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INTEGRATED DESIGN OPTIMIZATION RESEARCH AND DEVELOPMENT IN AN INDUSTRIAL ENVIRONMENT

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ABSTRACT

This paper presents an overview of a design optimization project that is in progress at the GE Research and Development Center for the past few years. The objective of this project is to develop a methodology and a software system for design automation and optimization of structural/mechanical components and systems. The effort focuses on research and development issues and also on optimization applications that can be related to real-life industrial design problems. The overall technical approach is based on integration of numerical optimization techniques, finite element methods, CAE and software engineering, and artificial intelligence/expert systems (AI/ES) concepts. The role of each of these engineering technologies in the development of a unified design methodology is illustrated below in Figure 1. A software system DESIGN-OPT has been developed for both size and shape optimization of structural components subjected to static as well as dynamic loadings. By integrating this software with an automatic mesh generator, a geometric modeler and an attribute specification computer code, a software module SHAPE-OPT has been developed for shape optimization. Details of these software packages together with their applications to some 2- and 3-dimensional design problems will be described later in this presentation.

In regard to the integration with AI/ES, a pilot expert system advisor has been developed to help an engineer use the optimization technology for complex design problems in an effective manner. Some remarks are also made concerning experience with the use of optimization methods for practical design applications. Finally, several topics of future research, like process optimization and simultaneous product and process design, are introduced; and the role of multidisciplinary optimization, multilevel design and decomposition models is highlighted.

TECHNICAL APPROACH

- INTEGRATION OF KEY ENGINEERING DISCIPLINES
  - ENGINEERING ANALYSIS
  - NUMERICAL OPTIMIZATION
  - CAE/SOFTWARE ENGINEERING
  - AI/EXPERT SYSTEMS

Figure 1

DESIGN-OPT SOFTWARE SYSTEM

A design optimization software system DESIGN-OPT has been developed by integrating the well-known numerical optimization codes COPES/ADS [1], the commercially available analysis codes like ADINA, ADINAT and ANSYS and also some in-house finite element software packages, the pre- and post-processing software packages like MOVIE.BYU, PLOT10 and IDEAS/SUPERTAB, and a number of CAE tools for automatic mesh generation, geometry modeling and attribute specification. A schematic of the software architecture is illustrated in Figure 2. The OPT-AN processor directs the flow of the data from the optimizer to various analysis codes, and update input files to incorporate changes in design parameters at various optimization iterations. It also provides an interface with the SHAPE-OPT module which will be described in a subsequent section. The data flow from the analysis codes to the optimizer occurs through the software module AN-OPT which retrieves relevant information from the finite element output files and utilizes it to compute the objective function, constraints and gradients. In addition, it also provides an interface with various post-processing software packages so that the user can graphically display the structural configuration, stress and temperature contours, mode shapes for dynamic problems, and the iteration histories of objective function and design constraints. Particular emphasis has been placed on the post-processing and interactive aspects for on-line design optimization so that the user can exercise his own judgment during the optimization process. The finite difference method of design sensitivity analysis was used for all the finite element codes mentioned above, except that the implicit differentiation approach was also implemented into the ADINA code. This will be elaborated upon in the next section. Some of the applications include size and shape optimization of 2D/3D structural components subjected to static and dynamic constraints including centrifugal and thermal effects.

