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Introduction

1.1 Background

Optimization formalizes the century's old trial-and-error method which engineers have traditionally used to reason through the complexities of a design process where the merits and demerits of a large number of alternatives are evaluated and the best combination selected. Originally, this was done using hand-based calculation procedures but has evolved, in the modern design environment, into the application of sophisticated computer-based numerical algorithms. Whether done by hand calculation or by employing an advanced computer program, the underlying procedure is the same; the optimization process starts the search for a best solution from an initial guess and then iteratively seeks to find better alternatives. These alternative designs are generated by varying parameters that characterize the design problem. If the design is characterized by cost, these would be cost factors; if the design is to have minimum weight, structural parameters related to the volume of structural material would be used. These parameters are the design variables which are used as the defining terms in a design objective; for example, the cost of manufacture is defined in terms of economic cost factors; the total structural weight can be defined in terms of structural sizes. By the intelligent application of the trial-and-error process, a computer-based algorithm, or the engineer, evaluates the quality of the trial to decide on the next move. Employing a computer, the engineer can engage a numerical algorithmic process that brings the power of computational numerical methods into play which iteratively changes the values of the design variables to modify the numerical value(s) of the design objective(s) while adhering to the limitations on the design normally termed constraints. By proceeding in this manner, the algorithm is driving toward a design

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judged best for a given set of circumstances. While engineers naturally turn to computer methods to assist them in the design process, we should, nevertheless, not forget that the most innovative computer is the human brain and the best designs are always a result of the engineer thinking first and employing computers second.

In real world engineering where a large and complex system, for example, an aircraft, a ship, or a car, is being designed, a process involving trade-offs takes place both within disciplinary subsystem domains and across their boundaries. Optimization in this environment becomes multidisciplinary design optimization (MDO). The complexity of modern systems shows itself under a number of different headings: compositional, behavioral, modeling, and evaluative complexity. The compositional complexity relates to the high number of system elements in the design process and their connectivity; if we take into account manufacturing cost, structural mass, dynamic response, and so on, each of these interacts with each other and calls into play a wide range of associated software tools. The behavioral complexity comes from the many aspects that influence the behavior that the designer is looking for, or trying to avoid, and is well described by the adage that in a system "everything affects everything." Modeling complexity is associated with the complex (physical) phenomena that need to be taken into account to analyze the system's behavior such as major structural analysis programs, computational fluid dynamics software tools, and so on which also interact. Finally, evaluative complexity appears when conflicting design characteristics are aimed for and trade-offs are needed between disparate properties.

Many of the methods applied to design optimization originate from the world of operations research (OR) which aims at optimizing operations of existing systems while MDO extends the approach to the engineering system design process, explaining the D in MDO. However, as explained in Chapter 2, there is a long history to the development of optimization principles and methods that have migrated to the design environment from variety of mathematical sources. The totality of these inputs is made clear through the various chapters in this book.

MDO can be defined as an assemblage of methods, procedures, and algorithms for finding best designs measured against a set of specified criteria for complex engineering systems with interacting parts, whose behavior is governed by a number of coupled physical phenomena aligned with engineering disciplines. Such designs are brought to fruition by teams of engineers, often dispersed on a country or global scale, employing organization methods and processes that accommodate commercial realities which might involve human factors components, costs and profit considerations, market competitiveness, and so on. Within the design environment, uncertainties are always present, and handling them when employing optimizing methods is not always straightforward and currently a major research area. Coupled with the presence of uncertainties is the need to undertake reliability-based and robust (uncertainty tolerant) designs. It is in the resolution of this type of design problem, with its range of interactions and uncertainties, that MDO finds its application.

Knowledge-based engineering (KBE) aims at drawing together the knowledge required to construct an MDO system into a computer-based knowledge base which can be logically interrogated by an engineer. It supports those wishing to employ MDO methods by making knowledge directly available at each stage of the development and application of an MDO system—it cannot be expected that a designer is an expert in all aspects relating to this task. Currently, KBE tools are in a rapid state of development and as time passes will become directly linked with MDO in its successful support for generating optimized designs for complex products.

1.2 Aim of the Book

The aim of the book is to offer a basis for constructing a logical approach to the application and understanding of modern MDO methods and tools and provide a background to supporting MDO with KBE technology. This is an ambitious target, and it is not claimed the book gives a complete and totally comprehensive coverage of these major fields. Rather, it provides a door through which the reader is invited to step and after crossing the threshold absorb or possibly develop the ideas in these rapidly expanding areas. In essence, it provides a knowledge base that allows the reader to take advantage of this technology in engineering design. In the case of an inexperienced or new user of MDO/KBE technology, it represents a robust starting point. For an engineer experienced in the application of optimization tools for designing a product, we hope the book will give insight into a new set of optimization and optimization support tools for solving complex design problems.

