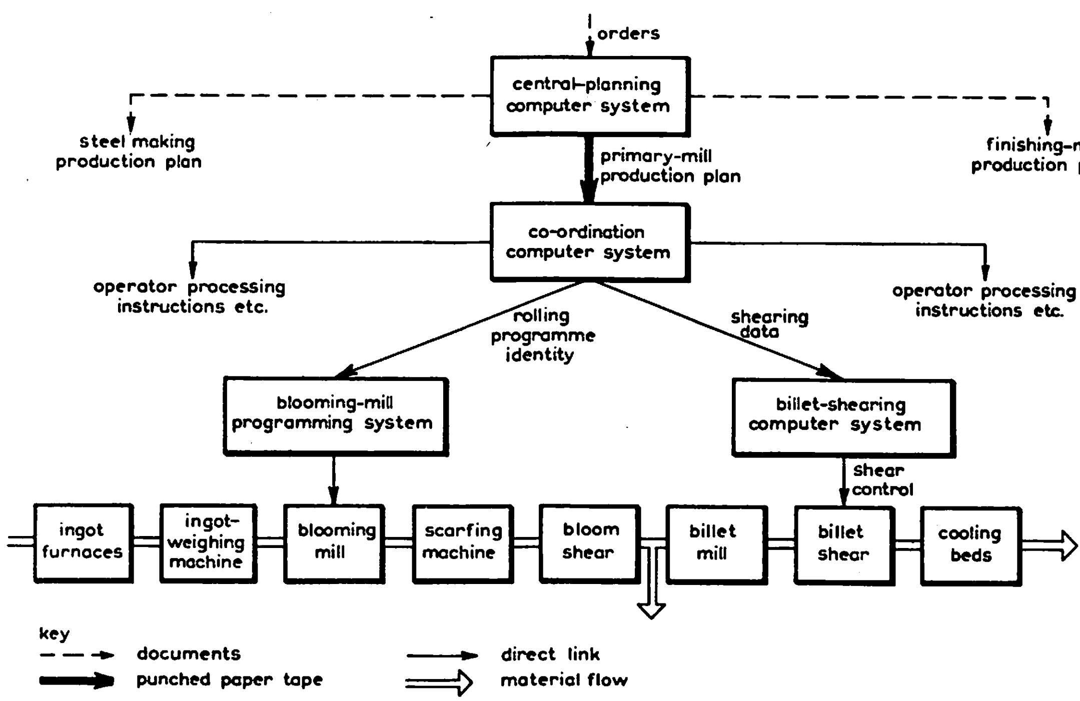

Fig. 14—Schematic of integrated computer control—Park Gate Iron and Steelworks

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individual processes to correct for unwanted fluctuations of the input materials resulting from variations in the earlier processes, but the overall optimization of a complete factory is not within sight.

The best that can be done, therefore, is to use operational-research techniques to calculate the best schedule of operations, as has been discussed above, and so determine the desired outputs of the different pieces of plant as functions of time, and then control the individual processes dynamically as far as is possible. This implies a hierarchy of control, as is employed both at Spencer Works, Figures 12 and 13, and at Park Gate, Figure 14, in which the computer systems are shown diagrammatically. In both these examples three separate small computers are used for convenience, but it would, of course be possible to use a single large computer, provided it was multi-access and had parallel programming facilities, In either case the problem at this level becomes one of data-processing system design and the provision of special computer programmes (software) for computing and updating the production schedules and issuing instructions to the different pieces of plant.

5. Possible Application to Agriculture

Quite clearly a farm as a whole is every bit as complicated as the steelworks we have considered and its operation is much more affected by the environment. As in the steelworks there are always a large number of interacting processes and the number of variables is very large indeed. It will have been observed that it only became possible to simulate the steel processes and to design better control systems for them when means of measuring the system variables had been developed. In agriculture it is quite evidently far more difficult to measure the essential variables and until this can be done it will not be possible to develop mathematical models of the processes, which are necessary if the systems approach is to be fully effective. Until some simulation of the processes is possible there can be no precise way of determining the control action that should be taken. Thus the application of systems science to agriculture will be extremely difficult but because agricultural systems are so very dependent upon their environment it is all the more necessary to make the attempt. Further this implies that better prediction of environmental conditions is an essential requirement for better planning and control. It is therefore well worth considering what might be done to further the application of systems science to agriculture.

As in the steelworks the individual processes will all be batch processes, although some, such as milk-production, may be able to be treated as quasi-batch processes by considering the herd as a whole on a statistical basis. To indicate the way in which the problem might be approached we will consider the management of a single field.

In this case the field may be considered to be the plant which converts raw materials, e.g. seeds, fertilizers, water and light, into the required products. In this case we must distinguish between the raw material inputs such as seeds and fertilizers which are under our control and light and water which probably are not. There are, of course, unwanted disturbances, such as pests, which affect the final product, many of which are outside our control and for which remedial action has to be taken. Thus we get a system of the type shown in Figure 15 in which there are a number of inputs v which include both the raw materials which can be measured and some unwanted inputs such as pests which may or may not be measurable. If they are not, they must be included in the model as unwanted fluctuations ξ (see equation 6 and figure 5). Just as the open hearth furnace is controlled by the appropriate application of heat, oxygen and certain additives, e.g. CaO and Mg_2O, to convert the raw materials into the required grade of steel in the most economic manner so in the case of the field cultivations, fertilizers and sprays should be applied to produce the greatest yield or better still the greatest profit according to a programme which will depend not only on the changing inputs v but also on the initial state of the field at the beginning of the season. Clearly since some of the inputs are changing throughout the season and outside our control the programme of

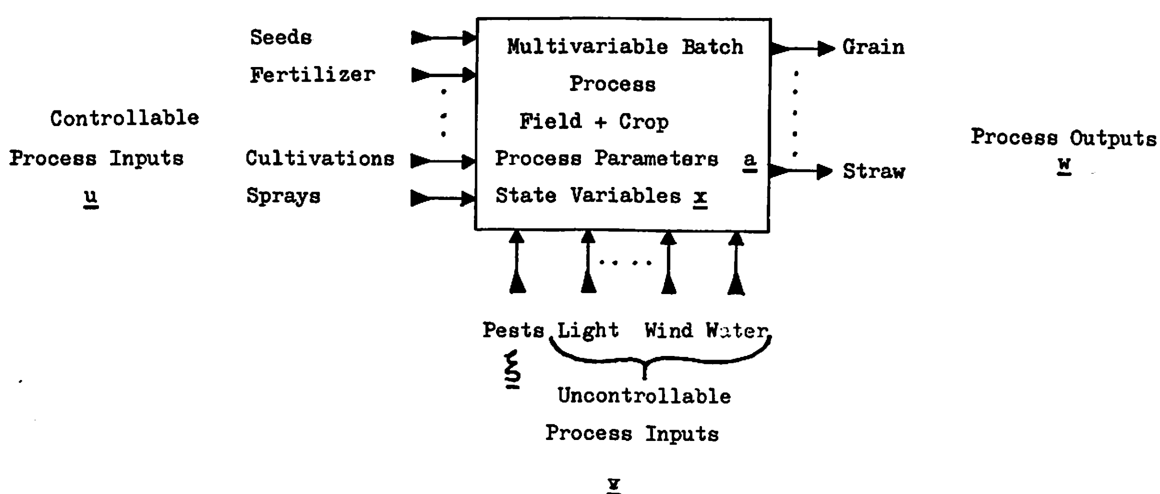

Fig. 15—A model of the field and crop as a Batch Process

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cultivations etc. will have to be continuously adjusted, if the output is to be optimized.

