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The objective of this research is to establish a methodology for product quality enhancement through advances in parameter design and the recognition of the role of the manufacturing system's dynamical behavior on the variability of the product quality characteristics. In addition, the role of logistical support, especially the planning and scheduling of production, was investigated.

The research has introduced several new concepts to the field of quality control, such as the "stage loss function", "loss function reflection", the role of sampling in the determination of the producer's loss function, the adoption of a "quality criterion" in process simulation, the modeling via Markov decision processes, and control system optimization via geometric programming.

The research has resulted in several findings which have been documented in twenty technical and four progress reports issued throughout the course of the conduct of the research, all of which have been transmitted to the ARO library. The majority of the

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FINAL TECHNICAL REPORT

on

"Development of a Methodology for Quality Control and Enhancement in Manufacturing"

Army Research Office Contract No. DAAL03-86-K-0039

Principal Investigator: Dr. Salah E. Elmaghraby
Associate Investigator: Dr. Yahya Fathi

1. INTRODUCTION

This research was initiated on February 1, 1986, supported by the Army Research Office Contract No. DAAL03-86-K-0039, for a three-year period, and was extended from February 1, 1989, through July 31, 1989, on a no-cost basis. Consequently, this final report reflects the results of some 3 1/2 years of research.

The research has resulted in several findings which have been documented in technical and progress reports issued throughout the course of the conduct of the research, all of which have been transmitted to the ARO library. The majority of the technical research reports have been submitted for publication in various scientific journals. The bibliography at the end of this document gives a detailed statement of these reports.

2. RESEARCH CONTENT

This section is devoted to a brief description of the content of the research and its findings.

Objectives of Research and Industrial Cooperation

The objective of the currently sponsored research may be briefly stated as:

> " To establish the methodology for the determination of the quality function (QF) which relates the product characteristics (i.e., the measurable entities that define the quality of the product) to the significant process parameters (i.e., the process variables that are measured and controlled, and that have the greatest impact on the quality of the product) for the purpose of, first, controlling and, second, manipulating the process to achieve improved product quality."

In order to anchor our research in reality, we sought manufacturing firms that would accept being the sources of data and fields of trial. We were successful in enlisting two radically different enterprises: one large (multi-billion dollar) process industry, and the second a small (80 employees) piece-part manufacturer. Cooperation with the large firm progressed satisfactorily, despite the (rather long) delays experienced by the research team in securing data. Unfortunately, cooperation with the small firm did not progress as well because of internal problems with the financial standing of the firm that caused it to declare bankruptcy once and dismiss its employees twice over the past three years. These problems have been finally resolved earlier this year, and since then progress has been satisfactory. Henceforth, our discussion is related only to the large manufacturer.

The Approach/Methodology

For a thorough investigation of the QF it was necessary to model the real life manufacturing process and assess its variables. We quickly discovered that it would be onerous to model the whole manufacturing process, mainly due to its relatively large size and the diversity of the different manufacturing operations involved. Consequently, we decided to perform two parallel investigations. We refer to these investigations as the "global analysis" and the "stagewise analysis".

In the global analysis we used statistical techniques to investigate the impact of different controllable process parameters on different quality characteristics of the product. This analysis was based on data obtained from physical experiments. Running these experiments proved to be a very difficult and time consuming task, which imposed serious restrictions on the size of the data sets that we could collect in a reasonable time frame. Despite the fact that our conclusions did not enjoy a high degree of statistical confidence, they still provided valuable insight with regard to the impact of the controllable process parameters on the product quality characteristics, and distinguished the more significant relationships. The results of that investigation have been reported upon in [Fathi (1987)].

In the stagewise analysis we focused our investigation on only one stage of what is basically a three-stage manufacturing process. Henceforth, we refer to the chosen phase of production as the "Component" in order not to be confused with the "stages" defined for the purposes of analysis. We do not feel that we have lost any generality by concentrating on one phase of a total process, since, first, it is representative of the general class of processes that may be amenable to investigation and analysis by our proposed methodology and, second, our aim is not to resolve the particular quality problems of concern to this manufacturer, but rather to establish a general methodology for constructing the QF.

The results of the research conducted thus far may be summarized as follows.

Statistical Analysis

We have argued that quality control has been consistently, and we believe erroneously, identified with *statistical* quality control, while it should have been identified instead with the *engineering* activities of product design and manufacturing, since these are the activities that determine the quality of the product, in whichever sense "quality" is defined.

The closest vision to ours of quality and its enhancement is that of the Japanese engineer N. Taguchi, who introduced many of the concepts that have been adopted in the Japanese industry and are beginning to find their way into the U.S. industry.