In order to meet the book's aim, we recognize the need to progress through the necessary background knowledge before launching into the complexities of the full MDO application. Before reaching the chapters devoted to multidisciplinary design, the book introduces and explains the basics of optimization and the method employed for single-discipline optimum design problems. Prior exposure to these basic optimization methods will assist the reader but is not a requirement as we start along the pathway to complex methods with a review of the necessary fundamentals. Readers familiar with the basics of optimization and optimization method may wish to pass by the earlier chapters. However, we all, from time to time, forget what we have previously learned, and in this situation, the early chapters can be viewed as a convenient aide-memoire that can be consulted when required. As regards prerequisite knowledge, we assume the reader is familiar with the vector and matrix calculus and the analysis methods commonly taught in undergraduate engineering courses.

Recent years have seen rapid development in computer technology leading to major increases in computer power and speed that have proved beneficial in general applications and for engineering design in particular. One development of particular importance in the field of MDO is massively concurrent data processing (MCDP) also popularly known as parallel computing. Therefore, throughout the book, we repeatedly point to the use of MCDP as an enabler for solving problems that, previously, were regarded as intractable.

Our objective is simple: to provide sufficient information for the reader to understand the basics of the MDO process rooted in the realities of engineering design practices and benefiting from the rapid advance in computer technology, to see how uncertainty can be incorporated, and to illustrate how KBE tools can give support to the implementation of an MDO design solution system.

1.3 The Engineer in the Loop

It is probably worthwhile to discuss the fact that no optimization process exists to take us out of the box set by the definition of the design space implicit in the initialization and the underlying design concept. In this context, we may note that optimization is always reductionist. For example, an aircraft optimization starting with a biplane could evolve into a monoplane with a low, mid, or high wing; but a biplane will not arise from a configuration initialized as monoplane. This underscores the importance of the initial design concept and why the engineer will remain the designer for the foreseeable future and MDO will remain his subordinate.

Once an initial design configuration has been selected, the engineer has the major task of setting up the optimization system to be used in the search for an improved design. It is tempting to think that the application of MDO methods is simply a question of selecting a method from the set of MDO "recipes" found in Chapter 8 supported by appropriate KBE tools as introduced in Chapter 9. This temptation should be resisted as complex design problems do not readily submit to being fitted into a set of preconceived methods. The engineer has, therefore, to come forward with a solution method that reflects the idiosyncrasies of the design problem. In configuring an MDO system, the reader should take account of the fact that the methods presented in this book are the best available and most often used in current mainstream applications of MDO. Our readers should recall that MDO is a major research field and, as a result, there is no doubt new methods will be developed in the future.

1.4 Chapter Contents

Most technical books are not read as a novel where it is essential to start at the beginning and proceed sequentially to the final chapter; rather, the reader selects those parts relevant to the technical issues being addressed. To assist the reader in making a judgment as to where relevant information can be found, we now describe what can be found in the other chapters of this book.

1.4.1 Chapter 2: Modern Design and Optimization

1.4.1.1 Aim

To introduce the role played by MDO/KBE methods in a modern design environment where products are complex and created by distributed design teams.

1.4.1.2 Outline

This chapter looks forward to what is to come in the ensuing chapters; it introduces the modern design environment and discusses the position and role to be played by MDO in this environment. It discusses the underlying realities of the design process then moves on to examine the role that optimization can play in achieving improved design solutions. Initially, this is done by focusing on optimal designs involving a single discipline and then moves on to discuss the multidisciplinary case. It also indicates that a role can be played by KBE tools in implementing MDO systems.

1.4.2 Chapter 3: Searching the Constrained Design Space

1.4.2.1 Aim

To introduce the fundamental mathematical principles on which the methods for solving optimization problems are based.

1.4.2.2 Outline

At the heart of any MDO system are the algorithms that guide the design process to an optimizing point, but before looking at them, we need to discuss and elaborate some of the characteristics and properties of the space within which an optimizing point lies. This chapter covers this broad topic area and can be considered as a precursor to later chapters which discuss optimizing strategies. The material presented is not comprehensive but covers the basic principles and methods that are used to solve constrained optimization problems. This includes the mathematical principles that underpin the application of optimization methods to solve design problems.