This is analogous to the open hearth furnace and if we had an accurate mathematical model of the field of the form

$$\dot{x} = f(x, a, u, v, \xi, t) \qquad x(o) = c \qquad (25)$$

we should theoretically be able to optimize the controls by the use of dynamic programming. Since it is a batch process we should have to use the integrated form of the equations and the initial conditions would be brought in as additional variables (c.f. equation 24) so the total number of variables would be large, certainly more than 40. Unfortunately, at the present time dynamic programming for a system with more than about 10 variables is not possible on account of the vast amount of computation required. However, when the mathematical model is available, experience with other systems has shown that it is usually possible to simplify the model to one with only about 10 variables significant from the control point of view and that then it is possible to develop a control strategy which will give much improved performance as indicated in the case of the steel rolling mill.

It is, of course, far more difficult to develop a mathematical model for a biological system, such as a field, than for a piece of manufacturing plant such as an open hearth furnace. Although a great deal is known of the qualitative effects of light, temperature, water table and application of fertilizers on the development of the crop it is extremely difficult to obtain precise measurements either of these parameters or of the state variables of the field and crop i.e. soil conditions, root developments etc. A further difficulty is that whereas industrial plant is usually not much affected by the ambient conditions of its environment, in this case the environment provides some of the raw materials and even some of the controlling variables. It therefore becomes essential at least to be able to measure the state of the environment continuously and preferably to be able to predict how it is going to change throughout the growth of the crop. For this reason as mentioned previously optimum planning of an agricultural enterprise is far more difficult than for a manufacturing plant, which we have already seen can only be approximated.

Quite clearly we are a very long way from having a usable model for any of the processes of agriculture but the goal is well worth pursuing because, if we had such a model for the field, its crop and the environment, we could plan the management of it in a much more precise manner. This in turn would allow a more precise systems approach to the development of agricultural machinery.

For instance several automatic systems for cultivations are being worked on, all of which are no doubt technically feasible and the decision on which, if any, should be employed on a particular farm should be based on economic criteria. At the present time the efficiency of any system can only be very roughly estimated on the basis of past experience but, if the required pattern of cultivations over a number of years could be predicted even approximately using a system model of the type described, a much more precise assessment could be made. So far we have only considered the simulation of the system in terms of physical parameters which can be used to maximise the output or minimise the controllable inputs for a given output. However, if this can be done it is a small step to convert the inputs and outputs into money terms and set up a cost function for a unit of output which can then be minimized using the classical calculus of variations. In this way various systems can be accurately compared.

Eventually the objective is, of course, to optimize the profit for the whole farm averaged or integrated over a number of years. Just as in the case of the steelworks, if we try to make a comprehensive model which includes all the operations, the number of variables will be far too many for us to obtain a workable model and, even if this were possible, an optimal control strategy could not possibly be calculated. However, if we could calculate optimal controls for the individual processes it would then be possible to use linear programming techniques to schedule these operations to give the best mix of products to maximize the profit provided market prices and production constraints, dictated by weather and other environmental conditions, could be predicted with adequate accuracy. That this is not beyond the bounds of possibility has been demonstrated by the fact that a scheme of this type has been developed and tested for a beet sugar extraction plant which is a complex of interacting batch and continuous processes and has more than 200 interacting variables.

To sum up, if we are to make any appreciable progress in the optimization of farm economics, we must first push ahead with the modelling of the individual farming operations, on the one hand, and with the prediction of weather, market and other environmental conditions on the other hand. Modelling of the farming operations requires a far better understanding of the physiological, chemical and physical processes than we have at present and also improved methods of measurement of the essential variables. However, we should not be disheartened because experience with industrial processes, such as the open hearth furnace, has shown that a useful start can be made with very rough measurements indeed and very frequently approximations can be made which greatly simplify the model as in the case of the steel-rolling mill.

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A SYSTEMS APPROACH TO FARM MACHINERY SELECTION

by

DONNELL R. HUNT PH D, MS, BS*

Presented at the Autumn Open Meeting of the Institution on 26 September 1968 at University of Reading

Two characteristics of a system are the interdependence and interaction of its elements. The collection of machinery on a farm has these characteristics, and as a result the selection of appropriate, economic elements (the individual farm machines) for a farm machinery system becomes more complex than the casual observer might suspect. If all farm machines were self-propelled, their interdependence would be minimal; but, most machines are tractor powered and it is the tractor that interacts with all the non-self-propelled machines to create an operational system that is sensitive to changes in any of its elements.

A successful farm machinery system is an economic one. That is, it must perform in such a manner that profit to the farm is maximized. Maximization is not always accomplished by minimizing costs, and such is true with the selection of a farm machinery system. Considerations have to be given to the economic value of operating machinery at that correct moment in time when the soil, the crop, the weeds, and the insects are most affected. The need for timely operations is a rather unique economic constraint on the farm machinery system.

The analysis in this paper describes the selection of a machinery system for a specific farm where the enterprise constants are known. The selection criteria is one of maximum profit. Consideration is given to the economic benefits of timely operations. Because the analysis is complex a digital computer programme is suggested as a computational aid.

The use of a computer is a practical tool for farm managers today. Availability of a computer facility is about the only limitation. Costs for running a machinery selection programme depend somewhat on the complexity of the farm considered, but would usually be less than the $5 or £2 for a minute's time on a large computer. The major costs are for assembling the data and punching the cards. Understanding the operation of the computer is not required since various compiler programmes have been developed that interpret the human language into machine language. The computer programme discussed here consist of a series of algebraic equations which are readily understood by people, and with the use of FORTRAN (a formula translation compiler programme), readily understood by the computer also.

Agronomic variability, enterprise variability, and topographic variability require that machinery system selection must be made on an individual farm basis. This requirement implies that such a programme must be adaptable to a large number of input data and should accommodate many special circumstances. It will be assumed that the farm enterprises are known and fixed, and that the selection of a machinery system is subservient to the needs of the farm enterprises. (Actually, sophisticated farm management should take into account the effect of the machinery system on enterprise selection)

Machinery system selection inescapably involves estimations. One may have a good history of performance data, costs, fuel consumption, etc. for implements, but variabilities among machines, farms, and regions make such data at best a range of values for which the average is but an estimate of an individual machine's characteristic. The absolute cost of a machine can be determined only after its replacement—a circumstance that is no help in the selection problem. Although one should use the best data possible to guide the selection process, one should also realize that the analysis is inevitably based on estimation and that some reasonable simplifying assumptions may be made without affecting the usefulness of the analysis.

Machine performance is a very important estimation. Performance, in this analysis, is limited to field capacity; and in no way will this selection programme consider differences due to design or manufacturer. Capacity performance is composed of field speed and geometric size variables. Of the two, field speed is the more nearly constant. Field machine travel should be as rapid as conditions will allow. Any lesser speed is uneconomic. While there is some evidence that larger machines are operated at slower speeds, this analysis assumes no interaction between speed and the size of machine.

Size of a field machine is most closely related to its effective width of action. This relationship is readily accepted for tillage implements and seeders. Harvesting and field processing machines are more commonly rated

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as to the throughput in weight or quantity per hour. Yet, for a specific farm having approximately constant yields during the life time of a machine, even harvesters can be rated on an effective width-of-action basis. A row crop harvester's width of action will depend on the row spacing. A baler's effective width will depend on the width of the windrow.

Machine capacity also depends on field efficiency, that percentage of the total time the machine is actually performing its intended function. Field efficiency does depend on the geometric size of a machine, but the numerical variation is not great.

Machine capacity can be described as in Equation 1.

$$C = \frac{S\,W\,e}{8.25} \qquad (1)$$

where
C is the field capacity in acres per hour
S is the field speed in miles per hour
W is the effective width of the implement in feet
e is the field efficiency expressed as a decimal

In the interests of simplification this analysis assumes that all the factors in Equation 1 are known constants except the effective width, W.

Selection of an appropriate machinery system may be stated simply as the process of determining those individual machine capacities (expressed as feet of effective width) which will optimize the economic performance of the whole system. Consideration must be given to machine costs, power costs, operational costs, and to the alternative of contracting the work.

