time between the obtaining of the position of the enemy and the passing and re-plotting of this position on the charts of the gun-boat was the same for the two Commands. In other words, there appeared to be no statistical difference between the times of the two flotillas. However, the average taken was a linear average, whereas the probability of interception is a function of the inverse third or fourth power of the time. Therefore, the average taken should have been of the times raised to the third or fourth power rather than to the first. When this was done, there was a marked difference found in the averages of the two flotillas, quite sufficient to account for the difference in success.

In other words, there were big fluctuations in the times of transmission. In the successful flotilla, there were fortunately quite frequently a number of short times of transmission and these were responsible for most of the interceptions. In the other flotilla, while the average time was the same, there were fewer exceptionally short times. This fact was not obvious in view of the large random factor involved in the interception problems.

These are examples in which common sense, by applying the scientific method, has been turned into quantitative common sense.

Causal Links

A discussion of causal links is liable to lead one into the realms of philosophy or at least into difficulties as to the meaning of cause and effect. However, there are many branches of science in which there is no ambiguity and in these one can predict with a high degree of certainty that if certain things are done, a known effect will follow; for example, a force can *cause* a movement. As one of the primary objects of operational research is to predict the future, it is necessary to find some assurance that a particular relation between two variables is a stable one. If the data go back some time and have consistently supported the relation, then stability can probably be safely assumed, but the best basis for security lies in an accurate knowledge of the causal link behind the empirical relation. With such a knowledge, it is possible to use data collected over a shorter time and to make all conclusions of much wider and more general application.

It has already been emphasized that statistical correlation between two variables gives no indication of a causal link. Indeed, the history of applied statistics is full of examples where inexperienced people have jumped to conclusions in this connexion. For example, during the War a graphical correlation between the numbers of pilots having various degrees of 'night vision' and the successes of pilots in intercepting enemy aircraft at night was taken to prove the importance of 'night vision' (the tests actually included intelligence and quickness of response as well). A closer scrutiny of the results, however, showed that the predominant factor was the distribution of pilots over the various degrees of night vision, and the coincidence of the maxima of the two curves at 'degree 22' merely showed that the successful night fighters had the same *average* night vision as the bulk of the pilots.

It is well accepted in the iron-making industry that the output of a blast furnace falls if the conditions are changed to produce iron with a higher silicon content. This, indeed, can be proved very clearly from statistical data. The real cause here, however, lies first in the fact that higher silicon iron requires a higher temperature to shift the equilibrium towards the reduction of silicon dioxide, and the blast furnace would require more coke and more air in relation to the iron produced. Blast furnaces are designed, however, to operate with a more or less fixed maximum quantity of air and, therefore, the output falls, simply because in practice the furnace cannot get more air. There is thus no direct causal link between output and silicon content. A furnace to give a fixed through-put of iron could be built, but it would require a different design.

Organisation of Operational Research

Operational research may be carried out in two ways: either as part of ordinary research work or in a separate section set up for the purpose. Each of these has its protagonists. Clearly, a man who undertakes the research and development leading to a new piece of equipment or a new process should learn for himself the many operational problems concerned therewith. He should also follow up his new equipment or process by studying its behaviour in actual use. This might or might not be called 'operational research' according to the use made of the methods outlined in this paper.

On the other hand, there are severe limitations on this latter type of organisation, limitations which can largely be overcome by the setting up of a separate section. If operational research is to provide executive departments or managers with a quantitative basis for decisions, the men carrying out the research must be in the closest possible contact with the men who make the decisions; the value of their advice will be directly related to the extent to which they can see the overall picture of the problem under consideration.

A second advantage of a separate section is that it frees the operational research workers from executive responsibility. They are thus able to initiate studies with greater freedom and are limited only by the confidence that can be built up between themselves and their colleagues. Executive responsibility, whether in a normal research department or in management, has not been found conducive to the best operational research, and most of the successes of this work have been associated with 'free lance' teams. On the other hand, operational research teams should, of course, have a good sense of responsibility towards their task and their employers; but, as 'common sense' is one of the first qualifications of an operational research worker, no difficulty should be found in practice. A full discussion of the organisation of operational research must, however, await further peace-time experience.

