Decision Making in Engineering Design

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NOMENCLATURE AND ABBREVIATIONS

AR: Aspect Ratio
AHP: Analytic Hierarchy Process
CKR: Common Knowledge of Rationality
CODA: Concept Design Analysis
CPF: Cost plus Fee
DAPCA: Development and Production Costs for Aircraft
DoE: Design of Experiments
FFP: Firm Fixed Price
HTOL: Horizontal Take-off Landing
INCOSE: International Council on Systems Engineering
K_i: Scaling Factor of i^{th} Attribute
MAUT: Multi-Attribute Utility Theory
MCDA: Multi-Criteria Decision Analysis
MCS: Monte Carlo Simulation
MDO: Multidisciplinary Design Optimisation
MoD: Ministry of Defence
MTTF: Mean Time to Failure
MTTR: Mean Time to Replacement
NBS: Nash bargaining Solution
NPV: Net Present Value
QDT: Quantum Decision Theory
QFD: Quality Function Deployment
RBR: Repair by Replacement
SE: Systems Engineering
SULSA: Southampton University Laser Sintered Aircraft
TRL: Technology Readiness Level
U: Utility Function
UAS: Unmanned Air System
UAV: Unmanned Air Vehicle
V: Value Function
VDD: Value Driven Design
VTOL: Vertical Take-off and Landing
X_i: i^{th} Attribute

PREFACE

This book presents an operational tool for decision-making under uncertainty in any engineering design, synthesizing well established classical decision-making methods, such as multi-attribute utility theory, analytic hierarchy process with game theory and quantum decision theory. The work presented concerns the development of a value driven design assessment framework employed as the decision-making tool in engineering design, and its application to the conceptual design of an Unmanned Air System (UAS). This research demonstrates the implementation of the value driven design philosophy in this framework, identifying value enhancing designs, with value not converted to monetary worth and as perceived by all stakeholders involved. A *multi-criteria* and *multi-stakeholder* decision-making analysis is adopted to address their preferences as well as to study their interacting strategic choices. The ultimate objective of this framework is to convert engineering design to a decision-making analysis with multiple conflicting objectives of multiple stakeholders considered.

This framework is capable of providing a product definition and estimation of all performance and cost related attributes during the conceptual design phase for a broad range of configurations. Value, related to the designed system's capabilities or performance and lifecycle cost, is used to compare different alternatives through the appropriate value model. Following a value-focused approach, a novel multi-attribute value model is introduced for objectively capturing the stakeholder's preferences and expectations. Furthermore, a more sophisticated multi-attribute utility model, based on standard Multi-attribute Utility Theory, is employed in the evaluation.

Game Theory as an optimization tool is used to develop a novel hybrid cooperative/non-cooperative non-zero sum, complete information game among all involved stakeholders as players. This game successfully addresses the stakeholders' preferences in a functional outcome-focused way, resolving the high indeterminacy of the alternative designs through a cooperative game. At the same time, their strategic interactions are captured in a process-focused non-cooperative game. Hence, the optimal design is identified through the simultaneous employment of the Nash bargaining solution and the Nash equilibrium.

A Quantum-based Decision-making model is also developed to capture the complexity of human decision-making related with risk attitude in the presence of ambiguity and uncertainty, by incorporating apart from rationality, the decision makers' different biases, emotions and subjective feelings. Based on Quantum Decision Theory, this model takes into account the dual nature, i.e. conscious and subconscious, of human decision-making, and exhibits a stochastic behaviour through the assessment of quantum strategic probabilities.

CHAPTER ONE

INTRODUCTION

"Several person-years of effort developing, modifying and verifying an elaborate simulation model that outputs the possible levels of several indicators of interest – and perhaps a week with the implications of the alternatives and then the decision maker chooses an alternative."
R.L. Keeney and H. Raiffa, Decisions with Multiple Objectives [illegible]

The application of multidisciplinary skills in engineering design requires an integrated approach to be successful. Following the systems engineering approach, designers consider each system to be comprised of other subsystems and components, all with a clear role to perform and all dominated by more than one requirement set at the system level, entangling the design task. The generic engineering design process according to Wiese [2] needs to be "*systematic*", in the way the potential solutions are proposed and evaluated, "*iterative*", using both simulation and prototyping to assess the solutions proposed, and "*multidisciplinary*", since several disciplines are needed to encompass all important considerations.

