Evolutionary Operation: A Review*

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Evolutionary operation, as originally presented by G. E. P. Box in 1957, is now an accepted means of improving the performance of industrial processes. Numerous articles have since been published relating to the successful application of this procedure and they indicate that the technique is one of general industrial importance. It is the purpose of this article to review briefly these applications, thus providing a source of references useful both to those familiar with EVOP and those wishing to examine the potential applicability of the method for an existing process.

1. INTRODUCTION

Nearly every existing industrial process has a potential for improvement in productivity. This potential arises not only from the inadequacies in the original design but also from changes which can occur during the lifetime of a plant. For example, the differences in optimum conditions of temperature and pressure for a given reaction in a test tube and in a large industrial scale reactor can be great. On the other hand, a slight change in feed composition between two periods of operation may demand different optimum operating conditions. However, a plant manager usually cannot allow periodic full-scale experimentation on the process to correct these difficulties, for such programs may produce a considerable amount of off-quality material. Also, highly trained specialists are required in addition to the personnel utilized in normal plant operation. In response to this apparent impasse, G. E. P. Box suggested a mode of *normal operation* which yields information on how to improve current operating conditions without the risks, special personnel and general expense associated with plant experimentation. To this philosophy of plant operation, Box (12) gave the name evolutionary operation (EVOP). A review of publications dealing with this subject is presented here.

2. THE GENERAL TECHNIQUE

The process application of EVOP generally emulates the evolutionary trends of improvement characteristic of biological species. It is well known, for example, that certain insects and microorganisms develop an immunity to some insecticides and drugs after a period of time. For an initial period of application of an effective insecticide a large fraction of the insect population under attack

succumbs to the insecticide. However, a small portion of the population which is relatively immune to the insecticide continues reproducing, thus producing insects similar to the resistant parents. The net result is a continual shift toward the more resistant end of the spectrum of the insect population. Eventually, a new and better drug or insecticide will be applied and adaptation on the part of the insect population will begin anew. The two important mechanisms on the part of the insect population in action here are: (1) variation and (2) the selection of the most favorable variant. Similarly, evolutionary operation introduces variation into operating conditions and provides means for the selection of a better region of operation than that at which the process is currently operating.

In industrial plants where EVOP is not used, a set of fixed operating conditions is usually selected and the operators attempt to maintain these conditions at all times. With EVOP, by contrast, slight systematic variations are introduced in the operating conditions, the sizes of these variations being selected so that the risk of producing off-specification product is small. In this way, essentially no more off-quality product is produced than with fixed operating conditions. The complete sequence of distinct variations in the operating conditions is called a *cycle*; for example, the best known cycle is that associated with two variables, consisting of five different conditions. This can be represented by
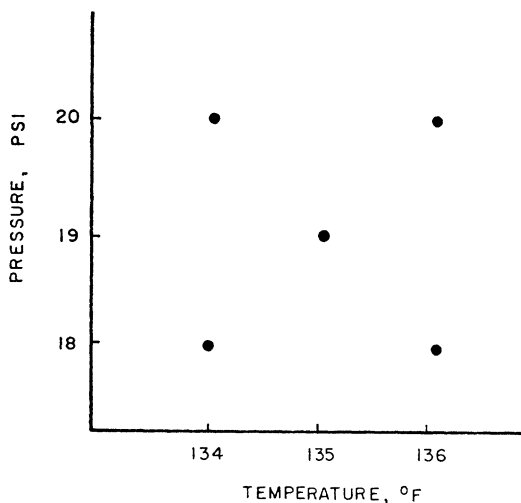
OPERATING CONDITIONS FOR A TYPICAL TWO-VARIABLE EVOP PROGRAM

a pattern of five points such as that shown in the illustration. The cycle is run repeatedly until the uncertainty associated with changing the levels of the variables is smaller than the effect of this change. Thus, naturally occurring background noise, which normally would have a masking effect, will be averaged out.

Once better settings of the variables are discovered in this way, they can be used to improve the performance of the unit. Then a new *phase* is begun at new levels of the same variables or perhaps at appropriate levels of new variables. For displaying and interpreting the available up-to-date data on the process,

Box suggested the use of an *information board* and an *EVOP committee*. The purpose of the committee, which is composed of specialists with varied backgrounds, is to assist the plant manager in interpreting the current results of the EVOP program and thus deciding upon the action to be taken for improved operations. An important benefit of successful EVOP programs is the continuous stream of new ideas for process improvement; the existence of such a committee function is essential for the full exploitation of these ideas. Thus, EVOP serves as a means for both generating and evaluating suggestions for increasing plant productivity.