PRESENT AND FUTURE OF OPERATIONAL RESEARCH

Application to Traffic Problems

The extension of operational research in peace-time activities is already in full swing, particularly in certain specific branches. Some of the most interesting recent applications have been in the fields of railway and road traffic. Both fields give a promise of useful results on the application of the scientific method.

One of the principal railways of Britain, the former L.M.S., has set up a special research unit attached to the operational side of the railway, and this unit has already completed thorough studies of some parts of the communications system, on which the effective running of a railway so much depends. These investigations have shown quantitatively where delays more commonly occur and have also predicted the likely improvement and saving that would result from certain possible changes in organisation and equipment. Those changes which show good returns are now being made. Needless to say, studies are also being made in the delays in the operation of the trains.

The road problem has two sides, the reduction of accidents and the improvement in flow. Losses due to accidents or delays on the roads to-day represent a serious loss to our national income or productivity. The Road Research Board of the Department of Scientific and Industrial Research has set up a strong team to study the problems involved. A wide range of the tools of modern science are at their disposal, a major one being the statistical method.

There are many problems in this field. For example, studies are being made of the factors affecting the usefulness of a typical road junction as controlled, say, by traffic lights. From a flow aspect, the main object is to get through the maximum number of vehicles and pedestrians with the shortest delay for each. From a road safety point of view, the object is to reduce the probability of an accident, and particularly of a serious accident, to the lowest possible value. These two objectives are to some extent conflicting, but the extent of the conflict may be very considerably reduced by studying all the factors associated with the junction and with its use. In other words, it should be possible to increase the flow-rate and reduce the danger of accidents at the same time. The way to do this can best be found by a close study of the operations of the various factors involved. A statistical study can be made of a number of road junctions of the same type and loading. However, there are severe limitations here because of the wide variations in type and loading, etc., and because of the fact that the frequency of accidents at each junction is low. It is necessary to deduce the relation between any two parameters from first principles, testing these relations where possible against such reliable statistics as may exist. These first principles are derived from studies of human reaction time, of the braking and manœuvring power of vehicles, of the conditions of the surfaces and the lay-out of the roads, of the timing and other characteristics of controlling lights, etc. Studies of this kind have, indeed, gone on for many years. As a result, London, for example, has one of the most highly developed and successful traffic signalling systems in the world. However, the development of this system is far from complete, but having been carried so far, much more powerful methods are now required to make further progress.

Most of the data in this field of traffic flow and accidents have been collected from studies of daily operations, with their associated mixture of variables, or by taking advantage of some change brought about for other reasons. In this field, however, changes introduced primarily to help disentangle data, that is, 'experimental operations', hold out great promise and, indeed, are already being tried.

There is one general point of technique worth referring to in connexion with this field. For example, it may be required to test experimentally the effect on a dependent variable, such as traffic flow rate, of increasing a given parameter, such as the width of a road section. The cost of increasing the width experimentally would be prohibitive, but a good approximation to the value of the partial differential coefficient in the neighbourhood of that particular road width can sometimes be obtained by experimentally *decreasing* the width of that section. This technique is based solely on the assumption, frequently a reasonable one, that the curve showing the relation between the two variables is a smooth one. The function need not be linear, but there should be no marked discontinuity or excessive curvature in the region considered.

There are also similar traffic problems more directly in industry. For example, the cost of transporting the fuel and raw materials and the products of the furnaces in an iron and steel works amounts to a large item in the cost of steel. This arises not only from the direct cost of traffic but also from hold-ups of parts of the plant awaiting materials, etc., or from more subtle points such as the need for close schedules. A full operational research into the details of this problem is now being made as a necessary preliminary to the engineering lay-out and design problems involved in improvements.