All essential aspects of all lifecycle stages need to be addressed to study the designed system, its elements and their interactions with the wider environment. Starting from the development and production to the final stage of disposal, appropriate features of the designed system are employed in the evaluation of any proposed solution. Thus, the multi-disciplinary engineering design needs to be performed at the full system level and evaluated at the highest system level, addressing all important complexities, changes in technology, following a whole lifecycle approach. Furthermore, the possibility of an optimal arrangement being significantly different to the current or commonly used should also be taken into account.

The work presented concerns the development of a value driven engineering design assessment framework, with value not converted to monetary worth, and its application to the conceptual design of a small Unmanned Air System (UAS) for defence use. This framework, through the use of appropriate models, estimates all associated variables and parameters required for the product definition. The designer assesses the value of proposed system solutions in an objective way, based only on the needs and preferences of the stakeholders involved. The value assessment relies on both performance and financial needs analysis, to capture all significant priorities and performance criteria. The design generation, following the value driven approach, is carried out more efficiently by relaxing all constraints and exploring the design space extensively while the multidisciplinary design optimisation applied within this framework addresses all significant for the conceptual design phase complexities of the system and identifies the optimum solution. Therefore, the ultimate objective of this framework is to convert engineering design to a decision-making analysis with multiple conflicting objectives of multiple stakeholders considered.

In general, design is either *customer driven/market pulled*, when customer requirements and needs drive the technology to design the products that address those needs, or *technology pushed*, when a breakthrough in a certain technology allows for significant improvements in the performance of products, Verganti [3]. One example of the first design philosophy is the Toyota's Design Quality Innovation Division, incorporating customer feedback in automobile design. Typical examples of the second type are the introduction of colour television, the electronic calculator or the Xerox copier.

Design has its etymological origin to the Latin *de-signare*, meaning distinguishing with a sign. One way to achieve this distinction is to relate to the value, usefulness, of the solution that is offered to the stakeholders of the designed system. Following the *Value Driven Design* (VDD) approach, the product value is related to the appropriate product characteristics. The design is distinguished/developed based on the full analysis of all their needs yet the process of blending these needs through VDD is hard to comprehend and for this reason sometimes not easily accepted. Collopy [4] points out that the commercial aircraft industry if left to its own, will naturally tend towards monopoly and technological lethargy', and although currently in the duopoly (Boeing and Airbus) stage, the application of value driven push strategy in the military aircraft design could address its inefficiencies, improving the design process.

The proposed work seeks to develop a value pushed/driven engineering design assessment framework that will propose alternative solutions and assess their value , relying on both performance and financial needs analysis. This framework will be applied to the conceptual design of a small UAS for defence use. The value assessment can be performed not only at the early abstract design stage but also at any stage of the design process, as the design concept gets more refined and its uncertainties are addressed.

This research aims to add new knowledge by developing a VDD Framework and applying it to the Conceptual Design of a defence system, namely a Small Unmanned Air System. As will be presented, the full application of a VDD framework has been limited up to now to the design of civil aerospace systems, with value mostly related or easily converted to monetary worth for military systems however, not all objectives/needs can be easily monetized. This VDD framework will identify the value enhancing designs, value perceived by the stakeholders and not translated to economic terms. The research hypotheses are the following:

H□□othesis □: A VDD framework, when applied to engineering design, can address all the non-economic and economic values of the stakeholders involved with the designed system, to identify the value-enhancing design(s).

H□□othesis □: Design exploration can be performed more efficiently, after relaxing most performance or cost related constraints and extensively searching the design space in a systematic way.

H□□othesis □: Multidisciplinary design optimisation can be applied within this framework to address most system complexities associated with the conceptual design phase.