We have discovered that despite its radical and advanced thinking, Taguchi's treatment lacks some rather important aspects that may seriously impair its application. For instance, Taguchi's work is almost completely based on 100% inspection of the product. In the majority of industrial enterprises 100% inspection of the product is a rarity. Rather, a sample is usually taken. The rectification of defective products, if any are discovered, and the subsequent "loss to society" are deeply affected by the sampling scheme adopted. We have demonstrated, through argument and by example, the changes that would result in the "producer's tolerance" as a result of such considerations. Our results in this area are summarized in [Fathi & Ferrell (1988) and Fathi (1988a)].

It has also become evident to us that current treatment of the non-constancy of the variance of the process response over the domain of variation of its parameters is poorly understood and largely ignored. This is true despite the fact that it evidently plays a central role in "parameter design". The theoretical discussion of these ideas may be found in [Fathi (1988b,c) and Fathi (1989a,b)]. Briefly, all work done on this problem, to the best of our knowledge, deal with it from a purely statistical point of view, in which experimentation is necessary to locate the optimal values of these parameters. The approach proposed in the above referenced papers develops the concept of parameter design from a purely analytical point of view, and defines its underlying optimization fromalism. The solution strategy proposed is based on conventional (nonlinear) optimization techniques. This strategy is applicable only if the analytical form of the functional relationship between the input and the output parameters is known or can be hypothesized, which is oftentimes feasible and practical.

The Stage Loss Function(slf)

On a different plane of thought, viewing the manufacturing process as a *dynamic* (i.e., time varying) system, in the sense of possessing its own dynamic response to input signals, it is evident that the variability of the output is dependent on the "transfer function" of the process itself. The main ideas that we have advanced in this regard are the following.

First, we have noted that Taguchi's "consumer loss function" is defined for the finished product, but the control of quality is effected throughout the stages of the manufacturing process. Hence there is need to "reflect" the *terminal loss function* (tlf) to the output of individual stages to secure a *stage loss function* (slf), in order to be able to judge the performance of the intermediate stages relative to product quality. Clearly, such reflection must take into account the dynamic behavior of intermediate stages. An immediate consequence of taking into account such dynamic behavior of intermediate stages of the process is that even if the tlf is quadratic in form, a frequently made assumption, *it need not be true that its reflection at intermediate stages shall result in quadratic slf's.* This fact introduces several rather significant complications to analysis and synthesis of the automatic controls. For one, it necessitates a departure from standard stochastic control theory which, in the main, adheres to the assumption of quadratic criterion functions. And for another, it raises the specter of the need for the specification of different performance bounds of the automatic controls.

Our concerns were justified: the transformation function of the stages of the manufacturing process that follow the Component in the sequence of plant operations resulted in an slf that is piece-wise quadratic with an intervening "dead zone"; a highly irregular loss function from the point of view of standard control theory.

The Simulation Model

Most significantly, the literature on control and optimal control theory assumes that the dynamic behavior of the process is available in the (usually linear) form of the dynamic system state transformation function given by:

$$\begin{aligned} \dot{x}_t &= A_t x_t + B_t u_t \quad \text{for continuous systems} \\ x_{n+1} &= A x_n + B_n u_n, \quad n=0,1,\cdots \quad \text{for discrete systems} \end{aligned} \tag{1}$$

where x represents the state of the system, and u the control (or "decision" in the vernacular of dynamic programming (DP)), both of which may be vectors, in which case A and B are matrices of the appropriate dimensions. The "output" of the system is also assumed to be a (linear) function of the state, typically stated as:

$$\begin{aligned} y_t &= H_t x_t \quad \text{for continuous systems} \\ y_n &= H_n x_n \quad \text{for discrete systems} \end{aligned} \tag{2}$$

where H is a matrix of appropriate dimensions. In our case, the "output" is the measure of performance (the "reward", in the vernacular of DP) as given by the slf. The classical view of stochastic control adds a random noise ϵ_t (ϵ_n) to eqn.(1)((2)).

In reality such transfer function, linear or otherwise, is rarely, if ever, available. Consequently, a great deal of the literature on optimal control is irrelevant, unless one can estimate the system transfer function. In place of the *analytical* transfer function we have constructed a simulation that is based on the physical laws governing the process (thermal and mass equilibria in some 103 "control volumes (cv)"). The simulation model was "validated", in the sense that its output was compared to the "real system" output under selected signals, and the behavior of the two was similar. That simulation then constituted the basic tool of analysis. A detailed discussion of these concepts is given in [Ferrell & Elmaghraby (1989)]; see also [Ferrell (1988)].