Application to Productivity and Output

Time and motion studies of operators of machines or of workers making repetitive operations have for long been one of the main research methods of the production engineer and the 'industrial consultant'. This method is steadily being improved and strengthened, recently by the exchange of lessons between this and other methods of operational research.

Extensive studies of productivity and of its reciprocal, O.H.P. (operator hours per unit of production) have been made by Tippett[6]. The factors governing O.H.P. in the factories of the cotton industry have, to a large extent, been resolved from a mass of data collected over a number of years. Decisions concerned with productivity by the management of individual firms, or policy decisions by Government Departments, are generally made with the results of these studies as a basis.

Similar studies have also been made of the processes occurring in chemical plant; but it is doubtful whether this should be called 'operational research'. It is probably better to consider this work as part of the normal type of research required to develop or improve existing processes.

Application to Inspection and Maintenance

Inspection has long been a field for the successful application of statistics; 'quality control' is now accepted practice with many large manufacturers. As an interesting example of a rather special type, an inquiry has recently been made into the distribution of the inspection effort in a steel works. In accordance with common practice, the inspection was made on a certain finished article at the end of a series of operations starting with the raw steel billet. Rejects at this final stage were, however, costly and the question arose: Could the faults leading to rejects be reliably detected at an earlier stage? A close statistical analysis, coupled with certain trial runs, showed that this was possible for several of the major types of faults, and the cost of the rejects has now been reduced to less than half without in any way lowering the standard. Furthermore, it was found possible to eliminate certain of the final inspection tests as they were now covered by the earlier tests, and hence the total inspection effort was not increased. The research here led to no new equipment or process, but merely to a re-deployment of inspection effort.

Good examples of operational research applied to maintenance problems in industry are not known to me and therefore I am tempted to return to one of the most striking examples of the War, the studies made by Dr. C. Gordon, in 1942–43, on the maintenance of aircraft, some details of which are given in "Science at War" (p. 104)[7]. These studies of the occurrence of faults in aircraft as a function of maintenance showed that it was possible to increase the flying hours at the expense of the hours an aircraft spent undergoing maintenance without any appreciable increase in the number of faults. As a result, the rigid schedules of maintenance were altered, with a very substantial increase in our fighting strength.

An obvious example where operational research is needed to-day lies in the maintenance of road traffic signals. It appears that the cost to the community of faulty signals and of maintenance is wrongly balanced. In the aircraft example, maintenance was overdone, whereas in this example, it appears to be underdone. It seems likely that operational research methods can be of great use to the maintenance engineer.

Application to Technical Progress

The change in public attitude to science in recent years has led to the question: Why is there such a long interval between the discovery of a new scientific fact and its application to the benefit of mankind? The answer to this would in itself require a lengthy research, but one factor is of obvious importance. A decision to try an idea out, when made reasonably, is based on a weighing of the pros and cons, many of which concern costs in money, coal or man-power. If it is not possible to weigh these sufficiently accurately to see which is the greater, a decision is naturally postponed or made on a 'hunch'. If operational research is successful in providing a quantitative basis for decisions, it should be able to shorten the interval between discovery and application.

There is, however, a danger here that operational research will be diverted to the routine task of 'vetting' inventions which arise through the initiative of individuals driven by parental interest. Operational research workers should be able to take a wider view of a problem, study its economics and its technicalities as a whole and, as a result, see how a proposed change or invention would affect the problem.

In certain research associations, such as that for iron and steel, operational research is already playing a major part in the formulation of programmes of applied or objective research by providing a logical basis for deciding what is worth while developing through its later stages.

Operational research is also playing a part in following up technical progress. The Ministry of Agriculture analyses regularly how far the knowledge of scientific research is being applied by farmers and thus obtains a basis for part of its educational and control schemes.