The Kuhn–Tucker constrained optimization conditions are developed together with the concepts of duality and dual bounding. Lagrange multipliers are introduced and linked to the concept of active and passive constraints. Readers familiar with the foundations of nonlinear optimization and optimization theory may wish to move directly to latter chapters. However, the chapter does include information which an engineer experienced in optimization methods might consider using as an aide-memoire.

1.4.3 Chapter 4: Direct Search Methods for Locating the Optimum of a Design Problem with a Single-Objective Function

1.4.3.1 Aim

To describe the methods used in the solution of problems with a single-objective function.

1.4.3.2 Outline

The chapter supplies the reader with sufficient information to understand what the various mono-optimization methods and algorithms require in terms of gradients, update formulae, and so on. With this information, an engineer can make rational choices on the selection of appropriate optimization tools for use in a practical MDO design system. It does not attempt to provide a comprehensive set of methods covering the entire range of such software. The reader wanting to obtain a comprehensive description of the methods touched on should refer to the references found within the chapter. The chapter considers first unconstrained optimization problems with linear or nonlinear design objectives. It then moves on to review a range of constrained optimization solution methods. The concept of shadow prices is used to show how changes in the constraint limits can change the value of the optimized objective function. As with Chapter 3, an engineer experienced in employing optimization algorithms to solve engineering design problems may pass this chapter by but may want to employ it as a resource base.

1.4.4 Chapter 5: Guided Random Search and Network Techniques

1.4.4.1 Aim

To discuss the use of genetic algorithms and artificial neural nets in the solution of optimization problems.

1.4.4.2 Outline

There are a number of methods that attempt to find optimum designs using techniques that avoid following a specified search direction exploiting gradient or quasigradient information discussed in Chapter 4. The repetitious use of directional searches is replaced by a process which either exploits randomized variations in the design variables or avoids the direct variation of design variables altogether by using learning networks. The first group is called guided random search techniques, and this chapter uses genetic algorithms to represent this class of optimum seeking methods. The second group, introduced in the chapter, is learning-based methods which are trained to pick out optimal solutions to very complex problems. In covering this group, the chapter discusses network-based methods and specifically covers artificial neural networks. As with Chapter 4, it does not present the reader with a comprehensive treatment of these algorithms as there is extensive and comprehensive literature available. It gives the reader a sufficient understanding of how these work so that intelligent decisions can be made if these techniques are encountered in the development or use of an MDO system.

1.4.5 Chapter 6: Optimizing Multiple-Objective Function Problems

1.4.5.1 Aim

To describe the methods used in the solution of optimization problems with multiple-objective functions.

1.4.5.2 Outline

This chapter introduces the reader to methods that can be employed when a design has more than one objective function which is normal when real world design optimization problems are encountered. It indicates that the design engineer is confronted with a number of, possibly, conflicting design requirements that normally result in a need to undertake trade-off studies. The chapter covers Pareto-optimal solutions, the concept of the Pareto frontier, goal programming, weighted sum methods, and the application of the methods introduced in Chapter 5 to solve this type of complex design optimization problem.

1.4.6 Chapter 7: Sensitivity Analysis

1.4.6.1 Aim

To introduce the mathematical methods and procedures for generating sensitivities at both single and multiple levels for both complex and simple design problems.

1.4.6.2 Outline

At this stage, in the pathway to applying MDO methods in the solution of complex design problems involving several objective functions, sensitivity analysis emerges as a tool necessary for design in general and for optimization in particular. This chapter reviews the fundamentals of the sensitivity analysis based on analytic derivative methods, including the recently gaining attention method of computing the derivatives of the real-valued functions via complex numbers. It introduces a method for obtaining derivatives using adjoint methods as a means for reducing computational effort. Shadow prices, originally discussed in Chapter 4, are reintroduced in this chapter. The use of higher-order derivatives is considered, and the sensitivity of an optimum to the problem parameters is presented. A solution to the problem of the sensitivity of complex internally coupled systems is introduced.

1.4.7 Chapter 8: Multidisciplinary Design and Optimization Methods

1.4.7.1 Aim

To introduce and describe the methods that can be applied to the solution of problems where both the objective functions and the design constraints involve interacting disciplines or subsystems in the context of a large engineering optimization process conducted by a team that may be dispersed organizationally and geographically.