This research aims to develop an implementation of the value driven design philosophy in a framework where all needs of the major stakeholders of the designed system are addressed and used in the evaluation of the proposed product solutions, with value not translated to monetary worth. This VDD framework will be applied to the test case of conceptual design of a UAS for a defence application. In this VDD implementation process, also presented in Figure 1-1, the following objectives will be addressed:

- Identification of the needs of all stakeholders involved with the designed system during its whole lifecycle.
- Development of multi-attribute and multi-stakeholder value models, based on all identified stakeholders' performance and financial needs, to assess the value of any proposed solution with appropriate design attributes as their inputs. MAUT supported by AHP will be employed to capture the preferences and risk attitudes of stakeholders involved with the designed product, while Game Theory and Quantum Decision Theory will be utilised to address the multiple stakeholders' preferences, biases, emotions and feelings.
- Selection of a wide range of different system configurations, associated technologies, design variables and other stakeholders' choices to widely search the design space.
- Definition of the designed system with appropriate models in a terminology and language relevant to the designer for quick and efficient conceptual design space exploration, easily amended and replaceable for higher accuracy during the later phases of engineering design.
- Development of predictive models to assess all design attributes and especially:
    - Unit acquisition cost modelling that is based on system geometry and material/labour rates.
    - Mission scenarios' definition to run simulations and obtain first estimates of lifecycle cost and performance/capabilities.
- Integration of all models in the design tool.
- Trade/parametric studies to identify the optimal solutions as well as the corresponding optimal ranges of all design variables.

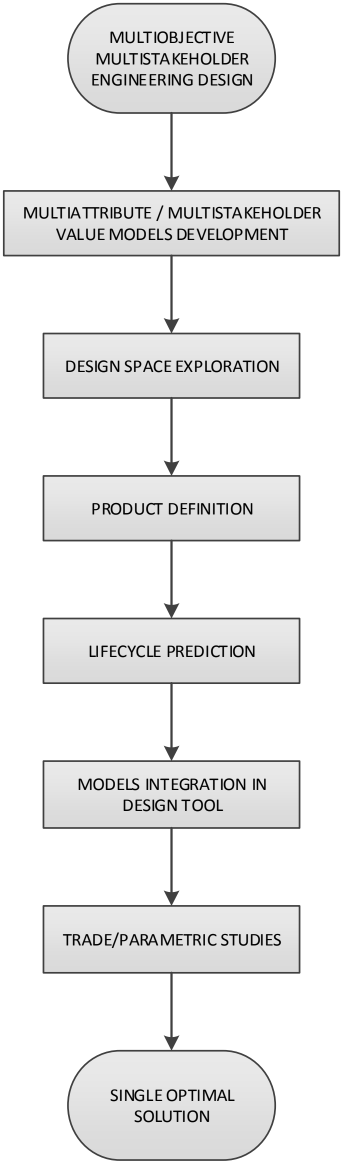

Figure 1-1 General VDD Implementation Process

The objectives set in the previous section are addressed in the following chapters. The foundation for the development of the proposed VDD framework is presented in the next two chapters, while the rest of the document is organised based on the general VDD implementation process of Figure 1-1. More specifically, the next chapter describes the general engineering design process, translating needs and functional requirements to design parameters. Systems Engineering (SE) and the VDD framework to obtain the best design are also introduced in this chapter. The basics of the Multi-Criteria Decision Analysis (MCDA), as appropriate tools for the development of multi-attribute value models, are presented in the third chapter. Thus, Multi-Attribute Utility Theory (MAUT), Analytic Hierarchy Process (AHP), Net Present Value (NPV), Cost Effectiveness and Cost/Benefits Analyses, Group Decision-making for aggregating the preferences of many individuals, as well as the employment of Game Theory and Quantum Decision Theory in Engineering Design are presented. In the fourth chapter, the VDD implementation process starts with a basic general UAS, employed as the test case of the application of the proposed VDD framework. Hence, a representative configuration/category is selected and the complete objectives/attributes hierarchy, reflecting the user's priorities and needs, is structured in this chapter. In the fifth chapter, multi-attribute non-financialised value models, utilised for evaluating any given design alternative based on the single stakeholder priorities/preferences in the Multidisciplinary Design Optimization (MDO), are developed as the next step of the VDD implementation process. In the sixth chapter, Game Theory as an optimization tool is applied to incorporate the preferences of more stakeholders in a Multi-Stakeholder value modelling. Also, a Quantum-based Decision-making model is presented, capable of capturing the stakeholders' biases, emotions and feelings. In the seventh chapter, appropriate product definition models are developed to perform design sizing within an extensive and systematic UAS design generation. Moreover, the predictive models are introduced for the estimation of the total lifecycle cost, including the costs of developing and building the aircraft, maintenance, replacements for aircraft losses and the cost related to combat damage. Next, in the eighth chapter, the integration of all models in the VDD framework for the automated optimisation is presented. The results obtained with the automated design space search, through the use of Designs of Experiments (DoE) and MDO, allow for comparison and evaluation of different designs based on their attributes. Finally, the last chapter is dedicated to the primary conclusions, contributions to the current state of knowledge, and future work recommendations concerning the application of the multi-objective, multi-stakeholder optimization approach in value driven engineering design.