Future Trends

While there were certain technical developments in regard to the methods of operational research during the War, it is likely that these methods will be developed very much further. The application of the statistical tool is still on the increase, but there is no need or likelihood of the tool itself being developed further. There are many other tools in science, however, which will be tried, and some of which we hope will be successful.

One of the most important of these is the general concept of forces, potentials and equilibria in relation to the Second Law of Thermodynamics. This Law may be expressed in a general form as follows: If there is any 'tendency' for a certain thing to happen, or if a process is potentially able to take place in a certain direction, it should be possible to harness that process to produce external work, the amount of which per unit of process is a measure of the 'tendency'. In certain cases the tendency may be realized as a force.

The generalized Second Law of Thermodynamics should be capable of wider application despite the fact that one cannot take advantage of the rigorous relation between force and work found in the physical sciences. One of the most important forces in sociological systems is that of incentive. If an individual or a group of individuals does something in a certain direction, then there must be a force or incentive, the net value of which determines that direction. If we can elucidate and estimate the various components of that force, we can predict the behaviour of groups of people in given circumstances.

The concept of equilibrium is also capable of wide application, particularly as it can be shown that a system showing an equilibrium position can change only in a direction towards that equilibrium (except under external influence). Furthermore, the amount of the external influence required to keep a system away from its equilibrium rises rapidly with the extent to which it is kept away. For example, the cost of food subsidies rises rapidly as the equilibrium (free economic or supply-and-demand price) departs from the actual fixed price.

We can look forward to the day when the *science* of economics will be sufficiently developed to enable man to gain better control over his circumstances. I believe this science will only grow by the methods of operational research and more specifically by developing its own versions of the First and Second Laws of Thermodynamics, the First being the law of conservation of equivalence, the Second the law of direction of changes as governed by (economic) forces and of the associated conditions of equilibria.

Self-compensating and Self-aggravating Systems

This last point about equilibria leads to a further point. Practically all processes occurring in physical or natural science can be divided up into two categories, those which are self-compensating and those which are self-aggravating. The first are those described by the well-known theorem of Le Chatelier. 'If a change is imposed on a physical system in equilibrium, there are automatically generated other changes which tend to offset the effect of the first change.' This theorem follows from the Second Law of Thermodynamics and is of general application.

In contrast, self-aggravating systems are those in which a small change leads to a further change which *enhances* the effect. In the extreme cases, the result is catastrophic. In others, the enhancement proceeds until other self-compensating or attenuating factors present bring the situation under control and possibly reverse the direction of the change. Such systems generally lead to vigorous oscillation.

There are many examples of each type of system in the ordinary operations concerned with our daily life. Of the first type, there is the example of the reduction of the blindness of a blind corner. Such a change should normally result in a reduction of the number of accidents at that corner, or at least the danger of an accident. As, however, it would be followed by an automatic increase in speed of the cars taking that corner (as a consequence of the greater security felt by the drivers), the net reduction of the danger will be less than would otherwise be expected. This simply means that danger and speed are in equilibrium.

A good example of the self-aggravating type concerns the movement of buses. Consider a system in which buses depart at regular two-minute intervals from a depot and pass along a route through a large town to another depot. Under normal loading and with no special obstacles, the two-minute interval can be retained fairly accurately throughout the entire schedule. If, however, a small delay takes place with one bus when the load is near the maximum designed value, this bus will then find itself faced with the problem of picking up a larger number of accumulated passengers than it would otherwise have had to do. This immediately adds further delays which further aggravate the loading on this particular bus. This, of course, is the basic cause of the 'convoys' of buses which form rather frequently in large towns such as London.

A very similar problem is found in connexion with the supply and demand of scarcity goods. On first thought, it might be assumed that a system, in which there was an even flow of cigarettes from the manufacturers to the shops and an even rate of smoking, would be one of stability. Indeed, in normal conditions when there is no thought of scarcity, it is. The stocks held in retailers' shops provide a reserve or buffer for fluctuations in demand. The ordinary person becomes used to the fact that he can buy cigarettes on demand and therefore it is not necessary for him to maintain a large stock of his own.