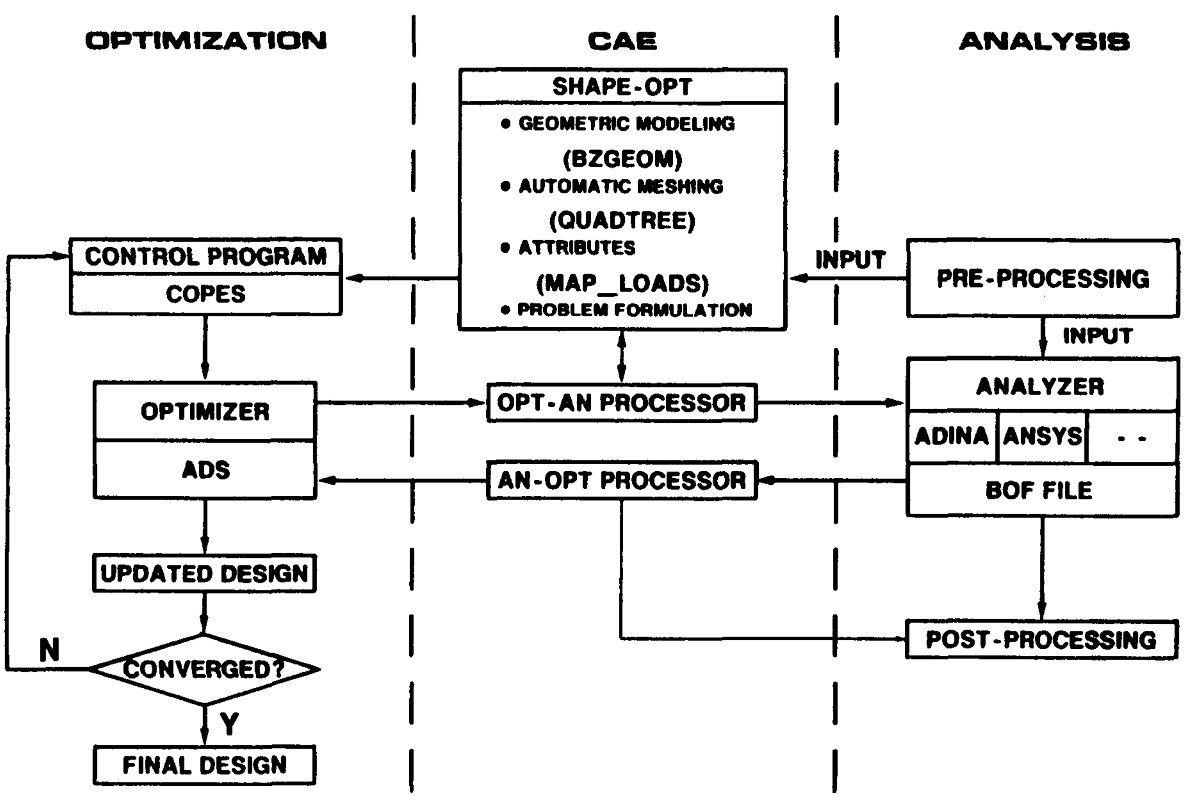

Figure 2

DESIGN SENSITIVITY ANALYSIS USING FINITE DIFFERENCE AND IMPLICIT DIFFERENTIATION METHODS

The finite difference method of design sensitivity analysis offers a simple, general and reasonably accurate approach for integrating analysis and optimization codes. The most attractive aspects of this approach are its ease for software implementation and the fact that it can be used external to a finite element code without requiring a source listing. However, it requires (n+1) function evaluations or finite element analyses for sensitivity calculations, n being the number of design variables; therefore, the associated computation time becomes rather large for many practical applications. The implicit differentiation or semi-analytical approach offers an efficient method of design sensitivity analysis requiring only one function evaluation or finite element analysis irrespective of the number of design variables. The implementation in this case, however, is carried out internal to a finite element software; the access to a source finite element code, therefore, becomes essential.In addition,considerable engineering effort and time are required to perform the associated software development. Since the source listing for the finite element code ADINA is available commercially, both the finite difference and implicit differentiation methods were employed when integrating ADINA with the DESIGN-OPT software system as illustrated in Figure 3. These developments were carried out for both size and shape variables, for static as well as dynamic problems, and encompassing a wide range of element types (truss, beam, plate, plane stress, plane strain and axisymmetric). Centrifugal and thermal loadings were also considered. Some closed-form solutions were used to benchmark the ADINA enhancements that were carried out. A comparison of the two approaches was also made in terms of the computational efficiency and solution accuracy. This development is presented in detail in Reference [2].