The papers published on EVOP can be broken down into three primary, but overlapping, areas. There are papers devoted principally to presenting an exposition or review of methodology, to reporting applications of the technique, and to advocating modifications of the techniques suggested by Box.

3. METHODOLOGY

As has been mentioned, the fundamental reference on EVOP is the original paper by Box (12) which clearly sets forth the basic ideas. Details of a simplified calculational procedure are presented by Box and Hunter (15). Examples are included in this latter paper. Box has also discussed the effects of serial correlation, applications to continuous processes (13) and the applicability of EVOP as a starting point for methods of adaptive optimization (14). More recently Box (16) has emphasized that information used in practical decision making comes not only from the information board (empirical feedback) but also from the minds of the men on the EVOP committee (scientific or technical feedback). That is, suppose the results on the information board when considered by themselves suggest merely changing the levels of the present variables. This is an example of empirical feedback. However, the results when considered together with the special knowledge of the detailed mechanism of the reaction known to a research chemist may suggest that the potentially most profitable action is not to pursue the present variables any longer but instead to consider two quite different variables. This is an example of scientific feedback. Box (16) points out that strategies in EVOP which give optimal empirical feedback do not necessarily ensure good scientific feedback. Furthermore, he states "the author's own experience has been that most of the successes of evolutionary operation have been achieved when it has been used as a means to learn more about the process. In this, scientific feedback has the most important although not the exclusive role."

Numerous articles of a general nature are available. One staff report (5) of a journal presents, among other things, a resume of a paper read to a Paper Industry Manufacturer's Association and another (1) includes a note about the EVOP courses frequently offered as well as general statements about EVOP by Box and other leaders in the field. Barnett (8) (9) has also dealt with such topics and Hehner has presented a series of lectures on EVOP (31) (32) (33). Several books, such as references (28) and (35), contain discussions of EVOP. Surveys of various types have also included discussions of EVOP (7) (10) (30) (43) (56) (59) (68).

Papers have been presented reviewing and explaining in detail the philosophy and statistics of EVOP, Hunter's papers (36) (37) being notable in this respect. Other papers on the statistics (44) (49) and philosophy (52) (55) provide interesting reading. Questions concerning multiple optima and qualitative factors have also been discussed (26).

Papers have been published on the means of implementing EVOP. Some of these papers provide test problems and answers as well as detail on the planning stages of EVOP applications (4) (11), considerations of how much and how often variables should be changed (19), and suggestions that proto-type equipment be used for EVOP demonstration (20). Some considerations in "selling" EVOP to manufacturing divisions (63), management's role in EVOP (62), and practical rules of application based on actual experiences (46) (65) (66) are also discussed. Nearly all of these references are of interest to those wishing to begin EVOP as a mode of operation.

Finally, a mathematical formulation of EVOP, which is applicable when only empirical feedback is available, is offered by Kitagawa (38) and some of the references in the bibliography of his paper.

4. APPLICATIONS

General discussions (3, 4) have been published on the use and misuse of EVOP and its beneficial effect on the productivity of plant personnel. It is stated that The Dow Chemical Company has increased a plastic extruder output by 37 per cent by applying EVOP. They report that Dow is also saving $4,000 per month after EVOP suggested an increase in a recycle flow rate. Monsanto Company's enployee-training program for EVOP is also mentioned. Through EVOP, savings of $250,000 per year between two products have been realized by Monsanto (34) because of reduced raw material usage and reduced time cycles in a batch operation. Monsanto has also applied EVOP in the operation of an ammonia plant (2).

American Cyanamid Company has used EVOP extensively and successfully. EVOP has contributed substantially to the understanding of their hydrogen cyanide process (18). In the production of hydrogen cyanide by converting ammonia, methane, and oxygen over a platinum gauze catalyst, those variables of critical importance from a control standpoint were discovered. By directing additional attention to the control of these variables, the hydrogen cyanide yield was increased by four per cent. Koehler (40) (41) (42) has indicated that a functioning EVOP committee is quite important to their successful applications of EVOP, and he discusses examples in which EVOP has increased yields and decreased costs for American Cyanamid.

Coutie (22) (23) points out that the factors entering most frequently into Imperial Chemical Industries' 40-odd EVOP programs have been temperature, time, and concentration while the most common responses have been yield, purity, or a composite cost function. He describes the evolutionary operation of a batch dyestuff process through ten phases of two to three factors at a time. In the first ten years of operation a yield increase greater than ten per cent was obtained. He also discusses the operation of a continuous catalytic reactor.

Varying the ratio of two reactants and temperature for this reactor resulted in an efficiency increase of one per cent, which, because of the volume of throughput and the value of the product, represented considerable savings.