CHAPTER TWO

ENGINEERING DESIGN BACKGROUND

> *“The first step of the engineer in trying to satisfy these wants is therefore that of translating as nearly as possible these wants into the physical characteristics of the thing manufactured to satisfy these wants.*
>
> *Walter A. Shewhart*
>
> *Economic Control of Quality of Manufactured Products*

In this chapter, engineering design background is presented as the foundation for the development of the VDD framework. Starting from the identification of needs and requirements, engineering design methodologies and tools are introduced to facilitate trade and optimisation studies. Furthermore, beyond the performance related inputs of the objective function which are dependent upon the specific system that is designed, cost engineering is also introduced as the scientific analysis to obtain an accurate estimate of the total lifecycle cost or other cost related characteristics of the product.

Complex engineering design can be divided into three phases, as Raymer [5] describes:

a. *Conceptual design*, requirements are set, technologies are defined, trade-offs between the design features are explored, while the goal is to obtain the general description of a viable and most preferable solution.
b. *Preliminary design*, during this phase the configuration is ‘frozen’, the exact definition is obtained, basic components are designed and further accuracy is obtained.
c. *Detailed design* phase, where all actual pieces to be built are designed, along with the design of manufacturing processes and appropriate tools.

In the conceptual design phase, the widest possible design space is explored and ultimately the most preferred designs between all alternatives, based on their evaluation against technical and economic criteria, are selected for further analysis. A set of objectives usually comprised of elements, from several operational, technical, economic, safety and other relevant factors is taken into account to derive the evaluation criteria used in the evaluation stage of the proposed solutions. To achieve the objectivity of this evaluation, these criteria should be independent of information, other data available or the proposed solution, but should reflect only the priorities, needs or values of persons involved. Engineering design is all about decision-making, aiming towards the identification of the most feasible design based on the customer needs/requirements.

Engineering design has been studied thoroughly both from academia and industry. Several applications, all aiming to systematize and accelerate the design process, have been introduced by Hubka and Eder [6], Pugh [7], Pahl and Beitz [8], Otto and Wood [9], Eggert [10], Ulrich and Eppinger [11] and Ullman [12]. The iterative engineering design process of Figure 2-1, as a decision-making process, involves the generation of several potential design solutions with different characteristics, evaluated against the primary objectives.

Hazelrigg [13] describes engineering design as the generation of all possible designs and the selection of the best one. There are, however, two inherent difficulties: Firstly, the number of all potential designs that can be generated is theoretically infinite, proportional to the number and range of the design variables, the configurations employed, and other design parameter choices the designer has to make and secondly, the selection of the optimum solution must rely on some commonly used metric, for the evaluation to be objective. Additionally, little technical information and data, other than some broad and vague needs to be satisfied by the concept configuration, size and shape, is available in the conceptual design phase. Cross [14] presents the applicable strategies for product design, starting with the clarification of the design objectives up to the generation and evaluation of the alternatives.

Engineering design formalized the synthesis of the design problems across different disciplines, starting from the early 1960s and by the mid-1980s evolved to more computable and automated methods, as Antonnson and Cagan [15] point out. The generation of the design point can follow a multidisciplinary design spiral, that is a sequential, iterative methodology originally developed for ship designs [16]. For an air system, Keane and Nair's [17] design spiral is illustrated in Figure 2-2, as the design process evolves from concept to detail.