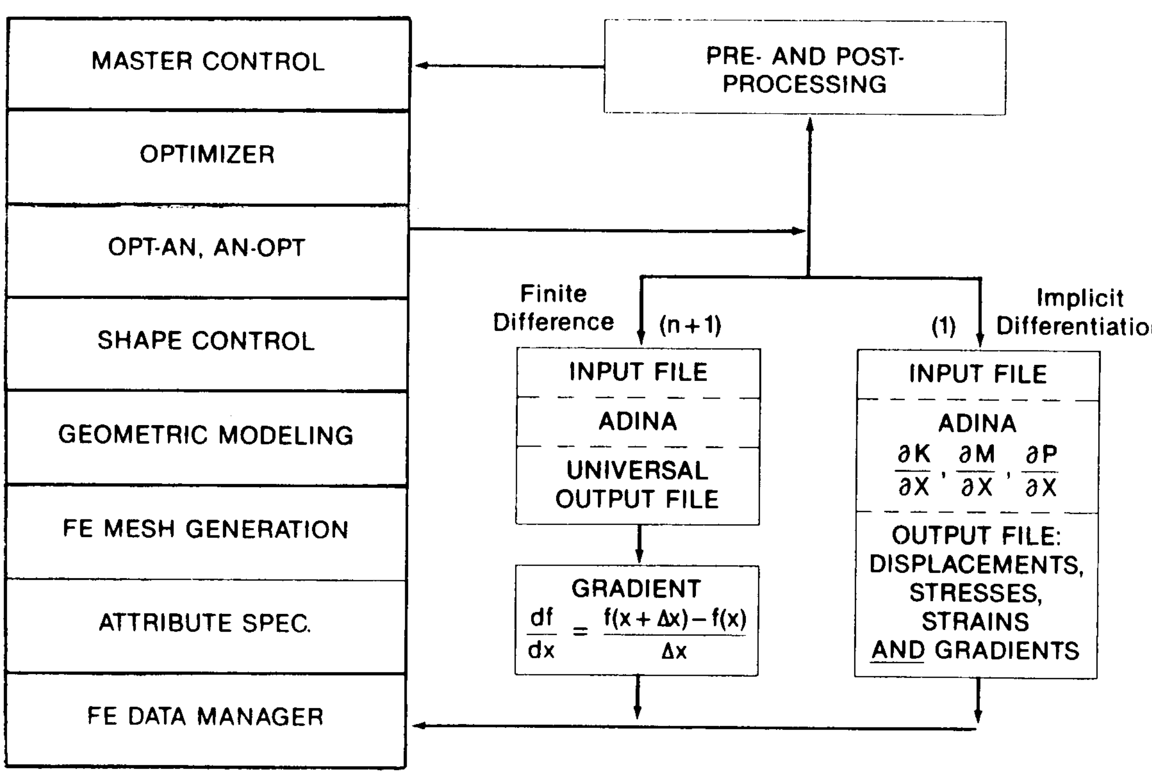

Figure 3

GEOMETRY-BASED SHAPE OPTIMIZATION METHODOLOGY AND THE SHAPE-OPT SOFTWARE

A geometry-based shape optimization methodology and a shape optimization module SHAPE-OPT was developed by integrating DESIGN-OPT with in-house automatic mesh generation, geometric modeler and attribute specification software packages as illustrated conceptually in Figure 4. The overall approach closely parallels the earlier work by Botkin and Bennett [3-5], and is described in some detail in Reference [6]. In this, the geometric modeling techniques (BZGEOM [7]) are employed for shape description in terms of boundary points (fixed as well as design variables) and geometric entities like lines, circular arcs and splines. The optimization formulation is also carried out at the geometry level in that the stress and other design constraints are specified in terms of boundary points, geometric entities and domains rather than individual finite elements or mesh points. An automatic mesh generation capability (QUADTREE [8,9]) is utilized for creating the initial finite element model and also for automatic remeshing as the shape changes during optimization. A strategy was developed for mesh updating between two successive remeshing and for design sensitivity calculations. An in-house software MAP-LOADS [7] is used for specifying attributes (tractions, displacements and temperatures) at the geometry level in an interactive manner via the use of the geometric modeler BZGEOM. A shape control procedure was also introduced for eliminating shape irregularities during optimization iterations; for example, by including constraints on slopes and curvatures at certain boundary points. The experience based upon several practical applications has shown that the geometry-based approach provides an effective method of dealing with different number of nodes and elements that result when using automatic mesh generation at various stages of the optimization process. The task of attribute specification also becomes much easier at the geometry level since the boundary conditions are not tied to finite elements and mesh points.