An appropriate cost-of-operation model is essential to the validity of the selection problem analysis. This analysis uses a simple fixed-variable cost concept which groups depreciation, interest on investment, tax, insurance, and shelter costs into an annual fixed cost charge. The quotient obtained by dividing the annual fixed cost charge by the machine's original purchase price is called the fixed cost percentage. This percentage is considered invariable over the life of the machine and is input to the analysis as a constant. The assumption of straight-line depreciation is thought not to be greatly in error. Table 1 lists values of the fixed cost percentages appropriate for various service lives. A salvage value of 10% of the purchase price is assumed.

TABLE 1

Service Life, years	*Value of FC%*
1	96
2	51
3	36
4	29
5	24
6	21
7	19
8	17
9	16
10	15
11	14
12	13
15	12
20	10

The variable costs add to the fixed costs to complete the cost model. The variable costs are composed of the hourly rates for repair and maintenance, labour, oil, fuel, and tractor use multiplied by the hours of use per year as shown in Equation 2.

$$AC = FC\%\,P + \frac{A}{C}(RMP + L + O + F + T) \qquad (2)$$

where:
AC is the annual cost for an individual machine's operation
FC% is the fixed cost percentage expressed as a decimal
P is the new purchase price
A is the annual acreage of machine operation
C is the capacity of the machine in acres per hour
RMP is the repair and maintenance cost per hour
L is the labour cost per hour
O is the engine oil use costs per hour
F is the fuel use costs per hour
T is the hourly charge for the tractor fixed costs
(T=0 for self-propelled implements)

Hourly charges for labour, oil, fuel, and tractor use are commonly accepted; but, hourly charges for repair and maintenance is not so common. Maintenance is commonly performed on a time interval, but the occurrence of repair tends to be highly erratic. Repair costs resulting from accidents are unpredictable of course. Their cost should be handled as an insurance premium. But repair resulting from wear is normal and can be assumed to be directly proportional to the machine's use. The procedure used is to express the hourly repair and maintenance costs as a percentage of the original purchase price of the machine. This charge is assumed to be constant throughout the life of the machine.

Missing from Equation 2 is the cost of untimely operations. While this item is not an out-of-pocket cost, it is truly a cost as it signifies a reduction in income. This analysis suggests that the cost of untimely operations can be included in the basic cost model as a cost for each hour the machine is used. Several field operations were examined for their effectiveness as related to time. Figure 1

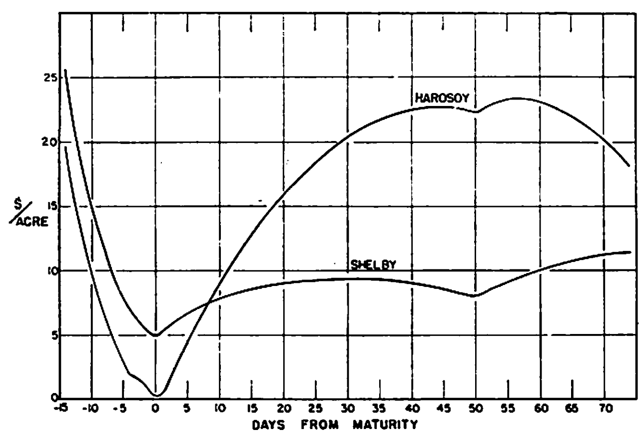

Fig. 1

Reduction in Income Associated with Untimely Harvesting of Two Varieties of Soyabeans

relates the reduction in yield and quality of two varieties of soyabeans to time of harvest. It is apparent that the optimum time for harvesting is of very short duration. Any extended harvest period will cause considerable reduction in income. Examination of the literature indicates there are similar relations for most all farm operations. In most cases the relation follows the simple linear relation shown in Figure 2. The slopes of the lines

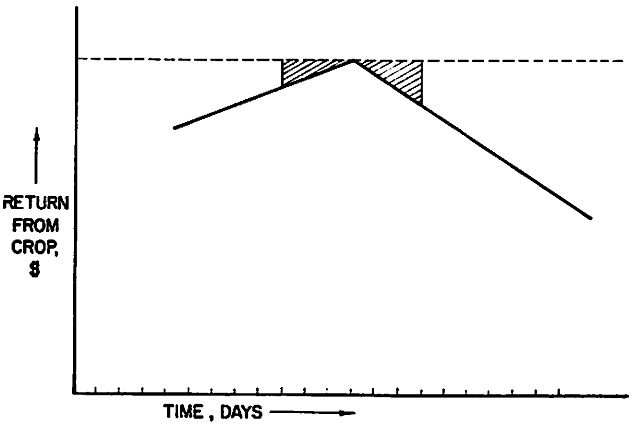

Fig. 2

Assumed Linear Relation between the return from the crop and the passage of time for any field machine operation.

suggest the economic penalty suffered during the passing of time. The absolute cost depends on the value of the crop, therefore, a relative timeliness factor called K was developed to give some generality to the analysis. It is suggested that the values in Table 2 are conservative timeliness factors applied to midwestern USA conditions.

TABLE 2

Operation	*K Value*
Tillage	.00005 to .0003
Seeding	.0003
Cultivation	.0002
Small grain harvest	.0002
Soyabean harvest	.0005
Corn harvest	.0003
Hay harvest	.0010
Green forage harvest	.0001

K is defined as the decimal reduction of the quantity and quality of the potential crop per hour of machine operation. Computation of the hourly cost due to timeliness involves multiplication of the K factor by the acreage, yield, and unit value of the crop under consideration.

Selection of an optimum system is initiated by the selection of the size of the machine which minimizes the annual costs where timeliness is included as a variable cost. A very acceptable method for minimizing the annual costs is to write the cost model in terms of the machine-size parameter (effective width), set the first derivative with respect to width equal to zero, and then solve for that width which is an optimum width for the machine in that circumstance. To do so requires that each term in the cost model be examined for its dependence upon the effective width of the machine.

$$(3)\ AC = FC\%pW + \frac{8.25A}{SWe}(rmpW + L + oW + fW + T + KAYV)$$

where:

- p is the purchase price per foot of effective width of the implement
- rm is the repair and mainteanance costs, decimal of purchase price per hour per foot
- o is the oil costs per hour per foot
- f is the fuel costs per hour per foot

Equation 3 is written with the dependence of the various terms on implement width, w,indicated.Obviously the purchase price, field capacity, and fuel consumption are direct functions of the width or size of the machine. Oil use by an engine is not so dependent but large engines require more oil per change than do smaller engines and such a demand may be related to implement size. Oil costs are very minor in the whole problem anyway.

The repair costs have been assumed to be a constant related to the purchase price of the machine and as such are related in some unspecified manner to the effective width of the machine.

The plots of Equation 3 in Figure 3 illustrate the variation in annual costs as the size of an implement varies for various acreages, A, and various purchase prices per foot, p. The optimum size or lowest point on any one curve is obtained by the differentiation of Equation 3. That width where costs are lowest is expressed by Equation 4.

$$(4)\quad W = \sqrt{\frac{8.25\ A}{FC\%\ p\ S\ e}(L + T + KAYV)}$$

Note that repairs, fuel and oil have dropped from consideration. Only labour, tractor fixed costs, and timeliness costs remain in the equation.

Equation 4 may be used without reservation for self-propelled implements and for selection of implements to fit into an existing machinery system where the tractor fixed costs, T, are known and are constant. But in many machine selections the tractor fixed cost charges are not unrelated to implement sizes, especially so if one is considering high power requirement operations such as plowing or forage harvesting. In fact, the optimum implement width may be more dependent upon the size of tractor than upon any of the other factors in Equation 4. Simply, Equation 4 is not adequate by itself to select a system of tractor powered machines because the value of T, the tractor fixed costs per hour, is not defined.