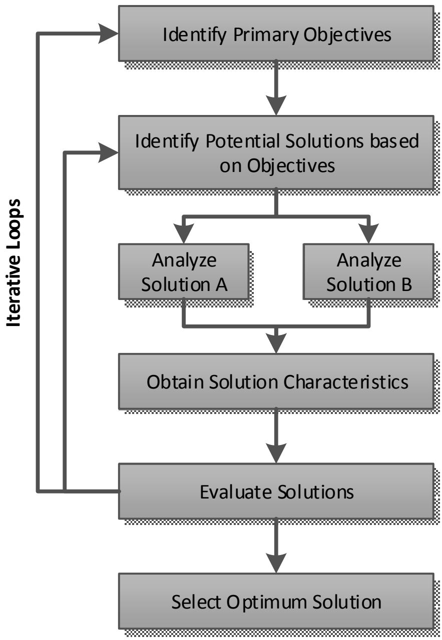

Figure 2-1 Engineering Design Process

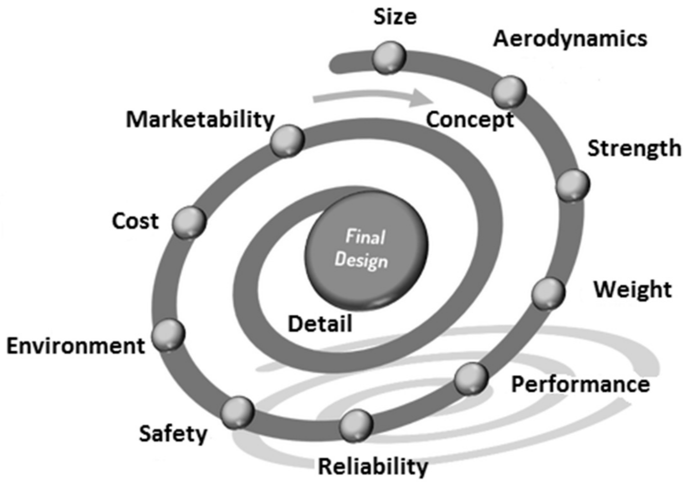

Figure 2-2 Aircraft Design Spiral [17]

Only the most basic of engineering disciplines, configurations and capabilities are circumscribed in the conceptual design, evaluating a number of configurations, while sensitivity analysis is performed through the variation of design parameters. Major parameters are selected in the concept phase, while the most promising design candidates are promoted to base configurations of the design project for further evaluation.

Engineering design is a highly knowledge intensive process and as such the advances in computational tools have allowed geometry manipulation and meshing, access to various databases and management of computing resources during the automated optimisation. However, the use of different type tools makes the linking of them a rather challenging job, to achieve their integration in the design process and therefore the exploration of the widest possible design space over many possible configurations, as Keane and Scanlan [18] describe.

The first step in the engineering design process is to define the needs of all associated stakeholders. The identification and structuring of objectives will articulate the values of the user and will direct the collection of information and decision-making, performed during the generation and evaluation of potential alternative solutions respectively, as Keeney [19] underlines.

According to Freeman [20], stakeholders are any group or individual who can affect or is affected by the achievement of the firm's objectives'. In the engineering design a stakeholder has interests/stakes in, is influenced by, or could influence any part of the whole lifecycle of the designed product from the initial steps of the conceptual design up to its disposal. For every stakeholder/organisation, further analysis and questionnaires are employed to define the requirements/objectives that should be addressed. The objectives of the stakeholders should cover the complete lifecycle of the designed product, from the identification of an opportunity for the design of a product, the preliminary concept phase, the full concept definition, the product realization, the product and service support up to its disposal.