- GEOMETRIC MODELING
  - SHAPE DESCRIPTION
  - PROBLEM FORMULATION
- AUTOMATIC MESH GENERATION
  - INITIAL FINITE ELEMENT MODEL
  - REMESHING AS SHAPE CHANGES
- ATTRIBUTE SPECIFICATION
  - TRACTION, DISPLACEMENT AND TEMPERATURE BOUNDARY CONDITIONS AT GEOMETRY LEVEL

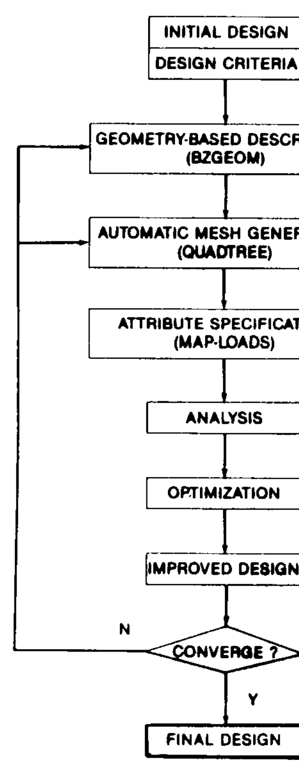

Figure 4

TURBINE DISC OPTIMIZATION

The DESIGN-OPT/SHAPE-OPT software was successfully employed for several practical applications including the design of rotating disc which represents a key structural component in several rotating machineries like gas turbines, steam turbines and aircraft engines. The optimization problem in this case usually consists of finding the axisymmetric shape of the disc to minimize the weight. Constraints are imposed on radial, tangential and Von Mises stresses, the disc burst speed, displacements, natural frequencies, and certain geometric considerations, etc. The disc is analyzed, in most cases, as an axisymmetric problem subjected to centrifugal and thermal loading. A uniform pressure is also applied at the rim (i.e., the top of disc) to model the centrifugal loading due to blades. Typical results are shown in Figure 5 in the form of disc shapes and weights versus optimization iterations. Finite element models, generated automatically by QUADTREE, are also illustrated. It is clear from these results that the disc shape and the corresponding mesh change substantially during the optimization process, demonstrating thereby the necessity of integrating an automatic mesh generation software into an effective and practically usable shape optimization methodology. Although the results are not shown here, it has also been noted that the same optimal design, in terms of the disc shape, weight and constraints, is usually obtained irrespective of initial designs. This observation provides some level of confidence that for the present class of problems we are able to achieve a nearly global optimal solution within the context of a given problem formulation and the solution approach. In most cases, it took less than 10 optimization iterations to converge to the optimal design.