Selection of an economic *system* of machines is highly dependent upon the horsepower level of the tractor or

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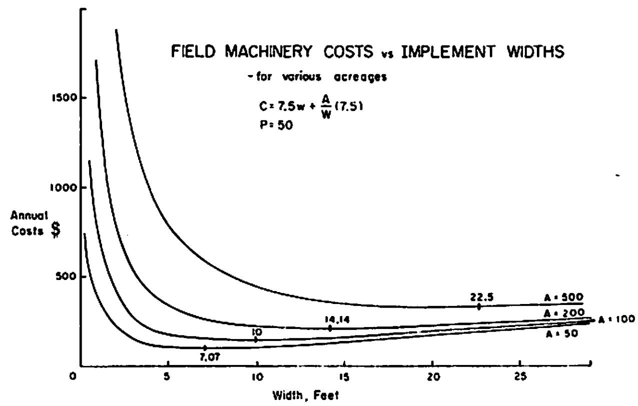

Fig. 3 (Part I)

Machinery cost variations with effective widths as functions of annual acreages and purchase prices

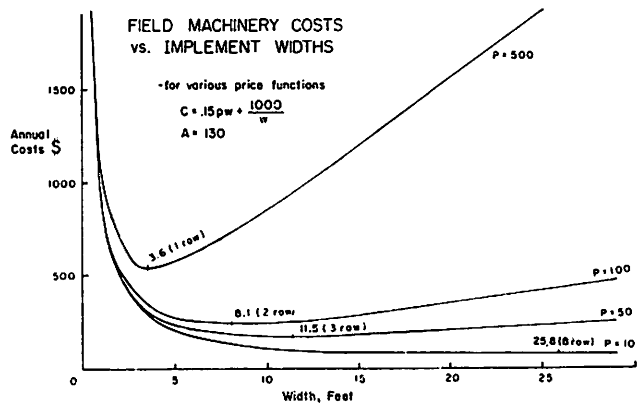

Fig. 3 (Part II)

tractors. The presentations in Figure 4 indicate the existence of an optimum horsepower level. The curves were obtained by plotting points of an equation for the cost-of-use of power (See Reference 1) considering only tractor fixed costs, operating costs, and timeliness for given circumstances. As with the analysis of implements, differentiation can define a least-cost power level. But the least-cost point for power does not guarantee optimum system costs since the costs of the equipment to utilize the power have been neglected.

The optimum system selection procedure, therefore, has to include the economic effects of horsepower level, implement capacity, operating costs, and timeliness. These relations are discontinuous mathematically, are not expressed adequately with partial differentials, and include extensive summations of energy requirements in the computations required for horsepower. A simple, useable mathematical analysis is thus impossible.

A trial-and-error method which utilizes the speed of a digital computer was selected as being a feasible, practical procedure for solution. The logic of the programme is as follows:

1. Estimate a horsepower level and establish a value for the tractor fixed costs, T.
2. Select optimum widths for all the implements in the system, carefully observing constraints on power, physical size, number of tractors used, etc.
3. Compute annual costs for the system of machines at this horsepower level, replacing those machines in the system with contract work should their annual operation costs exceed contractor's rates.
4. Re-solve at 8 other horsepower levels which establish a range of horsepower levels about the initial level.
5. Select and print out the results for the horsepower level and machinery system that has the lowest cost.

Skill in selecting the horsepower level for the initial trial is not necessary, although reasonable approximation of the eventual answer will save computer time. The interval between the various horsepower levels computed can be selected to be as small as desired; however, inter-

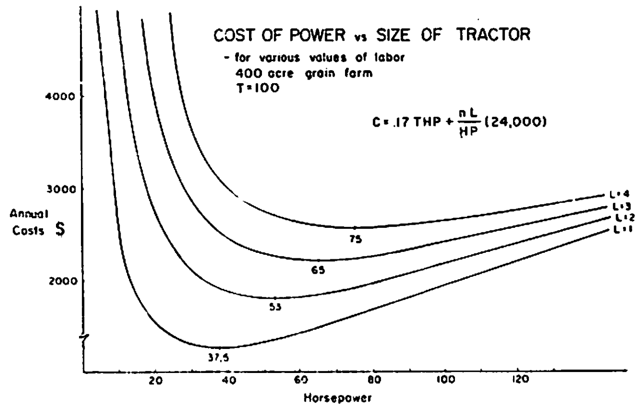

Fig. 4 (Part I)

Power Cost Variations at different horsepower levels for various labour costs and tractor purchase prices

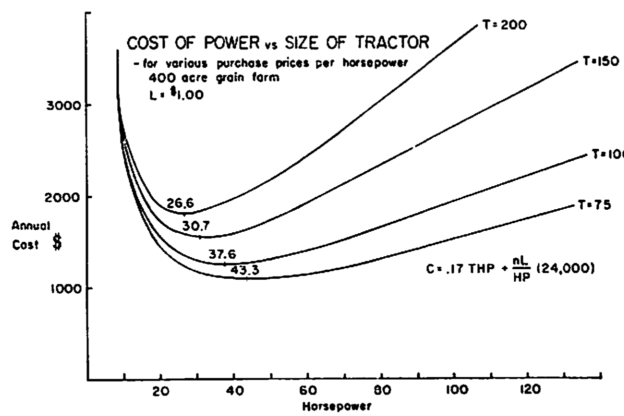

Fig. 4 (Part II)

vals of less than 5 horse-power are probably meaningless. Intervals as large as 50 horsepower may be appropriate for large farms having thousands of acres.

A description of the computer programme is intricate and filled with minute rules which require considerable explanation. The details of the FORTRAN programme will not be described in this paper but may be obtained by writing to the author. The requirements for input data are discussed in Reference 2. An examination of this list will indicate the amount of data required and will point out the voids that exist today in the data needed for making a machinery system selection.

The lack of timeliness cost data has already been mentioned but other data relating to the on-farm operation of equipment need to be developed. A range is known in the drawbar draft and p.t.o. data for many field operations. But for machinery selection problems such data is only indicative of true energy requirements. Costs of operation must include the additional energy required to overcome rolling resistance and other satellite and accessory energy requirements. This data should be reported on a pounds-per-foot of effective width of implement. The use of the tractor for non-field operations must also be taken into account and the energy requirements for these operations must be known.

Even after years of operating farm equipment, farmers are usually unable to produce reliable data on the economics of operating machinery. Machine service life and machine repair costs need to be estimated quite factually for this selection procedure to be valid. Implement purchase prices per foot of effective width are difficult to obtain and as the relation is not exactly linear, difficult to use. A definite replacement policy is also needed as an input to the problem.

Fuel consumption data is not required. The programme considers the use of any of three fuels (gasoline, diesel, LP gas). Typical tractor fuel efficiencies were determined for all degrees of tractor loading. These efficiencies are applied conservatively to the rate-of-energy use to arrive at a gallon-per-hour consumption figure.

The actual input data is punched onto cards which comprise the data deck that accompanies the FORTRAN programme deck. A farm operation having 10 field operations would require 30 cards to describe the field operations, two cards to input the system constants, and an additional card to describe each processing and transport operation performed by tractors. The arrangement of the cards in the data deck is critical and must follow precise rules.

The computer output from the typical problem is shown in Figure 5. The annual costs for the system at various horsepower levels are clearly indicated with the first trial selected as the least-cost system. The implements are coded with a numeral and their optimum sizes and other data are listed. The field operations are similarly coded and the cost of each operation, whether it was contracted (custom) or a part of the system, is reported.