Parameter Optimization

It is well known that the study of stochastic systems has three facets: The first is *analysis*, in which the (deterministic) dynamic response of the system is assumed given, and it is desired to determine the output under specified (stochastic) inputs into the system. The second is *parameter optimization*, in which the *structure* of the control system is defined *a priori*, and the problem is to determine the value of the parameters of the controls to optimize a given criterion function. The third is *stochastic optimization*, in which we are given a system (viewed as a "black box") with stochastic inputs and a criterion function, and we seek the optimal *control law* (i.e; *structure and value* of parameters) that optimizes the given criterion function.

We first undertook parameter optimization under the stipulated structure of the PID (proportional, integral, and derivative) control system through extensive experimentation, utilizing the simulation model constructed for the process, in which the input was varied in a systematic fashion to lead to reduced slf; see [Ferrell & Elmaghraby (1989)]. We discovered that this approach leads to a set of so-called "optimal" parameters relative to the slf but, when implemented, resulted in very poor dynamic performance of the system (undamped oscillatory behavior when subjected to a step input). As a consequence, we had to retreat from these "optimal" parameter values, through another set of extensive experiments, to finally settle on a set of parameter values that are a compromise between the current values and those derived through experimentation.

This experience convinced us of the futility of the use of the experimental approach in parameter optimization since, by its very nature, the experimental approach cannot cope with restrictions on the dynamic performance of the system.

Next, we attempted optimization through the methodology of nonlinear programming, and in particular, geometric programming (GP). This is reported upon in [Elmaghraby & Ferrell (1988)]. Basically, the PID control system lends itself to representation in the form of a rational function of two signomials, in which the variables are raised to integer powers. This approach is certainly much more economical in time and computer effort than that of simulation, and offers a wide opportunity for exploiting structure and testing alternatives. It should be noted, however, that this approach implicitly assumes that the system is linear; i.e., that the underlying representation of the dynamic response of the system is given by eqns.(1),(2).

Parameter optimization *via* GP proved to be superior to the experimental approach, but inferior to the modified experimental approach. The reason, we suspect, is that the GP model did not account for the dynamic behavior of the Component. This forcefully suggests the need for the *identification* of the

Component. This forcefully suggests the need for the *identification* of the transfer function of the Component as an integral part of the quality optimization procedure. Some effort was devoted to this end for the past few months, with mixed results; it is reported upon in [Elmaghraby & Kafeety (1989)]. The most worrisome aspect of the analysis appears to be the behavior of the simulation as a mass-less entity which manifests a disturbing lack of "inertia" in either of its dimensions, temperature and moisture content. We suspect that the absence of such "inertia" did not impact the performance of the simulation when interest was focused on the *statistical* aspects of the slf, but that its impact comes to the forefront when stochasticity in the input is eliminated and one is dealing exclusively with deterministic signals (step and/or sinusoidal inputs). We are currently working on rectifying this aspect.

We were most fortunate in getting the GP-optimal parameters that behaved well *vis à vis* both the dynamic behavior of the system *and* its quality-oriented slf, despite its sole concern with quality measures (the minimization of the mean squared error (mse) of the control system output).

Both of these approaches may be considered "classical" in the sense that they depend on the representation of the system as a linear system of the form given in eqns.(1),(2) to which is added a random noise ϵ_n.

Of a more fundamental nature is the question of *criterion function* to parameter optimization. The criterion adopted in our analysis was that of minimizing the mse of the control system, in the hope that it will necessarily lead to 'good' performance relative to the slf that is quality-oriented. But suppose that we had adopted the slf from the outset as the measure of performance; is there an equivalent expression to the classical expression for output mse? To the best of our knowledge, this is an open question.

Markov Decision Model

An alternate approach, which also has the distinct advantage of responding directly to the issue of stochastic optimal control directly, is to consider the future state and the elementary output ("stage reward") directly as r.v.'s, governed by a conditional probability distribution. Such perspective leads immediately to the interpretation of the problem as a Markov Decision problem (Mdp) which may be treated directly by the methods of DP.

The Mdp approach has a significant advantage over parameter optimization and, to the best of our knowledge, has not been implemented before, albeit its brief mention in the literature. Under the Mdp model one ends up with a *prescription* of the desired performance of the control mechanism, which leaves its structure and parameter values to be defined later. Details of the Mdp model have also been reported in [Elmaghraby & Ferrell (1988)].