There are no universal definitions of the terms, objectives and attributes but according to Keeney and Raiffa [1], each of these objectives in the decision-making process corresponds to an area of concern of the stakeholders. Since high level objectives tend to be rather abstract, these are further refined by utilising lower-level objectives, representing the goals to be pursued within the engineering design process. Hence, by subdividing the objectives into lower level objectives, a non-unique objectives' hierarchy is constructed up to the level where all aspects of the higher objective are accounted while the elimination of any of the lower level objectives would alter the selection of the design alternative (the so-called *test of importance*). The generation of the appropriate objectives is based on relevant literature, analytical studies and causal empiricism [21]. Examining how objectives of similar problems have been handled in the past, the modelling of the problem and surveys focusing on the needs and requirements of the stakeholders/decision makers will indicate the appropriate objectives.

For each objective, one or more attributes are associated, indicating the degree to which alternatives satisfy the objective. It is therefore imperative, to identify several attributes, that should be both *comprehensive* with respect to the objective and *measurable*. A *comprehensive* attribute provides the decision maker with the knowledge of the extent that the associated objective is achieved. The attribute is also *measurable*, if for each alternative a probability distribution over the attribute levels is generated and the decision maker's preferences are assessed. The non-unique full set of these should be *complete*, covering the overall objective, *operational*, *decomposable*, *non-redundant*, and *minimal* [1]. The set is *complete* if it indicates the degree to which the objective is met, *operational*, if it serves the purpose of the evaluation, *decomposable*, if the set can be broken down into subsets, *non-redundant*, no attributes are overlapping the same objective and *minimal*, the number of attributes should be as small as possible. This set of attributes will be the scalar input of the objective function, created ad hoc and reflecting the decision makers' attitude towards value trade-offs and uncertainty related choices.

The method of Multidisciplinary Design Optimisation (MDO) was systematically launched in the 1960's in an attempt to perform engineering design optimisations with multiple attributes across different functional areas. Sobieski of NASA Langley Research Centre defines MDO as a '*methodology for design of complex engineering systems that are governed by mutually interacting physical phenomena and made up of distinct interacting subsystems*', explaining that for such systems '*in their design everything influences everything*', [91]. MDO studies the application of numerical optimization techniques to the multidisciplinary engineering design. Since no single mathematical model can be solved for the optimum solution, different models in each discipline are created and solved separately, with their numerical results being forwarded to the next model, until convergence is achieved, providing the optimum solution to the multi-disciplinary problem. To reduce the high number of required calculations, a single approximate model is usually formed by fitting some mathematical surface to the large number of design variables. Several algorithms and MDO methods are applied in engineering design, and the choice of the appropriate method is dependent upon the specific goal. Martins *et al.* [92] provide a survey and classification of the most common architectures/methodologies used to solve the MDO problem. In general, the MDO problem is nothing more than a standard constrained problem of finding the values of the design variables that, subject to some constraints, optimize a particular objective function. The objective function, used to identify the best design alternative, could be a weight, drag or cost to be minimised, a performance related design attribute to be maximized or some other function to be optimised.

In the 1990's Hazelrigg [93] presented the systems engineering approach as a tool for rational decision-making in the design process. According to the International Council on Systems Engineering (INCOSE) Systems Engineering Handbook [94], Systems Engineering (SE) is a *discipline that concentrates on the design and application of the whole (system) as distinct from the parts, through an iterative process of top-down synthesis, development and operation of a system that satisfies in a near optimal manner the full range of requirements for it*'. SE is still currently the dominant integrating framework for engineering design.

During the previous few decades as systems became more elaborate, the fulfilment of engineering design requirements has experienced serious delays and cost overruns. In the U.S. Department of Defence, where a large number of programs are executed, a significant increase has been observed in delays, from 33 in the 1970's to 63 now and in cost, from 50 in the 1970's to 78 , which are mostly due to inefficiencies in the application of SE methodology, as Collopy and Hollingsworth [95] discuss. In the late 1990's Collopy introduced a value based optimisation process, breaking the system to subsystems and components, as proposed by SE, and flowing down the system objective function to the subsystems and components objective functions. For each component, a composition function would be a function that accepts as arguments the vector of the component's attributes and converts them to system extensive attributes, which would then be inputs into the system's value model thus, a value score would be assigned to rank this specific component design. The objective function/value model would be a scalar function of all appropriate extensive attributes, while the task is to create the design that yields the highest score at the system level.