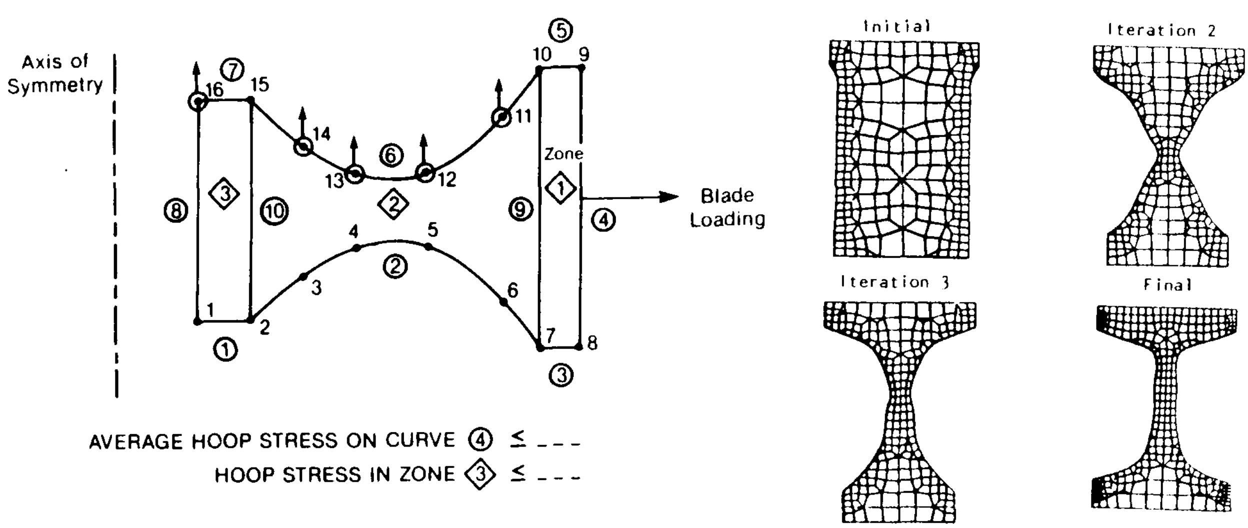

Figure 5

EFFECT OF SHAPE DESCRIPTION ON OPTIMAL RESULTS

In contrast with size optimization where the number of design variables are fixed for a given problem, the design variables for shape optimization can be specified in a number of different ways. The shape design variables are usually specified by the user at the problem formulation stage, and they remain fixed during the optimization process. A shape description involving a large number of design variables may lead to substantial increase in the computation time without adding any improvements in the final solution. A choice of too small a number of design variables, on the other hand, may not provide enough degrees of freedom for shape variations, resulting in a poor optimal design. it becomes necessary, therefore, to change the shape description during the optimization process in an interactive and dynamic manner. A strategy was developed and implemented in the SHAPE-OPT software that allows the user to specify different design models, i.e., number and locations of design variables, corresponding to different optimization iterations at the problem formulation and input file preparation stages. In other words, the user can specify n_1 design variables during the first k_1 iterations, n_2 during k_2 and n_ℓ during k_ℓ iteration stages, where $n_1, n_2, \cdots, n_\ell \leq n$ which is the maximum number of design variables in the overall optimization process. Several technical and software-related issues had to be addressed to implement this capability. For example, a reduction in the number of design variables necessitates change in the definition of the spline curve passing through the relevant design points. Also, the deleted design variables have to be kept updated on the newly defined curve so that any resultant discontinuities in the design and analysis models are eliminated. Further, one has to ensure that gradients with respect to deleted design variables are not computed. Some example results are shown below in Figure 6. The strategy consisted of performing several optimization runs, one keeping all the design variables throughout the optimization process and the other runs that employ different design variables at various optimization iterations. The results show that comparable optimal weights are obtained with different computation time for various strategies.