The existence of a computerized selection programme permits analyses of farm machinery systems that were previously too time consuming to consider. Figure 6 shows the effect of scale of farming on machinery systems

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IMPLEMENT SIZES, POWER LEVEL, AND OPERATION COSTS FOR THE LEAST COST SYSTEM
K=1, TOTAL ANNUAL OPERATION COSTS ARE $8111.97, OPTIMUM POWER LEVEL IS 70, TOTAL TRACTORS=1

Implement No.	*Optimum Size*	*No. Required*	*Range Permitted*	*Self-Propelled Power Level*	*Auxeng Power Level*	*Purchase Price*
1	13.5	1	10.2—13.5	.0	.0	942.31
2	6.9	1	5.6— 6.9	.0	.0	1389.71
3	26.7	1	21.4—33.4	.0	.0	1335.00
4	.0	0	—.1— .2	51.2	.0	.00
5	13.5	1	10.7—13.5	.0	.0	740.38
6	27.6	1	22.1—34.6	.0	4.9	829.24
7	7.3	1	6.3— 8.4	51.2	.0	3659.44

Investment Including Tractors=$13796.08

Operation Number	*Cost of Operation*	*Custom Cost*	*Combination W*	*No. of Comb. Imps.*	*Annual Hours Reqd.*
1	165.71	.00	.0	0	19.9
2	393.69	.00	.0	0	52.6
3	464.09	.00	.0	0	52.6
4	496.28	.00	.0	0	32.4
5	253.48	.00	.0	0	27.5
6	2532.31	1869.00	.0	0	.0
7	139.12	.00	.0	0	19.9
8	469.00	.00	.0	0	48.7
9	137.78	.00	.0	0	18.1
10	254.14	.00	.0	0	20.4
11	401.13	.00	.0	0	24.4
12	461.93	.00	.0	0	33.1
13	1065.83	.00	.0	0	57.1
14	877.48	.00	13.5	1	51.9
15	.00	.00	13.5	1	—.0

System Hours=458.8

Fig. 5

Computer Print-out of the Solution

A SYSTEMS APPROACH TO FARM MACHINERY SELECTION—*from previous page*

costs. A standard farm operation was specified and the acreages and timeliness factors were varied in proportion to permit comparison of optimum system power levels with size of farm. The maximum row crop tractor size available was assumed to be 100 horsepower. The selection programme was solved repeatedly at 10 horsepower intervals to define the curves presented.

Optimum power levels are distinctly indicated and are economically significant. In some cases the optimum may be double-valued as for the 800 acre curve in Figure 6—both 100 horsepower and 150 horsepower are equally low cost in this instance. Note that the curves are discontinuous; that is, there are sudden changes in cost as it becomes necessary to add an additional tractor unit and tractor driver to the system. The 200 and 400 acre curves are shown as constant, heavy dotted lines at the higher horsepower levels. At these levels, none of the field

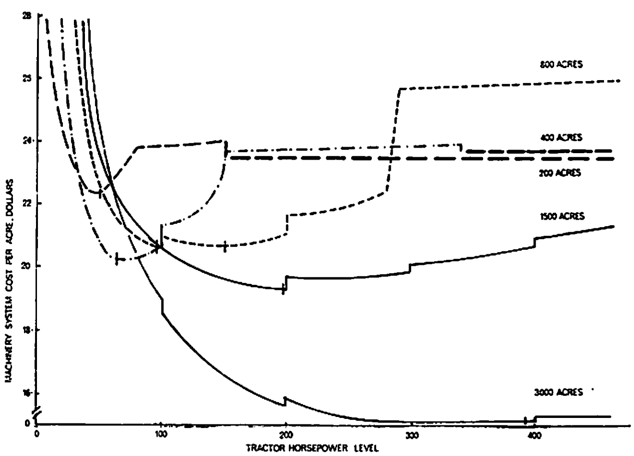

Fig. 6

Machinery system costs for a 2/3-1/3 acreage ratio of corn to soyabeans

operations were cheaper than a contractor's rate and the dotted lines indicate the resulting costs when all operations were contracted. The monetary penalty for untimely operations (considering timeliness costs) is greater for large farms, thus it costs more per acre to have a large farm's operations contracted than for a small farm.

As might have been anticipated, the larger the farm the less the system costs. (One might speculate about the existence of a point of diminishing returns in this respect). In most all instances the penalty for a given amount of underpowering is greater than for the same amount of overpowering. The apparent small variation in costs of high horsepower levels for the 3000 acre farm may be somewhat misleading because the costs are recorded on a per-acre basis. Annual cost differences of course would be the cost differential multiplied by 3000. This total would probably be significant to the farm manager.

This machinery selection programme has been used on many real farms. It often indicates that an existing, real life farm machinery system has too much tractor power. The validity of the conclusion, of course, depends upon the accuracy of the input data. Nevertheless, many farm managers have reached this same conclusion about American farm machinery systems. Most farmers respond that their excess power represents insurance against breakdown, labour shortage, and bad weather.

The evaluation of an appropriate risk factor for farmers to assume is probably crucial to the selection problem. Risk is a factor that is difficult to include in the selection programme. In its timeliness considerations the programme recognizes a need for greater power and capacity than would be indicated by simple economics, yet, farmers are apparently buying even more power and capacity than timeliness requires. It may be that our American farmers seek to avoid *any* chance of loss due to machinery failure or inadequate capacity. The price of a second or a third tractor is very reasonable if it is a few years old and doesn't have the power or the many comfort and convenience factors of the later models. Equipment to match these partially obsolete tractors is also very reasonable in price. Having duplication for many of the elements of the machinery system not only gives backup insurance in case of machinery failure, but it also creates a reserve pool from which additional operational capacity may be obtained in the event of limited field time due to bad weather. The costs of truly avoiding all risks must surely be prohibitive. Perhaps more knowledge about the economic aspects of timeliness will reveal a point where the risk of untimeliness should be assumed by commercial companies instead of by the machinery system. This judgement, as of now, will have to be made qualitatively by a farm manager after he has the results from the machinery selection programme.

In summary, the selection of an optimum farm machinery system is complex and cannot be described with simple mathematics. The validity of the system analysis inescapably depends on accurate estimations of future costs. A digital computer programme can use high-speed, trial-and-see methods to evaluate the economy of a machinery system. In addition to specific answers to specific problems, the computer analyses may be used to examine the interrelations in the machinery system itself. Comparisons of the computed optimum machinery system with actual farms indicate that the American farmer is overpowered. The degree and the manner in which the farm manager accepts the risk of under-capacity is a modifying factor in the selection of an optimum machinery system.

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THE SYSTEMS APPROACH TO ENGINEERING DESIGN

by

J. R. O'CALLAGHAN, PH D, MSC, FI AGR E*

Presented at the Autumn Open Meeting of the Institution on 26 *September* 1968 *at University of Reading*

Engineering design is one of the main links between engineering science and manufacturing processes. Design is concerned with both problems of synthesis and analysis whereas engineering science is mainly concerned with analysis. In addition to an understanding of the methods of engineering analysis, the designer is expected to have a capacity for invention and to be able to take decisions about his design which are largely of an economic or social nature.

In engineering analysis the objective of the analysis is closely defined and the problem very often has a unique answer. In problems of design the objective function is usually not so closely defined and it is hedged round with constraints. The engineering designer needs help in compiling the large and growing amount of information which is relevant to his design and in devising a structure in which new information can be incorporated in order to up-date continuously a chosen design. He must also take account of the business aspects of a project at the design stage. The designer needs to be relieved of calculation which can be mechanized so that he can devote more attention to the inventive part of the design. He needs a decision structure in which engineering, economic and other quantitative information about the design can be combined.

The systems approach uses as the design criterion the satisfactory operation of the total engineering project rather than the independent consideration of the efficiency of the component parts of the system. The attention of the designer is directed to the complete project and he is provided with a framework for examining it. Such an approach is complimentary to that of engineering analysis which directs the designer's attention towards a consideration of the component parts.

The need for a systems approach to design has arisen in handling complex design problems in defence, space and transportation. Such problems require a range of detailed knowledge which can only be provided by a team of specialists and the need for a general framework arises. In a simple project a single designer can grasp all the main points and guide the project, possibly at the risk of oversimplification. Even a simple design project becomes complicated if account is taken of the large amount of technological information which is available about

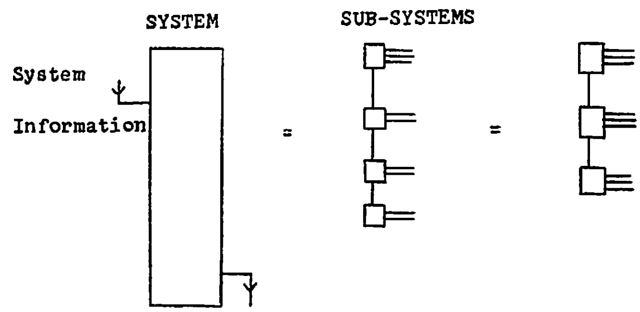

Fig. 1

materials and production methods, about operating performance and about marketing and economic conditions.