The application of EVOP has resulted in a substantial savings for Tennessee Eastman Company. A batch process is described (50) in which a chemical reacts to produce a desired product as well as an acid which is neutralized after a given length of time. The weight of acid-producing chemical and the neutralization time were varied, resulting in a yield improvement after the fourth phase of operation from 562 to 588 pounds. This represents a savings of $25,000 per year. DeBusk (25) discusses Tennessee Eastmen Company's problems with EVOP applications. He also discusses the application of three-factor EVOP on an established process which, after three phases, resulted in a savings of $27,500 per year. He points out that EVOP is used in approximately fifteen processes, with a savings of from $15,000 to $50,000 per year per process. Wilson (67) discusses the operation of a unit designed with a thousandfold scale-up factor, the product from which was to be used for market testing. From laboratory studies it was found that a step in the process involving a condensation reaction affected the total cost more than any other step. For the EVOP study reported, temperature and feed rate were the variables considered and cost, yield, and production rate were the responses. After four cycles the product cost was reduced five cents per pound and a 26 per cent increase in productivity was achieved.

The Chemstrand Corporation has also enjoyed success in EVOP applications (21). Riordan (53) (54) has discussed both administrative problems and technical rewards. He presents several examples of how EVOP led to equipment modifications and how EVOP yielded results appearing completely erroneous, thus stimulating an investigation which uncovered situations not previously suspected. Apart from the several hundred thousand dollars per year over-all savings and increased plant capacity, he points out the benefit of increased process understanding through evolutionary operation. From an administrative viewpoint, Riordan indicates how EVOP might be sold to the operating departments. He mentions that the EVOP program might be expected to require 30 man-minutes per day per program.

Several other industries have had success with EVOP applications. These applications include the automotive industry, in which EVOP has been applied to resistance welding of automotive sheet metal (60) and other manufacturing operations (61). It has been reported that Phillips Petroleum Company has successfully applied EVOP (50), (64), and a description of the training given to management, foremen, and operators for one of Standard Oil of Ohio's lubricating oil plants has been published (48). An application of a modified EVOP program to one of their catalytic cracking units has been discussed (39).

The food industry also has its examples of successful EVOP applications. It has been suggested that, although the large companies such as Swift and Company and Canada Packers Limited use EVOP, evolutionary operation can become an "equalizer" for small food companies in the race for process improvement (57). Swift has had successful applications in meat smoking and curing units, vegetable oil extraction mills, and in certain other processes (57). The

A. E. Staley Manufacturing Company has applied EVOP to corn grinding operations (45). The canning industry has also utilized this tool, notably in blanching times and temperatures for spinach canning (29). The use of EVOP for increasing the productivity of fermentation processes has been discussed (51). The many applications of EVOP to Maymee Chemical's plant operations include saccharin production, a biocide for sea lampreys, isatoic anhydride, anthranilic acid and benzotriazole processes (6). Other specific case studies have also been published (27).

5. Modifications of EVOP

Davidson (24) has described a slight computational modification which reduces the calculation required to find the optimum, with a small loss in efficiency. Klingel and McIntyne (39) have suggested a method for approaching optimum operation using completely arbitrary experimental designs.

The following modifications involve primarily empirical feedback and little, if any, scientific feedback (cf. Section 3). Spendley, Hext, and Himsworth (58) present a rather complete discussion of the use of simplex designs in EVOP instead of the more common factorial designs. The reasons for the choice of this type of a design are given as well as a formal procedure for the application of these designs in an EVOP program. The performance of the technique in the presence and absence of errors is examined. Carpenter and Sweeny (17) have also discussed this technique in some detail.

Lowe (47) discusses several modifications of EVOP. His discussion of the rotating square evolutionary operation (ROVOP) stresses that ROVOP eliminates uncertainty due to the size of the variant used. With ROVOP, each succeeding cycle on the same center results in an increase of the variant by the square root of two and a rotation of the factorial through an angle of 45 degrees. When a significant difference among the observations is found, the design is moved conservatively toward the optimum and the procedure begun again. Lowe also discusses random evolutionary operation (REVOP), a procedure claimed to be particularly useful when a large number of variables are under consideration. In essence, the procedure chooses randomly the next operating conditions within an allowable range, unless the previous experiments suggest a direction in which the center of the design should be moved. In addition, Lowe discusses the use of simplex designs in EVOP.

6. Conclusions

The basic principles and philosophy of evolutionary operation have been reviewed along with several applications of EVOP. Proposed modifications of EVOP have also been reviewed. To date, in spite of these proposed modifications, the basic procedure originally presented by Box has apparently been the most widely applied.

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