The construction of the Mdp for the Component was accomplished in a rather crude manner in order to secure a manageable Markov probability transition matrix: the stages of the system were grossly aggregated into 3 "stages" in the Mdp model, and the space of control policies severely curtailed from an interval to no more than four discrete points in that interval. The optimal strategy that was deduced from solving the MDP was gleaned from the optimal policy at termination of the DP iterations by heuristic reasoning (through "aggregation" of states), which leaves a great deal to be desired relative to a *methodology of deducing the optimal strategy from the optimal policy*. Note that in this approach one ends up with a prescription of the performance of the control mechanism, which leaves its structure and parameter values to be defined later.

The improvement in the slf performance secured from implementation of the Mdp-parameters suggests that a closer look be taken at using Mdp in designing controllers. The key aspects of the Mdp approach are: (i) the development of a model with sufficient detail to be useful, yet small enough to be 'solvable', and (ii) the proper interpretation of the massive amount of data to secure the optimal *strategy*.

Activity Networks: Representation and Scheduling

Throughout the life of this research some effort was devoted by Dr. Elmaghraby to fundamental issues in activity networks (AN's) and scheduling. The rationale for the expenditure of such effort is that we believe that the logistics of manufacturing (i.e., the planning, scheduling, storage, and conveyance of the product throughout its formation stages), and hence its 'residence' in the manufacturing facility, impinge on its final quality characteristics. AN's provide a powerful analytical model for the analysis and design of such logistical systems. Research in the area of AN's moved at a higher pace during the Spring semester of 1989 to take advantage of the visit of a young Polish operations researcher to the NCSU campus during the Spring semester of 1989.

Research was directed towards issues of representation of activities in network format. We were interested in the correct movement from the activity-on-node (AoN) mode of representation to the activity-on-arc (AoA) mode, and issues of 'complexity' of such network representations.

It is well known that the AoN mode of representation (in which nodes represent activities and arrows represent precedence) yields a unique graph and invariant floats in the temporal analysis of the activities. The same cannot be said about the AoA mode of representation (in which arrows represent activities and nodes represent 'events'): several graphs may result from the *same* precedence relations among the activities, and they may yield different activity floats. This may adversely impact any subsequent analysis, such as the scheduling of the activities subject to resource constraints. We were seeking a `correction' to the AoA analysis that would render its results identical to those secured via the AoN mode of representation. The fruits of that research are reported upon in [Elmaghraby & Kamburowski (1989a)].

It has been recognized for some twenty years now that the `strict precedence' imposed by the original CPM and PERT models is the exception rather than the rule, and that, in reality, more general precedence relations, including the so-called `start- and stop-lags', are more prevalent. Our research was directed towards the representation of such `generalized precedence relations' and the establishment of a correct framework for their temporal analysis. This was accomplished and reported upon in [Elmaghraby & Kamburowski (1989)c,d].

Finally, a major breakthrough in the measurement of the `difficulty' of analysis in AN's (especially in probabilistic models, such as in PERT, or in scheduling under conditions of limited resources) occurred when the optimal "node reduction problem" was solved in 1988 in polynomial time. We have reported upon such a development, and presented a brief survey of the areas of application of the new result in [Elmaghraby, Kamburowski, & Stallmann (1989)].

Continuation Research

As always, the research conducted over the past three and half years has raised several questions of fundamental as well as applied nature which could not be answered under the time restrictions of the current contract. Consequently, the research has spawned two proposals, one by the PI and one by the API. They are:

"Quality Enhancement and Manufacturing Systems Dynamics," by

S.E. Elmaghraby;

"Development of a Methodology for Robust and Cost Effective Design of Manufactured Products," by Y. Fathi.

Both proposals have been submitted to the ARO on January 18, 1989. We sincerely hope that both proposals shall be funded so that we can continue our research in this vital and fertile field.

3. PERSONNEL SUPPORTED BY THE RESEARCH CONTRACT

Faculty:

Dr. Salah E. Elmaghraby, PI, 6% time throughout the calendar year;

Dr. Yahya Fathi, API, 15% time during the academic year and 1-month to 2-months full time during summers.

Graduate Students:
(The duration and effort of these appointment varied from 1/2 time throughout the academic year plus full time support during the summer, to one month partial support during the summer. The details of the appointments have been reported in the regular progress reports.)

Mr. W.G. Ferrell, Ph.D. candidate (OR). Graduated in August 1988, and is currently assistant professor, Clemson University, SC.

Mr. D.J. Michael, Ph.D. candidate (OR); expected graduation date: August 1990.

Mr. H. Kafeety, Ph.D. candidate (OR); expected graduation date: June 1990.

Mr. G-M Jan, Ph.D. candidate (OR); expected graduation date: May 1990.

Mr. T.A. Gad (OR), M.Sc. candidate; graduated June, 1989.

Mr. Krishna Ginjupalli, M.Sc. candidate (IE); graduated June, 1989.

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