A large part of any design project is information processing—*data acquisition* in which specifications are formed;

data manipulation and decision-making in which alternative approaches are identified and evaluated and the optimum chosen. At this stage the behaviour of the system for various levels of input parameters can be examined;

data display so that the system can be built, tested and up-dated.

Design carried out in this way depends not only on the traditional combination of invention and engineering but also draws on the methods of operations research, mathematical programming, computer technology, decision theory and stochastic processes.

Data Acquisition

Many design problems are, in the first instance, only vaguely stated both in regard to the form of the machine which is to be produced and in regard to its relationship to the larger system of which it forms a part. The specification for the machine is usually evolved by the designer's consideration of the larger system of which his machine is to form a part, for example, the torque, power and cooling characteristics of a diesel engine are fixed by the system in which the engine is to be used. In framing a specification we have to identify the total system of which our machine is to be a part and we must also find the

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essential stream of information which flows through the whole system because these are the data about which the design must be organized. The methods of systems analysis can be used to find the most advantageous values of these data for the total system.

The most commonly used method of attack by designers on a large problem is to break the problem down into a number of sub-problems which are solved separately. A similar approach can be used within a systems framework.

At this stage it is necessary to have a structure that challenges the designer to investigate as many alternative solutions as possible.

The first stage of data collection consists of identification of the system of which the proposed machine is to be a part. The system is then decomposed into sub-systems for which alternative solutions are proposed and evaluated. Design in this phase consists of a succession of syntheses and analyses which are solutions to the system requirements. The performances of promising solutions are evaluated. Many of the proposals can be eliminated by inspection for there is no point in spending time on detailed analyses of sub-systems which can be seen by inspection to be inferior to others.

Sub-system	*Alternatives*
Cutting	Reciprocating mower, flail mower, horizontal rotary mower, cylinder, without cutter-blower.
Power	Tractor p.t.o., engine self-propelled
Rate	0 .. .. ∞
Field drying	Tedder, crimper, flail, thermal
Rate	0 .. .. ∞
Field Collection	Baler, field stacker, pick-up-pneumatic, pick-up-mechanical
Weight	0 .. .. ∞
Transport	Tractor-buck rake, tractor-trailer, truck
Distance	0 .. .. ∞
Unloading	Dump, controlled unloading
Time	0 .. .. ∞
Filling	Tractor-buck rake, tractor loader, pneumatic, mechanical
Processing	None addition of chemicals drying-wafering
Time	0 .. .. ∞
Storage	Dutch barn, bunker silo, tower silo
Capacity	0 .. .. ∞
Unloading	Manual, mechanical, animal
Rate	0 .. .. ∞
Transport	Manual, tractor, mechanical, pneumatic
Distance	0 .. .. ∞
Feeding	Self, blending, mechanical, pneumatic, manual
Rate	0 .. .. ∞

Fig. 2

Grass Harvesting Process

As an example I should like to consider the design of a grass-cutting machine. In the first stage it is necessary to imbed this problem in the total system of grass harvesting as shown in Fig. 2, where the grass cutting process is placed alongside the other sub-systems.

The purpose of a grass harvesting system is the production of nutrients either for direct sale from the farm or for feeding livestock and eventual sale of livestock products. It is possible to optimize the whole system to produce energy at minimum cost and satisfy constraints of moisture and protein content which are set by the livestock requirements. Such an analysis (Appendix 1) gives the amounts of fertilizer to be applied, the number of cuttings which are necessary and the grass yield per cutting. In this way the flow rate of grass through the grass harvesting system of Fig. 2 may be specified. The flow rate is the essential stream of information which runs through the whole system and about which the design of each of the sub-systems must be organized.

Data Manipulation and Decision Making
Design of System

At this stage the main problem of the design has been specified and placed in perspective with respect to the total system of which it must be a compatible part. As many alternative approaches as possible should be set up and the more promising ones evaluated in regard to the objective of the total harvesting system which in this case is the production of energy at minimum cost.

Inspection of Fig. 2 shows that there are several arrangements of the sub-systems, some of which are already in common use, e.g.

(i) cut-pneumatic load-trailer transport—dump—tractor—buck-rake fill—bunker silo—self-feed.
(ii) cut—field dry—bale—stack—mechanical pick-up, trailer transport—mechanical unload and stack in dutch barn, manual unload—transport—manual feed.
(iii) cut—field dry—mechanical pick-up—pneumatic load—tractor trailer transport—controlled unloading, pneumatic filling—tower silo—mechanical unloading, blending—mechanical feeding.
(iv) cut—pneumatic load—trailer transport—dump—tractor—buck-rake fill—drying—wafering—tower silo—mechanical unloading—mechanical feeding.

Looking more closely at the cutting sub-system it is necessary to establish if there is any interaction between the method of cutting and the other sub-systems. In the case of field drying, the rate of drying is influenced by the chop length, the degree of laceration and the formation of the swath. Some unloading mechanisms for silos and grass driers require that the grass should be chopped into short lengths.

We should examine in quantitative terms the most promising systems to see which combination will give the best solution to the overall objective of the harvesting system which is the production of energy at the lowest cost. The behaviour of each sub-system may be described approximately by its design equations, by performance figures and by economic assessments. At the present time there are large gaps in the data, largely because we have not called for them in this form. In these cases rough approximations may be used in a first try and they can be refined as further data become available. One valuable contribution of the systems approach to design is that it provides a framework in which the findings of research can be organized in a form which makes the results readily available to designers.

Suppose that evaluation of the different systems suggests that the most promising of the solutions proposed for the cutting sub-system is a self-propelled flail mower with a cutter-blower which is capable of handling 30,000 kg grass per hour.

Design of Machines

The design of a machine may be considered to take place in two stages. In the first stage alternative solutions are proposed and evaluated in the same way as were sub-systems in Fig. 2. In the second stage the most promising designs are optimized, usually using an economic criterion, either lowest capital cost or lowest operating cost.

When the outline form of a machine has been selected by the designer, the problem becomes one of finding the best way of using the different sets of components which are available to him. In many designs, the problem of designing a complete machine is broken down into the design of a number of separate elements. However some decisions taken at one stage of the design are reflected through the whole machine, e.g. in the grass-cutter selecting the width of the machine influences the number of flails, the design of chassis, the forward speed (and gearbox design), the drive to the flails, etc. In simple machines it is possible to test the sensitivity of the design to changes in the leading dimensions. In addition to the interaction of the dimensions of different parts of the machine on one another, there is the questions of their influence on the costs of the components. Exact costs are almost impossible to fix at the design stage but because the economics of a design are so important an attempt must be made to incorporate an estimate of costs as early as possible in the design. In the case of standard items it is possible to produce correlations between size and price for many of them; for non-standard assemblies approximate prices should be found. Obviously the qualityof the decision will reflect the quality of the data. Although at the design stage cost data are normally imprecise a systems approach allows the design to be recalculated easily with more reliable data as soon as it is available. During manufacture the costs of components usually change more than the properties of the materials which is another reason for a design system that can be easily up-dated.

The detail design problem may be regarded as the optimization of one particular factor, the objective function, which should attain the best possible value. In most cases the objective function is a cost, either lowest first cost or the lowest cost per unit of work. The objective function F depends on a number of control variables $x_1\ x_2 \ldots x_n$, for which values must be selected by the designer.

$$F=f\,(x_1, x_2, x_3 \ldots x_n)$$

There are also a number of secondary requirements, e.g. that the weight does not exceed a certain value, that the overall dimensions are within certain limits or that the power requirements do not exceed some value. These secondary requirements may be designated restraint functions $R_1, R_2 \ldots R_K$

where $R_i=f_i\,(x_1, x_2 \ldots x_n)$

In the design of the grass cutting machine, the principal components to be evaluated are the flail type cutter, screw conveyor, cutter-blower, transmission and engine.