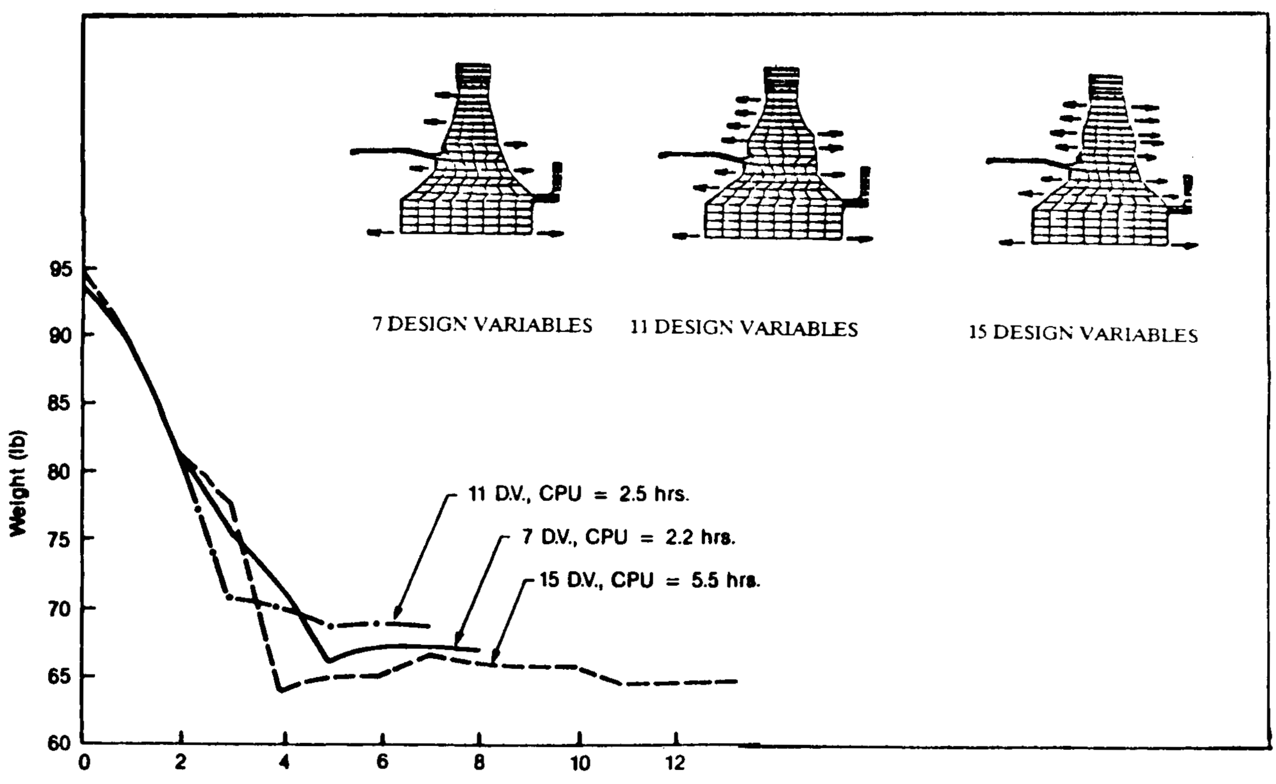

Figure 6

SHAPE OPTIMIZATION OF TURBINE BLADES

Design of turbine blades represents an ideal application of 3-D shape optimization involving multidisciplinary analysis in its real sense. The 3-D shape of a blade represents the primary design parameters, and the design objective and constraints are formulated in terms of aerodynamic performance, structural integrity requirements, aeroelastic stability margins, thermal constraints and certain other considerations as shown schematically below in Figure 7. The primary goal in almost all cases of blade design is to maximize the aerodynamic performance with secondary design objectives related to structural, aeroelastic and thermal behavior. The problem lends itself naturally into a multilevel design formulation employing decomposition models [10,11]. From a structural viewpoint, the design objective is usually to minimize the blade weight or maximize the frequency or stability margins subjected to constraints on steady state and/or vibratory stresses, frequencies and mode shapes, forced response in terms of modal participation factor, stability margins, lower and upper bounds on shape variations to maintain the aerodynamic performance, and several other considerations. In the present development, the focus so far has been placed on the structural optimization aspects of the blade design by integrating the DESIGN-OPT with in-house structural analysis and related preprocessing software packages. As one of the illustrative examples of practical interest, the shape optimization of a metallic solid blade was successfully carried out to minimize the increase in weight and maximize the range of resonance free performance so that the constraints on stresses, frequencies, forced response and shape variations are satisfied. The results obtained have clearly demonstrated the potential of numerical optimization tools for real-life complex design problems. The methodology and software system that is being developed in Reference [12] for this class of design problems is especially noteworthy.

MULTIDISCIPLINARY FORMULATION

- DESIGN PARAMETERS:
  - 3-D SHAPE, - - -
- OBJECTIVE FUNCTIONS:
  - MAXIMIZE AERO PERFORMANCE
  - MINIMIZE WEIGHT
  - MAXIMIZE FREQUENCY/STABILITY MARGINS
  - - - -
- CONSTRAINTS:
  - AERO REQUIREMENTS
  - STRESSES
  - FREQUENCY/MODE SHAPES
  - AEROELASTIC CONSTRAINTS
  - THERMAL CONSIDERATIONS
  - - - -

STRUCTURAL OPTIMIZATION

- DESIGN PARAMETERS:
  - 3-D SHAPE (MINOR VARIATIONS)
- OBJECTIVE FUNCTIONS:
  - MINIMIZE WEIGHT
  - MAXIMIZE FREQUENCY/STABILITY MARGIN
  - - - -
- CONSTRAINTS:
  - STEADY STATE/VIBRATORY STRESSES
  - FREQUENCIES/MODE SHAPES
  - FREQUENCY/STABILITY MARGINS
  - FORCED RESPONSE
  - GEOMETRY REQUIREMENTS
  - - - -

Figure 7

INTEGRATION OF AI/EXPERT SYSTEMS AND NUMERICAL OPTIMIZATION FOR ENGINEERING DESIGN

A framework has been developed for the integration of AI/expert systems concepts and numerical optimization techniques for mechanical and structural design. It is postulated that these two technologies are complementary to each other and will play a critical role in the development of a practically useful and computer-automatable methodology for engineering design. Numerical optimization methods offer a well established technology with its applicability successfully demonstrated in several fields of engineering. A large number of optimization software packages, like COPES/ADS, with a multitude of computationally efficient algorithms have also become available in recent years. These software packages have been shown to be very effective in iterative design improvements of structures and mechanical components which employ quantitative simulation models like finite element analyses. Artificial intelligence, Expert Systems (ES) and Knowledge-Based Systems (KBS), on the other hand, are based on symbolic computing and provide an extremely appealing framework for modeling non-numeric and human aspects of design. Design expertise, knowledge, experience and heuristics, etc., that are acquired through many years of strong effort and creative activities on the part of design engineers can be effectively stored in the form of knowledge data bases using AI/ES tools. In essence, the design process can be categorized in two major parts: numeric decision making and non-numeric or symbolic support systems. Numerical optimization techniques are ideal for addressing the numeric aspects, whereas the complementary symbolic or heuristics aspects are best modeled within the framework of an AI/ES concept. As illustrated below in Figure 8, both are essential ingredients of a unified, computer-automatable design methodology.