Under conditions of scarcity, however, the stocks of a retailer are considerably reduced and the stocks of the consumer are increased because of his bitter experiences in being refused. The situation fluctuates widely because should there be, by some initial fluctuation, a small deterioration in the supply position, a consumer's reaction is immediately further to build up his own stocks. This in turn aggravates the retailers' stock position and induces other consumers to take corresponding self-protective action. Thus a small decrease in the available supplies in shops can quickly lead to a complete emptying of the shops; a rumour can become a reality.

I once had the opportunity of studying a similar self-contained system. The supply of chemical apparatus from a college 'loan store' would collapse annually at a certain time due to a self-aggravating factor of this type. The collapse was preceded by a sudden falling off of returns of apparatus after use, the falling off in turn being due to the beginnings of non-availability of certain items. There are numerous other examples, such as a run on a bank or the locking of a traffic roundabout due to some small initial fluctuation when it is near its maximum loading point. The economic trade cycles are presumably kept in oscillation by self-aggravating factors of this type.

The method of combating self-aggravating systems by the damping effects of controls and reserves is also well known. This method is parallel to the use of resistances and condensers in electric circuits. Operational research can lead to more exact knowledge of these systems to enable a better balance between reserves and flow and a better phasing or timing of actions intended to damp down or offset an impending change. One of the greatest problems for the Government administration has been to obtain 'early warning' of a particular situation and thus to avoid the more drastic compensating action required if the problem is left until it has built itself up to a serious state.

Conclusion

The arguments in this paper are based partly on the experiences of War and partly on those of two and a half years of peace. There are obviously many differences between the two conditions. War leads to a great degree of centralization of control and consequently a lack of flexibility. This is a situation in which operational research is potentially able to produce enormous improvements, partly because in certain respects it is a situation full of weaknesses to start with. On the other hand, an industry consists of a number of units or firms each evolving its own methods and working independently. Accordingly, variations of working methods occur, if only by chance. In normal economic conditions, the variations of positive value will have a greater chance of survival than those of negative value. In other words, 'natural selection' can operate in the uncentralized systems, providing there is a freely competitive economic system operating. As a result, it might be argued that operational research would be less likely to make such startling improvements in peace as it did in war. However, the same is true for applied science in general: the results in war are much more startling than in peace-time.

History has shown that results in war are followed by extended application in peace-time, and the case of operational research is so far no exception. This technique is becoming a new tool for executives, alongside their older tool, accountancy. It is a tool that the executive man can readily understand; it is not wrapt in the 'mysteries of science'. For him, his business life is becoming more and more complex as the repercussions of any one act or decision become wider. As a result, the waste of time in arguing with 'half-truths' becomes more serious. We are entering an age of statistics collected with great consumption of man-power. The new methods of operational research are needed if these statistics are not simply to add to the half-truths but to play their proper part in the more highly developed thinking processes now required.

[1] See, for example, Pickard, R. H., *J. Roy. Stat. Soc.*, Supplement 1934.

[2] Kittel, Charles, *Science*, **105** (Feb. 7, 1947).

[3] *Nature*, **160**, 660 (1947). Summary of a discussion held by the British Association.

[4] The first general paper on this subject, entitled "The Methodology of Operational Research", was prepared by Blackett in 1943 and has been distributed privately since then.

[5] Davies, Owen L., "Statistical Methods in Research and Production" (Messrs. Oliver and Boyd, 1947).

[6] Tippett, L. H. C., British Cotton Industry Research Association, Shirley Institute Bulletin (1947).

[7] Crowther, J. G., and Whiddington, R., "Science at War". Pp. vi+185+51 plates. (London: H.M. Stationery Office, 1948.) 2*s*. 6*d*. net.