Some of the variables which can be selected by the designer and which influence the whole of the design are: width of cut, forward speed, speed of flails, diameter of flails, number of flails, speed and diameter of conveyor, speed, diameter, width and number of knives for the cutter-blower. Then power consumption influences the selection of engine and transmission and their costs.

A flow diagram for the design is shown in Fig. 3. It shows the combination of the two stages of the design. In the first stage the design equations are set in order to give the dimensions of the different components. In the second stage the costs of these components are entered. The design is improved until the lowest cost machine to cut 30,000 kg grass per hour is selected using the data which are provided for the design.

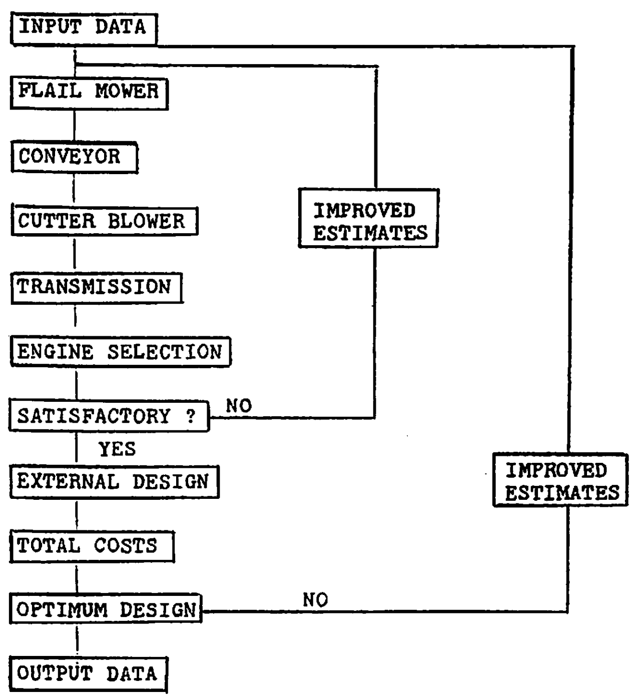

Fig. 3

Flow Diagram for Design

In specifying the general layout of the machine, the designer in effect is simplifying to a very large extent the problem he presents for optimization, He is using his

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skill and design experience to select for the computer the arrangement which he feels is worth calculating and costing in detail. He is leaving to the computer the calculations and manipulation of data.

Data Display

Data can be presented either as a print out or a drawing or in certain cases even as a tape for a numerically controlled machine tool. In the course of a design study several assumptions have to be made in regard to data. As the machine goes into production more reliable cost figures become available. During testing and servicing actual performance is measured. When a systems approach is used, it is possible to incorporate these results and examine the effect of them on the whole design.

Optimization Techniques

The classical method of locating the extreme value of a function is by using calculus. However it is of very limited value in design problems because it is only applicable to functions which are continuous and differentiable.

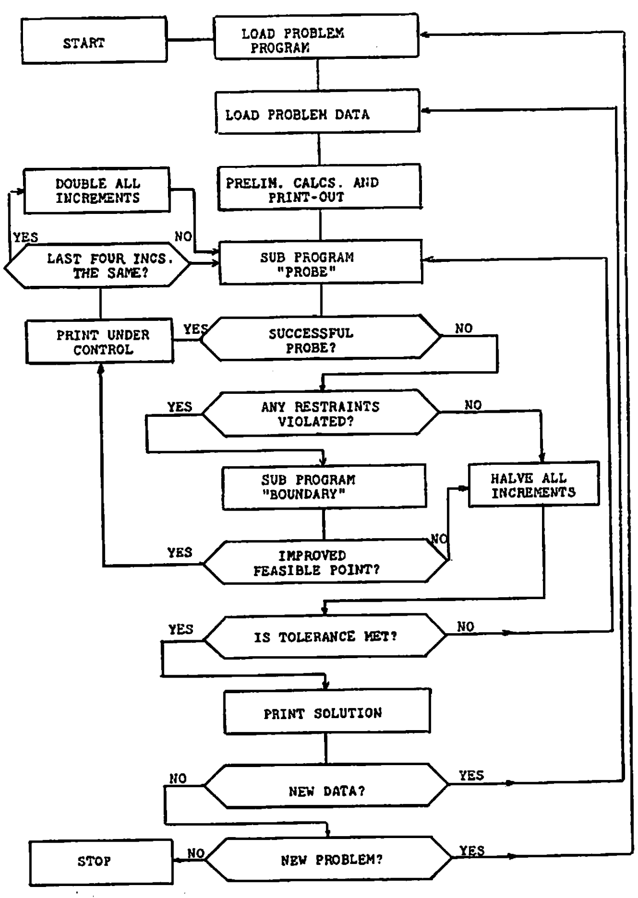

Fig. 4

The Optimizer Programme

Direct search methods are practical for problems in which the number of degrees of freedom is small. A direct search method, shown in Fig. 4, was used to optimise the design of the transformer described in Appendix 2. An existing design was used as a starting point and excursions made from this point until another point was found where the objective function was better. This new point then became a new base for further probing. Such search methods make no assumptions regarding the linearity of functions nor that they can be differentiated. The amount of computation which is required in search methods increases rapidly as the number of design variables increases.

Linear Programming is the most highly developed method of optimization which can handle several thousand variables. It is restricted to systems which may be described by linear relationships. However, non-linear relationships may be approximated by combinations of linear segments.

Dynamic Programming is a method whereby a large multi-stage optimization problem can be broken down into a sequence of simpler sub-optimization problems. The technique relies upon decision-making at each stage rather than trying to solve the complete problem simultaneously. The decision-making in a sub-optimization problem may be either by the technique of direct search or linear programming. Dynamic programming has been used by Porter[1] for the synthesis of optimal dynamical systems.

APPENDIX I

Linear Programming Model of Grass Production

The yield of grass during the cutting season which is very dependent on nitrogen application varies in the way shown in Fig. 5[2]. The cutting sequences can be specified by dividing the growing season into a sequence of time periods.

Time period	N—1		N		N+1		N+2		
	G_1	G_2	G_1	G_2	G_1	G_2	G_1	G_2	
	1	1	–1			–1			= 0
			1	1	–1			–1	= 0

These equations state that the total acreage used to produce grass of any maturity in the first period may be used to produce grass of one time period maturity in the next period (N) or grass of two periods maturity in the second next period (N+1). By continuing the equations throughout the season we ensure that the acreage allocated by the model at the start of the season is retained for grass production. If more than one form of utilization is intended, e.g. grazing and silage production, then separate variables must be employed. Associated with each of these acreage variable are nitrogen variables which represent the amount of nitrogen applied to each cut the programme selects.

The next series of equations in the model introduces the restraints imposed by the resources of the system, e.g. in grass drying, production is restricted by the drying