1.4.7.2 Outline

This chapter provides a detailed explanation of multidisciplinary design and optimization (MDO) and the methods for solving this class of optimization problems that represent the core topic of this book. It exploits the terminology, notation, and methods, introduced in the chapters preceding this chapter, augmenting them to support the discussion of MDO. The chapter describes how the large and difficult task of designing a complex engineering system can be decomposed into a set of smaller and simpler tasks that may be carried out concurrently by a geographically dispersed team with the aid of parallel computing technology and utilization of a formal data management. A review of a sample of methods applicable to engineering system optimization is then presented, contrasting the traditional sequential approaches that may be shown as leading to acceptable but suboptimal designs, with the MDO-based approach that has the potential for both reaching an optimum and reducing the cost and time of the design process. It is asserted that MDO supports “design agility” meaning an ability to quickly revise design decisions made early in the design process as required by new information obtained downstream. The chapter concludes with a summary of the key elements and features of MDO and assesses the current state of the art focusing on strength and weaknesses together with a forecast of future potential.

1.4.8 Chapter 9: KBE

1.4.8.1 Aim

To describe the role played by KBE methods in supporting the application of MDO methods.

1.4.8.2 Outline

This chapter discusses the fundamentals of KBE and illustrates how this technology can support and enable multidisciplinary design optimization of complex products. A definition of

KBE is provided, and its application in engineering design, supporting the use of MDO, is discussed. The working principles and main features of KBE systems are described with particular focus on their embedded programming language. This language is the core element of any KBE system and allows the capture and reuse of the design knowledge necessary to model complex engineering products. Of particular importance in this book is the facility it offers to automate the preparation phase for the multidisciplinary analysis process. The main categories of design rules that can be embedded in a KBE application are described, and several examples are given that pinpoint the main differences between KBE and classical rule-based design system and, in particular, conventional CAD tools. Finally, a section is provided describing the major steps in the evolution of KBE and its current trend in the broader CAD panorama.

1.4.9 Chapter 10: Uncertainty-Based Multidisciplinary Design and Optimization

1.4.9.1 Aim

To introduce methods that allow MDO solution methods to incorporate uncertainties.

1.4.9.2 Outline

The scope of this chapter is to systematically introduce the uncertainty-based multidisciplinary design and optimization (UMDO) theory and present a concise introduction to the typical UMDO methods. The chapter specifically focuses on the fundamental theory and general UMDO approaches but does not include a comprehensive review of the state-of-the-art algorithms. The chapter is structured to first present the preliminaries of UMDO, including the basic concepts and the general process for solving UMDO problems. Second, the key steps of UMDO, including uncertainty analysis and optimization under uncertainty, are expounded. Finally, an example is presented to illustrate the application of UMDO methods.

1.4.10 Chapter 11: Ways and Means for Control and Reduction of the Optimization Computational Cost and Elapsed Time

1.4.10.1 Aim

To describe methods that can be deployed to reduce the cost and time of an engineering design process based on the MDO methods.

1.4.10.2 Outline

This chapter reviews a variety of ways and means available for controlling and reducing the computational effort of both single-discipline and multidisciplinary design optimization. It takes into account the notion that “computational effort” may not be measured by a single metric. The chapter addresses the issues of speedup and cost reduction as scored by a number of different metrics that include the central processing unit (CPU) time, data transfer time, data storage, number of processors, and so on. Various techniques are presented that relate to these metrics in different ways and in varying degrees all utilizing the technology of parallel computing.

1.4.11 Appendix A: Implementation of KBE in Your MDO Case

1.4.11.1 A.1 Aim

The aim of the appendix is to outline the implementation of a KBE system and describe its role in supporting the creation of a working MDO system.

1.4.11.2 A.2 Outline

The appendix provides information that can assist in incorporating a multimodel generator (MMG) in a commercial or self-made framework. It covers the steps necessary to go from the stage where the design problem is analyzed to go the point where a working framework has been developed. This includes the capture of basic design knowledge, the codification of product knowledge, and the application of this to support the creation of a Design and Engineering Engine (DEE). The different stages are illustrated with simple examples.

1.4.12 Appendix B: Guide to Implementing an MDO System

1.4.12.1 B.1 Aim

To provide an overview of the basic structure and process necessary for implementing a working MDO system (a DEE).

1.4.12.2 B.2 Outline

This appendix addresses the problem of constructing a framework which can house a DEE and make it into a working reality. It approaches this from the viewpoint that a process is required which can handle, manipulate, and operate with data across the entire design spectrum from requirements definition to a design tool. It, therefore, focuses on the software and other requirements need to convert the basic MDO systems, introduced in Chapter 8, into a working system.