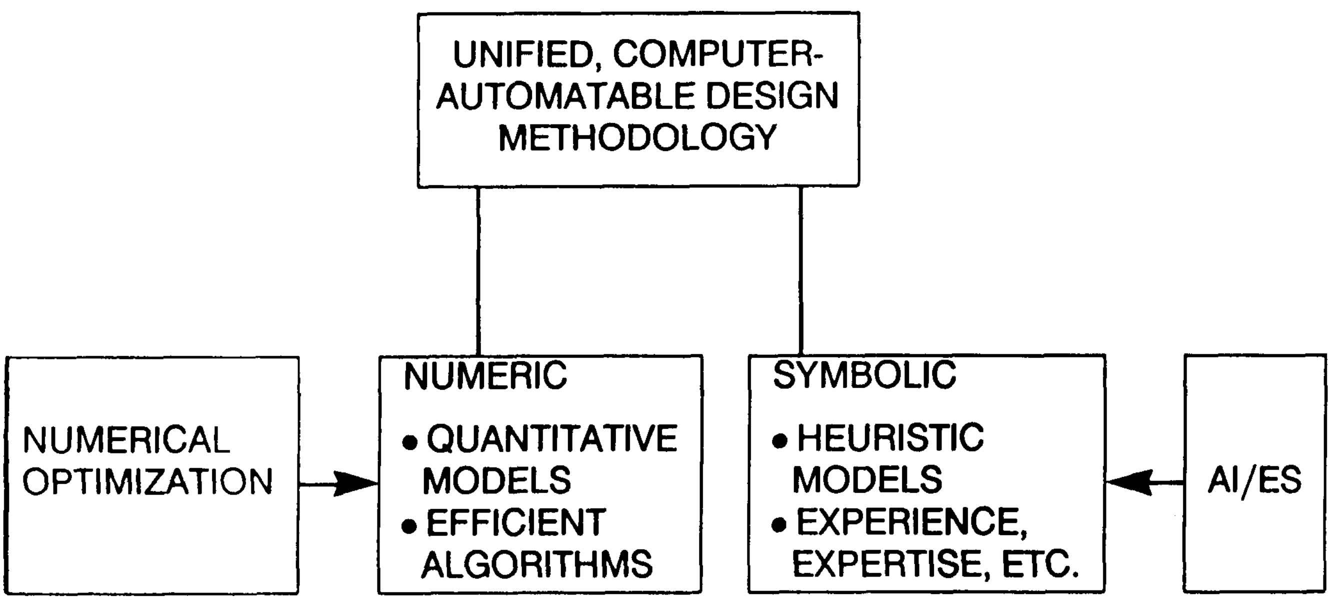

Figure 8

AN EXPERT SYSTEM ADVISOR FOR THE USAGE AND ENHANCEMENTS OF DESIGN OPTIMIZATION SOFTWARE

A pilot expert system advisor DESIGN-X is being developed for the usage and enhancements of the DESIGN-OPT software described previously. The present development environment consists of the OPS5 rule-based production system [13] COMMON LISP and the VAX machine; the system will be transferred in the near future to a SUN micro system employing KEE [14] as the ES shell. The objective of this development is to provide expert advice or assistance to the user of DESIGN-OPT at various solution stages of a given design problem: namely, problem formulation, problem solving, and solution evaluation processes (Figure 9). The problem formulation process is further subdivided into several categories such as the development of design and analysis models and the selection of numerical optimization algorithm. For example, the module related to advice on developing design models deals with issues like consistent shape description, identification of design objective and constraints, use of approximation concepts and the overall optimization strategy. Similarly, the optimization algorithm module addresses the selection of strategy, optimizer and 1-D search methods and the associated control parameters in a manner that is conceptually similar to but substantially different in details from the development reported in Reference [15]. When the optimization process terminates during execution prior to converging to the optimal solution, the problem solving assist is aimed at diagnosing the probable execution termination cause(s) and suggesting some corrective measures to the user. It can also provide on-line consultation to the user regarding changes in the optimization formulation during the software execution. The solution evaluation module is intended to assist the user in examining the quality of the final solution and at giving some expert feedback for a subsequent optimization run in case the results obtained are not satisfactory. Finally, a framework is also being developed for extending the scope of this system to another domain related to further enhancements and maintenance of the DESIGN-OPT software and is accordingly aimed at the code developers rather than the users.