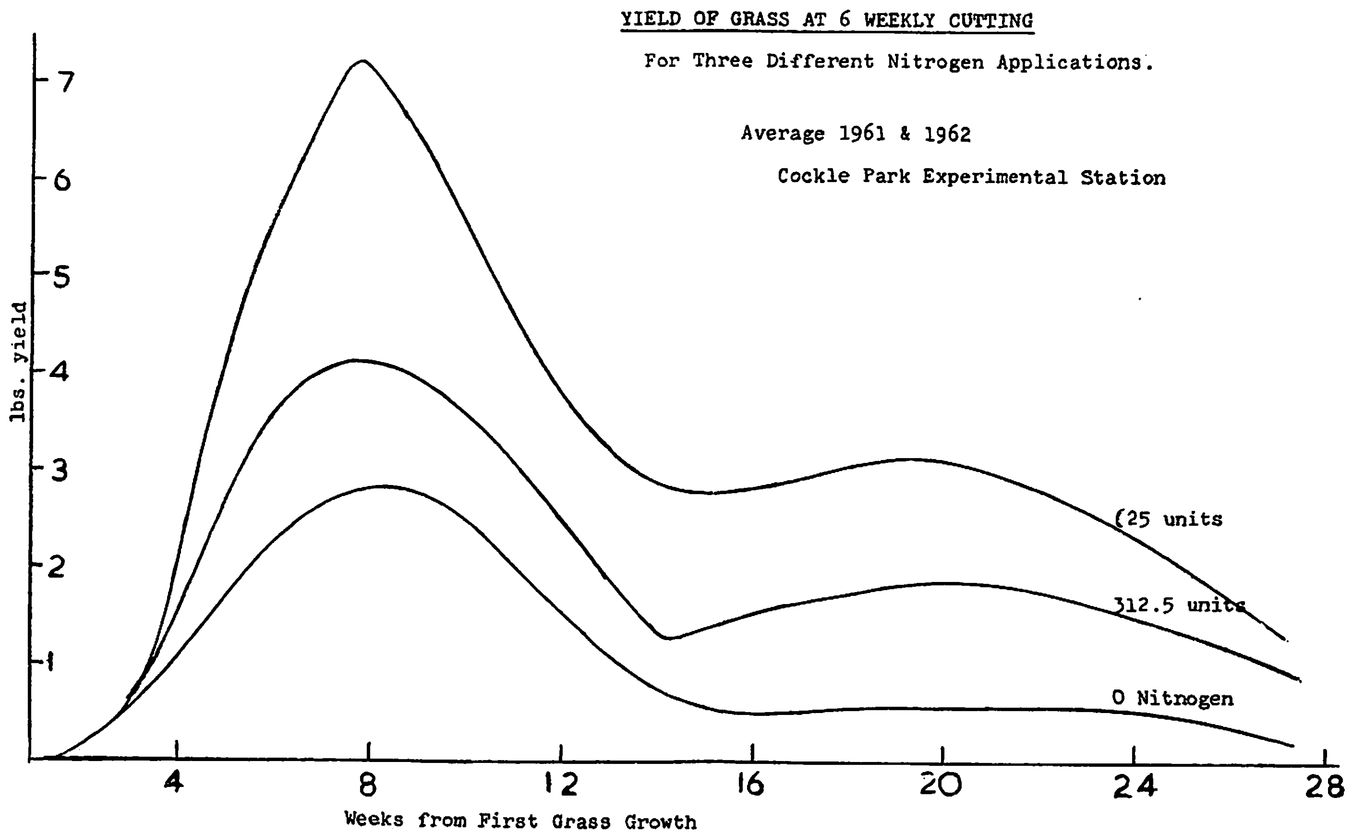

Fig. 5

capacity and field machinery capacity, e.g.

$$\begin{matrix}\text{(acres } G_1 \text{ grown)} \\ \text{(in period N)}\end{matrix}\left[\begin{matrix}\text{(yield/acre x)} \\ \text{(drying rate)}\end{matrix} + \begin{matrix}\text{(yield/unit N)} \\ \text{(x drying rate)}\end{matrix}\ \text{Units N}\right] \ldots$$

$$\ldots \begin{matrix}\text{(acres } G_2 \text{ grown)} \\ \text{(in period N)}\end{matrix} \leq \begin{matrix}\text{Available} \\ \text{drying capacity}\end{matrix}$$

A similar set of equations represents field machinery.

It is possible to link the grass production variables to the consumption variables by the equation Grass Production Variables—grass consumption variable=0 (Nutrient yields)—(amount fed+amounts sold)=0

The model may be further extended to consider the livestock production variables.

In the model the equations describe the resources and the inequalities describe the restraints of the system. The objective function, which is a profit equation, is optimized using a linear programming technique.

APPENDIX II

Design of core and windings for electric transformer.)[3]
Rating of transformer: 400 kVA, 3 phase.
Voltages: 10 kV/394
Objective function=cost of iron+cost of copper+capitalization charges on iron and copper losses.
Control variables.

x_1	half number of high-voltage layers	
x_2	overall diameter of high voltage coil	(m)
x_3	copper diameter of high voltage coil	(m)
x_4	core cylinder diameter	(m)
x_5	core window height	(m)
x_6	yoke depth	(m)
x_7	major core dimension	(m)
x_8	flux density	(webers/m²)
x_9	half number of low voltage layers	
x_{10}	radial depth of low-voltage conductor (m)	Cross-section of rectangular Conductor
x_{11}	axial depth of low-voltage conductor (m)	

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x_{12}	radial depth of low-voltage coil	(m)
x_{13}	axial depth of low-voltage coil	(m)
x_{14}	number of high-voltage turns	
x_{15}	number of low-voltage turns	

Restraint Functions

iron losses	960 W
copper losses	5,000 W
percentage reactance	4%

DATA

Two sets of data are required during the programme.

(i) Constants required by the problem programme, e.g. cost of copper (shillings/kg), cost of iron (shillings/kg) primary and secondary voltages, percentage maximum tapping, capitalization charges for copper and iron losses (shillings/kw).

(ii) Data for the optimizer programme, namely number of variables, restraints, printing frequency, initial values of the variables, upper and lower bounds of the variables, initial increment size for each variable, tolerance on increment sizes.

The programme accomplished an optimization by changing three of the variables (x_2, x_6, x_{13}) in the existing design which was used as a starting point for the programme. These changes produce a reduction of 9% in the cost of the winding and core.

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2. Morris, D. W. PH.D. Thesis 'Environmental factors affecting grassland production'. 1963.
3. O'Callaghan, J. R. & McCarthy, T. T. 'Devising a Decision Structure for Design Problems'. *The Engineer*, 289-91, August 23, 1968. 'Reproduced from *The Engineer* by permission of the Editor'.

ELECTIONS AND TRANSFERS (*continued from page 11*)

Graduate

.. .. ..	Mann, R. E.	Essex
.. .. ..	McKee, F. A.	Lancs
.. .. ..	Howard, P. W. J.	London
.. .. ..	Froud, R. J.	Lincoln
.. .. ..	Goord, R. B...	Kent
.. .. ..	Godbold, M...	Suffolk
.. .. ..	Barber, A.	Hants

FORTHCOMING EVENTS

NIAE OPEN DAYS 1969

7-8 May 1969

Wrest Park, Silsoe, Bedford

For details see 'Newsdesk' on page 9.

Further information available from

The Information Department,
National Institute of Agricultural Engineering,
Wrest Park, Silsoe, Beds.
Telephone: Silsoe 421, Extension 13

8TH INTERNATIONAL COURSE ON LAND DRAINAGE

1 September-12 December 1969

Wageningen, The Netherlands

The course aims at offering all those who, in the performance of their duties are dealing with drainage systems, a thorough picture of the relevant problems within a period of three months. The course serves the needs of engineers, agricultural hydrologists, drainage and irrigation agronomists, involved in investigations, planning and design of drainage systems.
Fur further details apply to:

The Director,
International Agricultural Centre,
P.O. Box 88,
Wageningen, The Netherlands

CIGR VIITH INTERNATIONAL CONGRESS OF AGRICULTURAL ENGINEERING

6-11 October 1969

Baden-Baden, Germany

The programme is very comprehensive and includes pre-conference excursions to many places of agricultural interest.
For further particulars and registration apply to:

VIIth International Congress of
Agricultural Engineering,
Baden-Baden, Germany

OBITUARY

The Council of the Institution records with deep regret the death of the following members:

HARROD, E. J.	Associate
PATERSON, A. H.	Member
WATTIS, F. J.	Associate

APPOINTMENTS VACANT AND WANTED

APPOINTMENTS VACANT—Classified advertisements appearing under this heading are charged at 9s. per line, or part thereof.

APPOINTMENTS WANTED—Members wishing to advertise under this heading will be charged 5s. per line reckoning 10 words to the line [minimum charge 20s.]. The use of a Box Number incurs no additional charge.

Last date for the acceptance of Appointments advertisements for the next issue of the Journal: 10 June 1969

Index to Advertisers

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