PRESENT SCOPE

- PROBLEM FORMULATION
  - DESIGN MODEL
  - ANALYSIS MODEL
  - OPTIMIZATION ALGORITHM SELECTION
  - - - -
- PROBLEM SOLVING
  - SOLUTION GUIDANCE/CONTROL
  - ERROR DIAGNOSIS/PROGNOSIS
  - - - -
- SOLUTION EVALUATION
  - FEASIBILITY/OPTIMALITY
  - FORMULATION PHYSICS
  - 'ABNORMAL' TERMINATION
  - - - -

EXTENSION TO A NEW DOMAIN

- SOFTWARE ENHANCEMENTS
- SOFTWARE MAINTENANCE AND SUPPORT

Figure 9

CONCLUDING REMARKS AND FUTURE DIRECTIONS

Demonstration studies which have been performed on several real-life complex design problems during the past few years have established beyond doubts that the optimization methods will play an essential role in the development of a unified design methodology of the future. From a practical viewpoint, the greatest difficulty lies in identifying various aspects of a design problem in a complete manner and in developing appropriate optimization formulations. Experience has shown that expertise-based development of optimization formulations is crucial for arriving at an acceptable optimal or final design. A straightforward mathematical programming formulation of a given design problem may lead to frustrating experience during the problem solving process if the requisite attention is not given initially at the problem definition stage. Further, it has also been observed that because of system requirements and time constraints a design engineer is most interested in finding a feasible design with a reasonable concern towards optimality of the solution. For these and many other reasons, an ES-based advisor or consultant will play an increasingly important role in practical applications of design optimization software systems. As illustrated in Figure [10] below, the present effort was initially driven by optimization applications to design problems of real-life complexity as it should be in a diversified industrial environment. Following considerable technical and software developments in subsequent years, a stage has now been reached where research, development and application efforts are being carried out in an integrated manner. Several new optimization opportunities have been identified: namely, materials processing optimization, simultaneous product and process design, and integrated conceptual and detailed design. Since most of these topics involve multidisciplinary analysis and correspondingly large-scale and complex optimization formulations, the concepts of multilevel design and decomposition model as developed by Sobieski and co-workers [10,11] will become very useful. Efforts are under way to address these new optimization applications and toward developing an integrated design methodology for industrial applications.

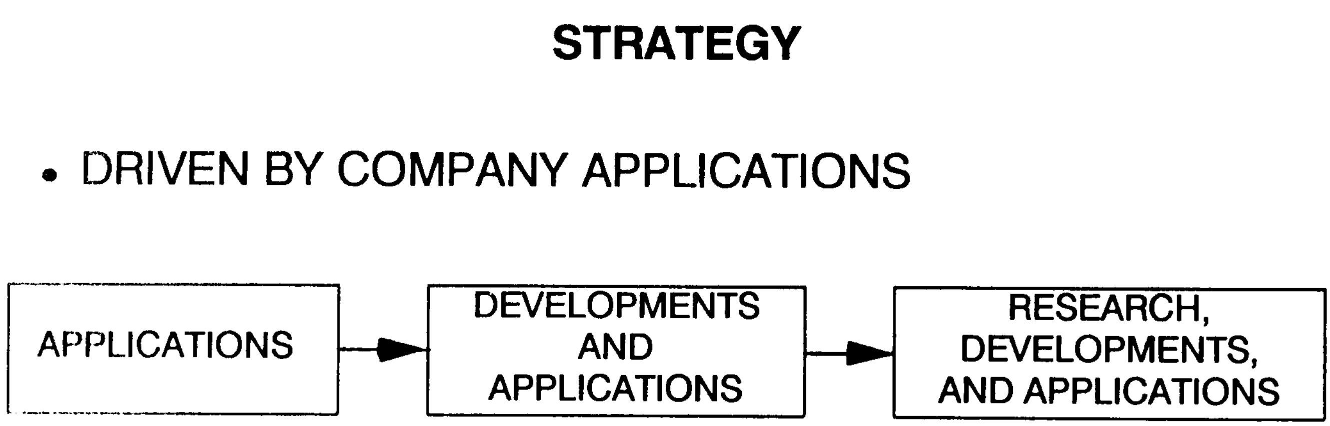

Figure 10

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